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GRANITIZATION AND HYDROTHERMAL ALTERATION AT BINGHAM, UTAH

BRONSON STRINGHAM

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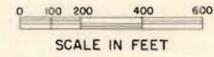
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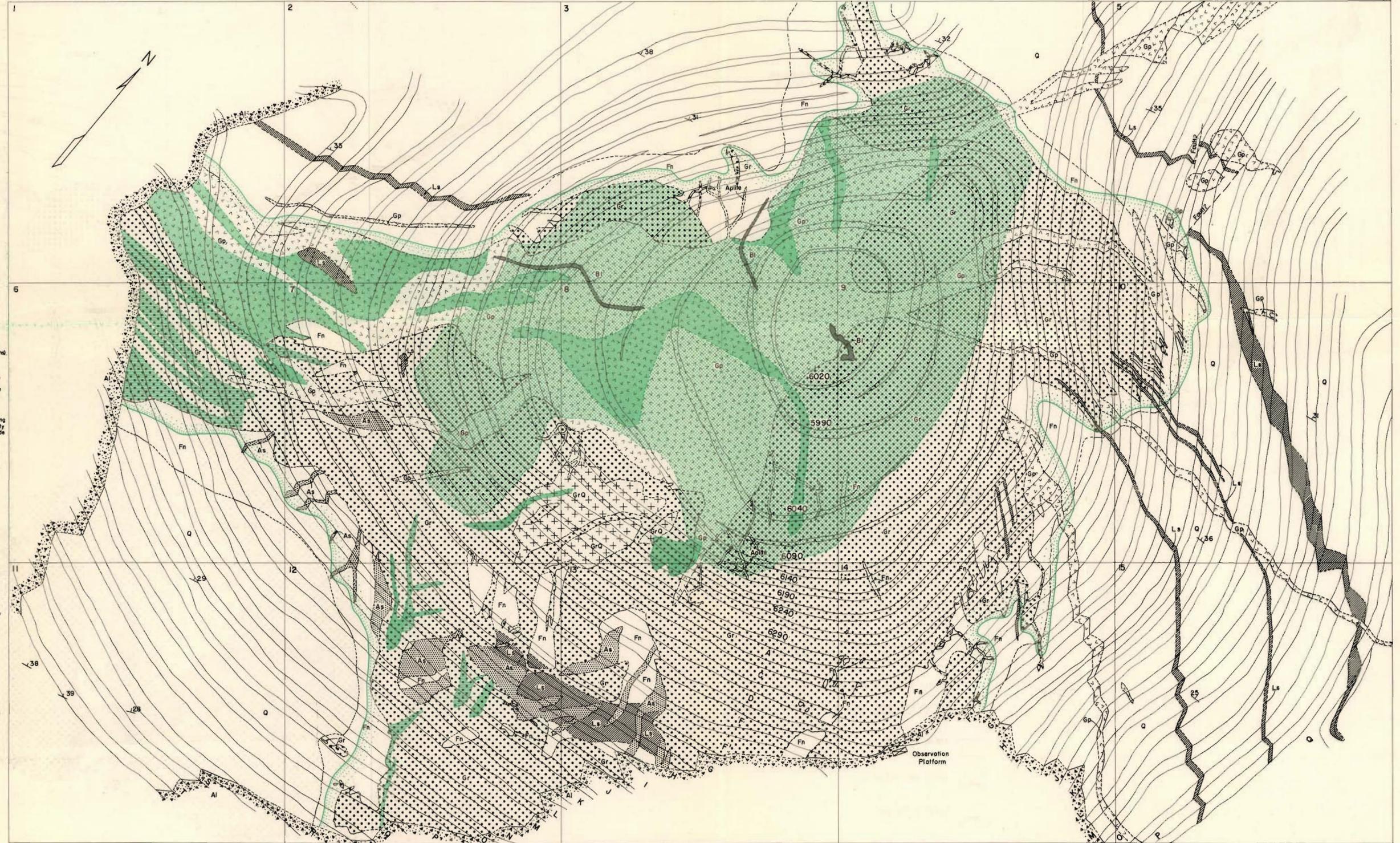
Notes

SURVEY AND GEOLOGY BY BRONSON STRINGHAM,
JAMES F. SYLVESTER AND ALLEN O. TAYLOR
1947 — 1949



EXPLANATION

- ALLUVIUM AND MINE FILL
- QUARTZITE AND IMPURE QUARTZITE (dolomitic and limy)
Medium grained, occasionally arkosic. Color white, gray and brown. Impure beds slightly greenish near granite due to presence of actinolite, chlorite and diopside.
- LIMESTONE (dolomitic and sandy). Dense and gray to light blue. Beds may lense rapidly. Colored greenish to brown near granite due to presence of diopside, actinolite, chlorite, and andradite.
- FELDSPAR NETWORK IN SEDIMENTS (outer boundary approximate). Microscopic feature: orthoclase and some oligoclase introduced between quartzite grain boundaries forming network appearance.
- GRANITIZED QUARTZITE. Fine grained, grayish with small white chequy patches and occasional brownish spots. Composed of microscopic quartz, orthoclase, oligoclase, and biotite. Frequent quartzite streaks (inclusions).
- GRANITE. In small part syenite, quartz monzonite, monzonite, granodiorite, quartz diorite, etc. Texture chiefly granitoid but sometimes fine grained or porphyritic with pink orthoclase crystals. Color gray to dark gray. Biotite always present. Orthoclase, oligoclase and quartz rarely determinable in field.
- ACTINOLITE SYENITE. A greenish gray medium granitoid rock containing orthoclase, oligoclase, biotite, and interstitial actinolite with frequent irregularly shaped solid patches of actinolite, diopside, and epidote. Interstitial diopside and epidote are occasionally present.
- GRANITE PORPHYRY. In part quartz monzonite porphyry. Phenocrysts constituting 10% to 80% of rock are pink to white orthoclase, oligoclase (often altered) and a little fresh biotite in a green to brown groundmass.
- BIOTITE-QUARTZ LATITE PORPHYRY. Phenocrysts constituting 30% to 50%, are white altered oligoclase and a little fresh biotite which often shows alignment in a greenish groundmass.
- STAGE I. KAOLINITE-ILLITE. Boundary determined by thin section. The alteration is thoroughly disseminated and does not follow channels. Kaolinite and illite, observable only through the microscope, are always mixed and have developed mostly from feldspar.
- STAGE II. HYDROTHERMAL BIOTITE-SERICITE (outer boundary approximate). Fine grained hydrothermal biotite has developed chiefly from primary biotite and feldspar and is recognizable in the field. Microscopic sericite present only in the feldspars. Disseminated type of distribution.
- STAGE III. CHLORITE-HYDROTHERMAL BIOTITE. Dark green to black, very dense appearing rock, occurring in streaks within granite. Microscopic chlorite and hydrothermal biotite are very fine grained and intimately mixed.
- STAGE IV. QUARTZ-SERICITE. Light (in granite) or dark (in granite porphyry) streaks of quartz and sericite. Most rocks have been affected to some degree but within mapped areas more than 15% of the rocks has been altered.
- STAGES V, VI, B, VII NOT MAPPED (SEE TEXT).
- LEVELS AND BANKS. Contacts on banks solid lines. Interpolated contacts on levels dashed lines.
- STRIKE AND DIP.
- LEVEL DESIGNATION.
- LEVEL ELEVATION.



GEOLOGIC AND HYDROTHERMAL ALTERATION MAP, UTAH COPPER MINE, BINGHAM UTAH

GRANITIZATION AND HYDROTHERMAL ALTERATION AT BINGHAM, UTAH

BY BRONSON STRINGHAM

ABSTRACT

The rocks exposed in the disseminated copper deposit at Bingham, Utah, consist of folded Pennsylvanian quartzites, limestones, and dolomites within which have been formed granite, actinolite syenite, granite porphyry with associated aplites, and biotite-quartz latite porphyry. Field and petrographic evidence shows that the granite porphyry and biotite-quartz latite porphyry are magmatic. That the granite and actinolite syenite may have been formed by granitization is strongly suggested by: (1) the presence of a microgranitic rock in the granite, recognized as being granitized quartzite, and (2) the replacement of quartzite by feldspar, observable only with the aid of the microscope, that occurs along the contact of the granite. Other chemical, textural, compositional, and other evidences support this hypothesis.

The hydrothermal activity attending the ore deposition took place in seven stages following the formation of the igneous-appearing rocks. Except for the first two, which can be separated on good microscopic evidence, all stages can be differentiated by structural field relations. Stage I saw the formation of kaolinite and illite. During Stage II hydrothermal biotite and sericite were widely developed. In Stage III, chlorite and hydrothermal biotite were formed, but in restricted areas. In Stage IV, quartz and sericite formed over wide areas, while during Stage V quartz was deposited in open fissures without accompanying alteration. Stage VI is the sulfide stage, and Stage VII saw the development of sericite and allophane in open fissures.

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PART I.—GRANITIZATION

INTRODUCTION

The results of the most recent mineralogical study of the copper mine at Bingham, Utah, were published in 1920, and the works of Boutwell (1905, p. 73-390), Keith (1905, p. 29-70), Beeson (1916, p. 2191-2236), and Butler (1920, p. 335-362) were the most extensive. The writer undertook a new study in the summer of

1947; the objective was to investigate the hydrothermal history of the disseminated copper ore deposits. During the course of the work, the possibility that some of the rocks at Bingham were formed by granitization became evident, and after further investigation it was decided to present the full results of the Bingham study in two parts. Part I deals specifically with detailed descriptions of rock units as well as

the granitization and related processes. Part II covers the hydrothermal history related to ore deposition.

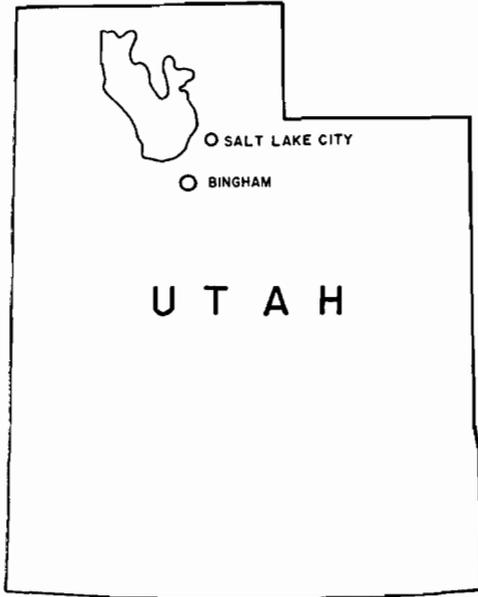


FIGURE 1.—INDEX MAP SHOWING THE LOCATION OF BINGHAM

Early workers on the Bingham copper deposit could observe considerably more area than is now exposed since recent dumping of waste has covered several critical areas. On the other hand, since the ore body now has been cut much deeper, less weathered rock and ore are now observable.

The present work has been greatly facilitated by a very favorable geographic coincidence, in that mapping could be done in the field concurrently with laboratory investigations conducted at the University of Utah. This has contributed immeasurably to the quick understanding of the nature of the rocks and has added to the confidence and speed of the mapping.

The Utah Copper open pit mine is situated just south of the town of Bingham, Utah, in the Oquirrh Mountains, a typical basin and range mountain about 20 miles southwest of Salt Lake City (Fig. 1).

The Kennecott Copper Corporation mines the disseminated copper deposit as an open-pit operation employing the level and bank method.

The levels carry railroad, power-line, and electric shovel facilities and are separated by approximately 50-foot high banks from which the rock is blasted. The ore contains values in copper, gold, molybdenum, and a little silver.

ACKNOWLEDGMENTS

Expressions of thanks and appreciation are offered to the management of the Kennecott Copper Corporation for permission to make the study and to the management and geologic staff for their whole-hearted co-operation and encouragement during the work; to The Geological Society of America and to the University of Utah for their financial aid without which the study could not have been made; to T. S. Lovering for his helpful suggestions and guidance and to G. E. Goodspeed for a very stimulating discussion of the granitization problem; to Dan McLachlan, Jr., for invaluable advice on crystallographic problems; to James F. Sylvester and Allen O. Taylor for their very able assistance in the field and laboratory; to Edwin W. Roedder who read the manuscript and offered valuable criticisms.

LIMITATIONS OF THE STUDY

No geologic map or other such information regarding the mine was received from the operating company, and the data and interpretations presented here were arrived at without any influence other than that gained from the literature. The conclusions are strictly the writer's and do not necessarily represent the views of the operating company. For various reasons, no direct intensive observations were made on the ore body or in areas beyond the open-pit boundaries, and hence no correlation of the disseminated copper deposits with the replacement lead-silver deposits of the district has been attempted. Since the original plan was to study the hydrothermal alteration and later the granitization, little attention was given to the larger sedimentary or structural features. This present work should be considered as a contribution to only one phase of the general problem. So many new questions constantly arise regarding the geology and mineralogy of the copper deposit proper that it would seem that the present work could still be carried on

for a considerable length of time with profit, and much more work is necessary to complete a full-scale geologic study of the district.

FIELD WORK

Intensive study began in the copper mine in the summer of 1947, and mapping and sampling continued through the field seasons of 1948 and 1949. During the summer months of 1950 and 1951 occasional trips were made to the mine for final checking.

Triangulation points were established on different levels around the periphery of the open pit, and, from these, triangulations were made with the plane table and alidade when accurate locations within the pit were necessary. Most of the work was done, however, with a steel tape and Brunton compass traverse along each level tying into surveyed points at either end of each level. This established fairly accurately, regardless of high-voltage power lines, the positions and distances on each level. The solid rock banks were examined foot by foot, and specimens were collected wherever laboratory examination was thought necessary. In this manner some levels were covered as many as four times, while all levels were traversed at least twice. There was much confusion in identifying rock types during the early stages of the mapping, but considerable confidence was gained after laboratory examination had established the true nature of the rocks. During the entire mapping of the pit no thought was given to granitization, and it was not until the end of the 1949 field season, when a peculiar rock type was definitely recognized as granitized quartzite, that granitization was considered a possible origin for many of the igneous-appearing rocks in the deposit.

Contacts were found only on the banks between the levels in the mine, and extension of these contacts was interpolated along the levels between banks. Solid lines on the map (Pl. 1) indicate contacts observed, and dashed lines represent interpolated positions. Some interpolated contacts were checked when later excavations exposed a new area, and these positions were also placed on the map as solid lines. As is readily apparent, different interpolations of contacts between banks can in many instances produce different map patterns. Some contacts

were drawn between banks with a fair degree of certainty, while others are drawn in positions thought to be most reasonable. No major contacts were reinterpolated after the granitization was recognized, and the map stands essentially as it was when first completed. Continued excavations make obsolete most mapped contacts, and in some very active areas contacts are obsolete within a week. Few contacts on cut banks are in exactly the same position as when mapped. The map (Pl. 1) represents geologic conditions during 1947 to 1949 only. Checking in 1950 and 1951 revealed that most of the rock units and contacts are at least in the immediate vicinity of the previous survey. Constant careful mapping of an area being mined at such a rapid rate as this would show some interesting and worthwhile information on the three-dimensional aspect of the deposit.

Almost all rocks collected were thin sectioned, and 803 sections have been studied. Seven large lantern-sized ($3\frac{1}{4}$ by 4 inches) slides were prepared of critical contacts. Many x-ray studies on minerals were made, and in two instances specimens were sent to experts for precise determination. Differential-thermal analysis, universal-stage, and other standard optical equipment was freely used.

The co-ordinates on the map (Pl. 1) are entirely artificial and are placed there only as an aid to the description of the area. Each square is numbered from 1 to 15. These section numbers are used for conveniently locating a specific area.

CHEMICAL ANALYSIS

Nineteen complete and six partial chemical analyses were made on the rocks and minerals at Bingham. Some of these pertain to the hydrothermal problem and are not presented in Part I. However, 13 complete analyses and 2 partial analyses regarded as pertinent to the problem of the origin of the rocks are included.

The quality of the samples available for analysis was poor. Since so much alteration has affected the Bingham rocks probably no entirely fresh specimen was obtained. The difficulties of obtaining a representative sample of Bingham rocks are manifold. The rock breaks into very small fragments due to innumerable post-mineral and pre-mineral frac-

tures, and most of the latter are faced with quartz and/or pyrite which must be scaled off. In some instances, the analyst was supplied with only a very small fragment, and in two instances (Analyses 4 and 5, Table 1) not more than 20 grams could be made available. The large bulk samples which are so highly desirable for analytical purposes were simply not obtainable. The interpretative value of the analyses, therefore, is not so reliable as is usually encountered.

The attempt to calculate a norm from several of the analyses did not work out at all reasonably, and the complications arising because of the extreme abundance of biotite with its variable composition made almost impossible any calculation which would correspond with the actual mineral content of the rock. Measured modes were made in the thin section of each rock analyzed except four which were estimated, and these are all given directly below each analysis. Except for analysis 12—feldspar network, 11—Last Chance stock, and 9—actinolite syenite, all the rocks show a low SiO_2 content and a high MgO , Fe_2O_3 , and K_2O content for granitic type rocks. It is believed that the extreme abundance of biotite, being low in SiO_2 and high in MgO , iron, and K_2O , accounts for these anomalies.

GENERAL GEOLOGIC SETTING

The oldest rocks within the area covered in this study are Pennsylvanian quartzites, impure quartzites, limestones, and dolomites which have been folded and locally faulted and within the mine area dip moderately to the northeast apparently without serious displacement. A younger irregular body of quartz monzonite called the Last Chance stock occurs beyond the borders of the mine to the south and west, while within the mine area itself granite, actinolite syenite, and an unusual rock, thought to be granitized quartzite, was formed. Intensive silicate mineral development is found around the periphery of this complex mass in the limestones and impure quartzites, as might be expected along a contact of a granite. The quartzites near the granite have been feldspathized to a moderate degree, visible only with the microscope. All these rocks were intruded first by a large mass of granite porphyry with offshoot

dikes, then by a biotite-quartz latite porphyry which appears only in very small dikes and irregular pipes. Extensive hydrothermal activity altered the rocks and culminated in the deposition of the main metalliferous ores.

SEDIMENTARY ROCKS

General Statement

All the sedimentary rocks exposed in the pit belong to one formation described and named "Bingham quartzite" by Keith (1905, p. 35), who estimated its total thickness to be 10,000 feet or more. G. H. Girty (Keith, 1905, p. 36) determined its Pennsylvanian age on the basis of two collections of fossils. Gilluly (1932, p. 34), in an area south of Bingham but in the same mountain range, distinguished the upper part of this formation as the Oquirrh Series.

The sedimentary rocks within the pit proper were found to be altered. Since very little work was done during this study on rocks beyond the pit, it is perhaps proper to quote excerpts from the excellent description by Keith (1905, p. 33-35) for the unaltered formation.

"The Bingham 'quartzite' is composed in the main of quartzites and of sandstones that are more or less silicified. The strata are for the most part white and frequently streaked. . . . In the upper part of the formation are many layers of argillaceous sandstone containing feldspars and mica in fine grains. . . . These sandstones are also slightly calcareous and locally developed into thin limestone beds. . . . which are of the same lenticular nature as the limestones that are mapped, and they are so small that it is not practicable to map them or trace them for any considerable distance. . . . Almost any section where the rocks are continuously exposed for 100 yards will show one or more layers of limestone or calcereous sandstone. . . . It is not possible, however, to connect the individual layers of one series with another. Usually the contacts of the limestones and quartzites are sharp and distinct and the transition from one rock type to another takes place within a few inches. In other cases. . . the quartzite passes downward into limestone through several feet of calcareous sandstone and sandy limestone. In still other cases, there is an alteration of limestone and sandstone layers for a few feet. The limestone lenses thin out along the strike and disappear in two ways. Either the closing quartzites approach each other and coalesce. . . or else the quartzites in the strike of the limestones are calcareous. . . . In a few places. . . thin layers of quartz conglomerate appear, but these are fine grained for that class of rock. . . . The uniformity of the grain makes the bedding of the quartzites very difficult to ascertain except where argillaceous, calcareous, or banded beds are present."

If the quartzite contains lime, even as little as 3-4 per cent, local usage classifies it as limestone.

Structure

The general attitude of the sedimentary formations in the pit is quite uniform. Many measurements on quartzite in regions considerably removed from the igneous-looking rocks showed that an approximate strike of N. 70°-85° E. and dip of 25°-40° N. is predominant over the entire area mapped. Near the igneous-looking rocks, alteration and cementation obscure the bedding. Only one sedimentary rock area close to the granite, near the lower center of Section 3, is questionable in regard to a change from the conventional regional dip. The rocks here are extensively altered and probably somewhat faulted, but this faulting is believed to have preceded the formation of the granite. Measurements of the attitude of the beds here were highly questionable, and hence none were placed on the map. A few faults were noted in other areas; their recognition was incidental to the mapping of the limestones. (See Section 5.) However, lack of time prevented giving too much attention to this feature since it would not contribute greatly to the major problem. Quartzites and impure quartzites could not be correlated from one level to another. Such a job would require very detailed sampling with accompanying thin sections as well as extremely close surveying control. However, in the mapping of some readily recognizable limestones, it was necessary to call upon faulting to explain their displacement from one level to another (Section 5). Some faults are known to extend into the granite, as extensive slickensided breaks and crush zones are found within it, but most of the major faulting is considered pre-granite. Joints in many attitudes are noted, but no over-all pattern was evident, and an extensive study into this feature was not deemed advisable. The granite rocks and closely adjacent sedimentary rocks at Bingham break up readily under the hammer into very small fragments due to the presence of minute fractures which intricately traverse the rock.

Bingham Quartzite Within the Mine

Pure quartzite.—The grains in the quartzite range from very fine ($\frac{1}{4}$ mm. in diameter) to a somewhat coarse grit (3-5 mm. in diameter).

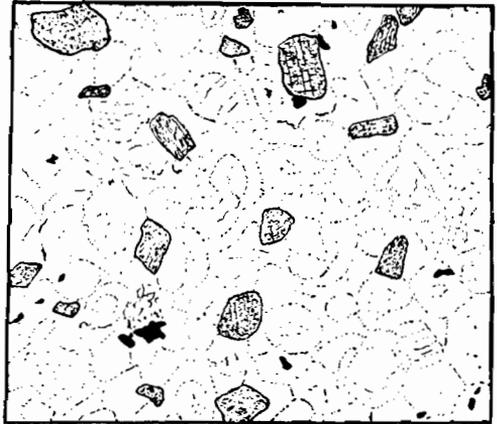


FIGURE 2. ARKOSIC QUARTZITE FROM OUTSIDE THE MINE AREA, NORTHEAST OF BINGHAM. Cloudy grains are orthoclase. Note that ghosts of rounded quartz sand grains are still present. Opaque areas are pyrite. Tracing from photomicrograph. $\times 30$.

No true conglomerate was discovered. Where not stained with limonite, the rock is usually white, gray, or tan. On the upper levels in regions removed from the granite, bedding is plain, but near the granite the bedding is obscure, and the rock is massive and glassy due to strong cementation by silica. Much pyrite is found in veinlets and as small disseminated crystals.

Under the microscope the pure quartzites remote from the granite show some porosity, but the boundaries between grains are interlocking, and ghosts of rounded quartz sand grains are present. In most sections, a little sericite is found interstitially. Rocks near the granite show suturlike grain boundaries and no ghosts of sand grains. Occasional quartzite specimens containing as much as 4 per cent detrital feldspar grains may be found within the pit. These feldspars, usually orthoclase, are scattered in more or less of a random distribution (Fig. 2), and all exhibit smooth, sub-rounded boundaries.

Impure quartzite.—Many sedimentary rocks differ considerably in composition from the

normal quartzite. Some beds are white and chalklike and much lighter in weight than normal quartzite, suggesting considerable porosity. Some are white to tan, while others range from tinges of green to an intense green. Individual specimens from areas of greenish rocks show blotches, irregular patches, and randomly oriented stringers of deeper greenish material. In many exposures a green streak or veinlet traverses as much as 10 feet through an otherwise massive-looking dense tannish quartzite.

Thin sections of the white impure quartzites show fine interstitial crystals of sericite, tremolite, or, in a few instances, wollastonite. Though generally interstitial the tremolite and wollastonite commonly penetrate quartz grains. Original impurities in these types of rocks are dolomite, calcite, and clay. The pale-green and greenish rocks contain greenish biotite, actinolite, and chlorite. The chlorite is thought to be an unusual variety since its index of refraction, near 1.54, is lower than ordinary chlorites. Quite evidently the greenish colors in the rock are due to different concentrations of chlorite, green biotite, and actinolite. The green stringers that traverse the quartzite may be explained on the basis that the original interstitial impure substances—lime, magnesia, alumina, and iron—were mobile enough during the development of the minerals to migrate through channels and form veinlets or group themselves in clumps and patches.

The impure quartzites may be found on all mine levels where sedimentary rocks occur. However, on the upper levels in regions more remote from the granite, the greenish colors are less prominent, indicating that here the development of these greenish minerals was not pronounced.

Impure limestone.—The impure limestones, which occur in thin beds, are found mainly on the east side of the pit where eight limestone lenses were mapped (Sections 4, 5, 9, 10, 14, 15). One limestone lens was mapped on the west side (Section 2), and two isolated limestone bodies mapped in Sections 2 and 7. Most of these rocks appear dense and greenish. Many specimens contain macroscopic quartz grains, but no carbonate was found. Occasionally some minerals, such as long blades of actinolite or patches of epidote and chlorite, are readily

identifiable in hand specimen. The beds range in width from a few feet to as much as 60 feet thick on some levels. The typical lenslike character of the limestones seems to be quite pronounced in some of the beds, and the thickness usually ranges rather markedly along the strike. Introduced pyrite is universally present and locally constitutes as much as 50 per cent of the limestone bed.

Microscopic examination reveals actinolite, chlorite, and occasional epidote and tremolite as the principal minerals of the impure limestone. Quartz grains appear scattered among these minerals. A greenish mineral, which otherwise looks like sericite, is common, as well as garnet which is believed to be near grossularite (index 1.74) in composition. These garnets are rarely seen in hand specimen. One carefully traced bed grades from a rock high in greenish silicates near the granite to a rock lighter in color and containing less silicate minerals, indicating that probably less silica and iron were introduced away from the granitic rocks.

Throughout the granite mass are large and small irregularly shaped inclusions of quartzite and impure quartzite with sharp megascopic borders. Many of the larger inclusions were mapped (Sections 12, 13, and 14 for example), but there are so many in parts of the area that only some could be represented on the map. Bedding on those observed is so obscure that true strike and dip could not be secured with confidence. Petrofabric work on these inclusions as well as the country rock showed no preferred orientation of the quartz grains, and hence no correlation of the inclusion attitude with the dipping country rock could be made using this method.

Dolomitic limestone.—One bed of what is believed to have been a more or less pure dolomitic limestone is found on the southern intermediate levels in Sections 12 and 13. Its mineralogy differs from the other limestone beds. It was identified and mapped principally on the presence of hydrothermal and skarn type minerals, but the outlining of its boundaries seems to be fairly accurate. The bed is judged to be between 30 and 80 feet thick and probably represents a segment of either the Jordan or Commercial limestone member (Keith, 1905, p. 38-41) of the Bingham quartzite. The ap-

pearance of the rock is extremely varied, as different minerals predominate in different areas. The following minerals were found: andradite (index 1.873), grossularite (index 1.74), very fine-grained massive-appearing diopside, actinolite, chlorite, epidote, and much coarse glassy introduced quartz. These minerals occur not in streaks and lenses along bedding, as might be expected, but as irregular patches up to 15 feet or more across. The boundaries between these different minerals are usually very irregular, and veins of one mineral may extend deeply into another. Veinlets of chalcedony, some of which are yellowish, and a few irregular small bodies of magnetite are introduced. In this area occurs the largest irregular veins and bodies of pyrite found in the pit. Fractures which ordinarily cause the rock to break into smaller fragments seem to be absent in this area, apparently because of the silicate minerals, and large blocks generally compose the talus on the bank of the level.

Weathering.—Weathering of the quartzite seems to be confined to the development of limonite, hematite, and some nontronite. On the upper levels near the position of the original ground surface are extensive brown stains. On the east side are areas where limonite and hematite are concentrated enough to color the rock brownish red. Also on the east side, apparently due to channeling of meteoric water, are large streaks of limonite which extend down along the bedding into the white quartzite. On the upper levels, nontronite is extensively developed as a result of weathering of pyrite (Stringham and Taylor, 1950, p. 1065).

GRANITE

General Statement

The term granite is here used in a broad sense to include several varieties of rock found in the pit. If classified according to Johannsen (1939, p. 141-159) they could be termed orthoclase granite, granite, orthoclase syenite, quartz monzonite, monzonite, syenodiorite, quartz diorite, granodiorite, or diorite. In mapping, all these types were grouped because no structural boundaries separated them, and megascopically they could not be readily differentiated. Seemingly they were all formed by the same proc-

ess during approximately the same period. All the rocks are rich in biotite, and each rock name probably should be prefixed by the word biotite. The term granite is here used for all the group since normal granite constitutes at least 75 per cent of the whole. The other types vary widely in amount and are found in irregular areas, large and small, randomly scattered over the entire granite exposure.

Early workers classified this rock as a monzonite, quartz monzonite, and monzonite porphyry; it was designated by Butler (1920, p. 351) as the "dark porphyry."

The granite constitutes the largest mass of an igneous-appearing rock within the copper pit and covers about two-thirds of the area. The largest uninterrupted mass, on the lower eastern levels of the mine in Sections 4, 9, 13, and 14, extends high on the south side (Section 12) where it presumably connects through to the granite found in the first 1000 feet of the Niagara Tunnel of the U. S. Mine. A large mass with irregular borders also extends on the upper levels toward the west in Sections 6 and 7. A small isolated area is found on the north intermediate levels (Sections 2 and 3).

Megascopic Features

It is practically impossible to classify the granite megascopically. The quartz, in all hand specimens observed, is in such small units that, except in rare cases, it could not be observed even with a hand lens. Orthoclase and plagioclase are generally both so altered that they appear white to gray and are indistinguishable from each other. Biotite is always recognizable but may be present in such fine flakes that its presence is determined only by its dark color. A granitoid texture characterizes all specimens examined, but four varieties were noted, and a description of each follows.

A medium-grained granitoid texture is found in places over the whole area mapped as granite, and it is by far the most abundant textural type (Pl. 5, fig. 2). In the lower eastern part of the pit where the granite is exposed this texture is very extensive and uniform. The grain sizes range from 1 to 3 mm. in diameter with an average of about 2 mm. The rock is gray. Distinction between orthoclase and plagioclase is

practically impossible except when larger (5 to 25 mm.) pinkish-lavender well-shaped orthoclase crystal are present. In many places these are as much as 20 or 30 feet apart, whereas in some areas they may be within 1-2 feet of each other. The biotite may be euhedral, or it may be in ragged, irregular black or brown patches and may vary in amount from a minimum of about 20 per cent, giving a spotted appearance to the rock, to about 50 per cent when the rock becomes extremely dark or almost black. Some of these dark granites on the intermediate levels of the south side (Section 7) carry plates of biotite up to about half an inch in diameter.

All minerals in rocks with fine granitoid texture are so small that they are not readily differentiated, and the rock takes on a uniform massive appearance. Close examination, however, reveals the ever-present crystals and irregular patches of brownish biotite. The overall color is usually a uniform dirty bluish gray, and the rock somewhat resembles a dense spotted limestone. This fine-grained type is common near the edges of the granite and in small apophyses, but small irregular areas of it may also be found deep within the granite mass. The occasional large pinkish-lavender orthoclase crystals are much rarer in this textural type than in the medium-grained rock.

Coarse granitoid texture is simply a coarser variety of the medium-grained granitoid texture. The individual crystals range from about 2 to 7 mm. across with an average near 4 mm. and therefore offer a much more normal granitic appearance than any other rock in the mine. Despite the larger grain size, biotite is the only definitely identifiable mineral, except for the frequent large pinkish-lavender orthoclase crystals. The quartz, plagioclase, and orthoclase of the main part of the rock cannot be differentiated from one another. This type is found only on the upper western levels of the mine in a fairly restricted area.

In many places the large well-shaped pinkish-lavender orthoclase crystals become so abundant that they make up 30 to 40 per cent of the rock. These are usually set in a groundmass of fine, medium, or coarse granitoid groundmass, and the rock has a porphyritic (or porphyroblastic) granitoid texture. Measurements

revealed no preferred orientation or alignment of the crystals. This porphyritic type occurs in scattered irregular small patches at irregular intervals. It is particularly abundant on the southwestern middle levels of the mine.

Near the old ground level the granite has been turned somewhat whitish with brown streaks due to surface weathering. In most cases, however, where weathering is deep, the biotite lightens in color, and a little brownish montmorillonite develops on some of the altered feldspars giving the rock a dull tannish-gray appearance.

Microscopic Features

Except for the size of the crystals, there is only a superficial correlation between the megascopic and microscopic appearance of these granite rock types. Of the 283 thin sections of granite examined, nearly each one is individualistic. However, the mineral species in these varieties are generally quite similar. Thorough preliminary observations revealed six textures which seemed distinctive enough to serve as standards to which all the textures could be referred. However, all combinations of these types exist. The minerals, which are nearly the same in all cases, occur in different proportions, and occasional absence of quartz, orthoclase, or plagioclase, or combinations of these, account for the variety of classifications recognized. Characteristics of each mineral and each texture in the granite type rock are here detailed.

MINERALS: Quartz is anhedral and interstitial. A texture similar to the sieve texture is very common and could be described as a group of interstitial quartz anhedral from 0.1 to 1 mm. across which extinguish simultaneously indicating their optical and crystallographic continuity (Pl. 2, fig. 1). This type is called "sieve" quartz. Quartz may also appear as interstitial dimensional granules .05 to 1 mm. in diameter, but with very ragged outlines and random extinctions. This type is called "granular" quartz. These two types are not to be confused with the "introduced" quartz, which appears in veins, and "alteration" quartz, which is associated with fine hydrothermal biotite and sericite.

Two types of orthoclase occur. Type I crystals are usually small and always euhedral against granular quartz. Of particular note is its anhedral character against itself with most boundaries irregular enough to resemble sutures. Most of this orthoclase is perthitic with a plagioclase (An₀₅). However, all gradations of perthite or antiperthite have been observed from 90 per cent orthoclase and 10 per

cent plagioclase to essentially 90 per cent plagioclase and 10 per cent orthoclase. The grain sizes are less than 1 mm. and average around 0.2 mm in greatest dimension.

Orthoclase of Type II forms the large pinkish-lavender crystals, seen in hand specimen, and are always much larger than the other minerals in the rock. The borders are usually ragged and very thoroughly scalloped, though the crystals as a whole are roughly euhedral. The groundmass minerals quartz, orthoclase, plagioclase, and biotite are in many places incorporated within the large crystal, especially near the margins; the plagioclase inclusions usually are oriented with (010) parallel to the edge of the large phenocrysts. Islands of quartz with scalloped borders are common within the crystals; several islands may have unit extinction. A full chemical analysis and a partial one was made of two of these orthoclase crystals (Table 1, Nos. 13 and 14). The high Na_2O (3.14 and 2.60) is probably largely due to included plagioclase crystals, but some of it may be in solid solution in the orthoclase.

The plagioclase composition ranges from An_{05} to An_{25} ; the more albitic plagioclase greatly predominates. Almost all the crystals are euhedral to subhedral except where they constitute cores within orthoclase crystals (Pl. 2, fig. 2). The size ranges from 0.1 to about 2 mm. In most instances albite twinning, although usually present, is somewhat obscured by alteration. Plagioclase cores with orthoclase rims (Type I) of various sizes (0.1–1.5 mm. in diameter) are very common (Pl. 2, fig. 2). The boundaries between the two are extremely irregular, and many are scalloped toward the plagioclase as though the orthoclase were replacing plagioclase. Several islands of plagioclase with unit extinction and optically continuous twinning may remain within orthoclase. Relic or ghostlike alteration patches of sericite having an outline similar to a plagioclase crystal in some places appear wholly within an orthoclase crystal suggesting that this was the position of a former plagioclase crystal which has now been replaced by orthoclase. The proportion of core material to rim material may run from 90 per cent orthoclase to nearly 90 per cent plagioclase.

Biotite, identified by x-ray methods (J. W. Gruner, personal communication), appears in all the granites examined and in some specimens constitutes as much as 60 per cent of the whole. Microscopically much of the biotite forms well-shaped crystals 0.05–1 mm. across. Some of the biotite is prominently scalloped and may poikilically enclose orthoclase, plagioclase, and quartz. The biotite quite commonly is frayed and ragged due to ran-

domly oriented biotite "foils" around the edges, and some entire crystals, maintaining their original shape, show a mat of fine-grained biotite with identical optical properties; this in reality is a pseudomorph of biotite after itself. In many cases, however, the biotite has altered to secondary biotite accompanied by quartz so that pseudomorphs may range in composition from pure biotite to as much as 5 per cent biotite and 95 per cent quartz (Fig. 8). Fine flaky biotite, as well as sericite, also commonly replaces any of the principal minerals as veinlets or irregular patches. The whole problem of this secondary biotite is more thoroughly described in Part II. A chemical analysis of the alkalis in some mechanically separated coarse biotite was made (Table 1, No. 15). The total alkali content, 10.8 per cent, is near the theoretical figure for biotite, but in this specimen Na_2O seems to be rather high, amounting to .75 per cent.

In all the slides of granite examined, no pyroxene or amphibole was found. However, in 10 of the slides, the outline of the secondary biotite patches simulates the outline of pyroxene and/or amphibole.

In every thin section apatite is an accessory mineral. In some cases it appears in fairly large (0.05 mm.) crystals, but in general crystals are very small and occur interstitially. In almost all slides rutile is present as very small stubby crystals often grouped in clumps. Long needle-like crystals in some slightly altered biotite are also thought to be rutile.

MICROSCOPIC TEXTURES: A true evaluation of the distribution of the different microscopic textures is almost impossible since only the orthoclase porphyritic type can be recognized in the field, and there was no attempt to delineate them in mapping. However, certain generalizations based on the locations of each specimen can be offered. The sutured texture with sieve quartz (2) is by far the most abundant and was found in all parts of the granite area, while the sutured texture with granular quartz (3), next in abundance, was restricted more to the lower eastern part of the pit (Sections 4, 9). Specimens showing the pure sutured texture (1) were encountered only occasionally and in random locations throughout the granite area. The porphyritic and lamprophyric sutured textures appeared principally on the higher levels on the west side of the pit.

The six distinct types of microscopic textures recognized were:

(1) Sutured Texture. Where orthoclase predominates, the extremely irregular boundaries between the orthoclase grains become very striking (Fig. 3). Weinschenk-Johannsen (1916, p. 200) called this texture sutured, and the term fits very

well the texture of much of the Bingham granite. All the orthoclase grains are roughly equidimensional and average around 0.5 mm. across. Biotite and plagioclase may be present between orthoclase grains in this and all the other textures.

(2) Sutured Texture with Sieve Quartz. Orthoclase is euhedral against the quartz but as in texture (1), anhedral and sutured against itself. The presence of sieve quartz is the distinguishing characteristic of this texture.

(3) Sutured Texture with "Granular" Quartz. The quartz appears as small interstitial equidimensional granules between the extremely sutured orthoclase crystals (Fig. 3). The individual quartz grains extinguish independently, as contrasted with the sieve quartz. The boundaries between orthoclase and quartz are irregular in most cases.

(4) Lamprophyric Sutured Texture. This texture may be similar to any of the three textures above, except that most biotite is euhedral giving a texture similar to the type found in some lamprophyres. Biotite usually constitutes 40-50 per cent of the rock.

(5) Porphyritic (or Porphyroblastic) Sutured Texture with Orthoclase of Type II. Large crystals of orthoclase of Type (2) are set in a groundmass of the typical sutured type. In rocks containing abundant large orthoclase crystals, plagioclase is more abundant and slightly basic in composition to An_{25} .

(6) Porphyritic (or Porphyroblastic) Sutured Texture with Plagioclase. In a very few rocks, crystals of plagioclase of about An_{25} are found in a groundmass having a typical sutured texture.

Chemical Analysis

Chemical analyses numbers 1-4, Table 1, are all of granite type rock. Number 1 is the least altered rock found, and this analysis gives the best account of the original composition of much of the granite. Most of the high content of K_2O in this rock is in perthitic orthoclase. Analysis No. 2 was made on the porphyritic variety of granite since this type was always high in plagioclase, and this accounts for the high Na_2O .

Number 3 is of a moderately altered rock of granitoid texture. It is characteristic of a large portion of the granitic rock found particularly in the southern and eastern portions of the granite exposure. The slightly higher Fe_2O_3 and MgO reflect the abundance of the alteration mineral biotite, while the remainder of the analysis approximates analysis Number 1. The

specimen for analysis Number 4 was secured about 1 cm. from the granite-granitized quartzite contact (Pl. 5, fig. 4). Here biotite and plagioclase are present in high concentration as indicated by the lower K_2O and high Na_2O

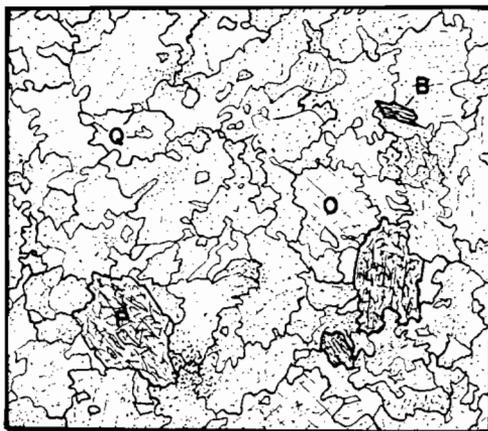


FIGURE 3.—GRANITE SHOWING SUTURED TEXTURE WITH "GRANULAR" QUARTZ

Quartz is in small equidimensional clear grains (Q). Cloudy orthoclase (O) has sutured boundaries. Plagioclase (P) and biotite (B) are also present. Tracing from photomicrograph. $\times 55$.

and MgO . This rock is near quartz monzonite or granodiorite in composition.

Contacts and Classification

Contacts between the granite and quartzite, limestone, or granite porphyry are very sharp, and thin sections across the contacts show that it is fairly sharp even on the microscopic scale (Pl. 5, fig. 6). On all contacts observed either in the field or under the microscope, no flow arrangement was found in the minerals of the granite. A petrofabric analysis of the biotite in some of the thin sections across contacts, showed no preferred orientation. However where the granite is next to quartzite, the quartzite exhibits the feldspar network feature, which will be discussed later.

The outline of the contact in places is of particular interest, as in Sections 9 and 10 on the east side of the pit, where beds of limestone and quartzite extend down into the granite mass for two or three levels without any apparent disturbance in the bedding. In Section

TABLE 1.—CHEMICAL ANALYSES OF RELATIVELY UNALTERED BINGHAM ROCKS AND MINERALS

Walter J. Saviournin, Analyst

University of Utah

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|--------------------------------------|-------|--------|-------|-------|-------|-------|--------|-------|--------|--------|-------|-------|--------|-------|------|
| SiO ₂ | 68.16 | 61.73 | 66.71 | 65.48 | 62.28 | 69.04 | 67.50 | 65.39 | 54.68 | 61.58 | 59.42 | 89.68 | 65.20* | | |
| Al ₂ O ₃ | 15.23 | 18.13 | 16.21 | 15.25 | 16.52 | 15.77 | 16.07 | 14.91 | 10.80 | 14.52 | 15.10 | 2.78 | 20.46 | | |
| Fe ₂ O ₃ | 1.29 | 1.87 | 2.70 | 1.88 | 2.72 | 1.26 | 1.70 | 3.90 | 5.56 | 6.54 | 6.52 | 1.95 | | | |
| MgO..... | 2.30 | 3.06 | 3.61 | 4.10 | 3.48 | 1.96 | 2.47 | 3.27 | 7.79 | 4.66 | 3.93 | 1.10 | | | |
| CaO..... | .62 | 1.16 | .30 | 1.48 | 1.21 | 1.16 | .52 | .98 | 11.38 | 1.41 | 4.56 | .41 | .60 | | |
| Na ₂ O..... | 1.24 | 4.28 | .82 | 3.63 | 4.29 | 4.55 | 2.18 | 1.71 | 1.50 | 2.02 | 4.04 | .57 | 3.14 | 2.60 | .75 |
| K ₂ O..... | 8.67 | 7.74 | 6.83 | 4.35 | 4.87 | 3.91 | 7.40 | 7.00 | 6.16 | 5.06 | 4.03 | 2.23 | 9.55 | 10.25 | 9.05 |
| TiO ₂ | .66 | .75 | .67 | .79 | .42 | .44 | .61 | .54 | .76 | .69 | .76 | .17 | | | |
| H ₂ O..... | 1.78 | 1.59 | 1.75 | 2.86 | 3.91 | 1.68 | 1.67 | 1.84 | 1.61 | 3.77 | 1.01 | .20 | 1.05 | | |
| Sp.Gr..... | 99.95 | 100.31 | 99.60 | 99.82 | 99.70 | 99.77 | 100.12 | 99.54 | 100.24 | 100.25 | 99.37 | 99.09 | 100.00 | | |
| | 2.61 | 2.54 | | | | 2.57 | 2.50 | 2.63 | 2.49 | | 2.69 | | | | |

Modes Measured

| | | | | | | | | | | | | | | | |
|----------------------------|----|----|-----|-----|-----|-----|----|----|----|----|----|----|--|--|--|
| Quartz..... | 25 | 12 | 13+ | 20+ | 19+ | 28+ | 23 | 19 | 4 | 12 | 9 | 75 | | | |
| Ortho. incl. Perthite..... | 62 | 52 | 66 | 28 | 30 | 26 | 56 | 51 | 61 | 34 | 23 | 13 | | | |
| Plagio..... | 5 | 25 | 4 | 32 | 35 | 34 | 8 | 10 | 2 | 22 | 34 | 4 | | | |
| Biotite..... | 7 | 10 | 15 | 18 | 16 | 12 | 12 | 18 | 1 | 32 | 6 | 8 | | | |
| Rutile and Apatite..... | 1 | 1 | 2 | 2 | — | — | 1 | 2 | | — | 1 | — | | | |
| Sphene..... | | | | | | | | | 2 | | | | | | |
| Actinolite..... | | | | | | | | | 11 | | | | | | |
| Diopside..... | | | | | | | | | 19 | | | | | | |
| Augite..... | | | | | | | | | | | 12 | | | | |
| Hornblende..... | | | | | | | | | | | 15 | | | | |

Note: All results are calculated to a 105° C. moisture-free and sulfide-free basis. The compensation for the latter is based on the amount of sulfur and copper present calculated to the theoretical formulas of first chalcopyrite then pyrite. The Fe₂O₃ value represents total iron as Fe₂O₃, minus the iron used for pyrite and chalcopyrite correction. The presence of sulfide prevented analysis for FeO. Any P₂O₅ present is included in the figure for Al₂O₃ but probably does not exceed 0.25%. No calcite was found in any of the rocks chosen for analysis, and hence CO₂ was not determined. The H₂O value was obtained by ignition at 1150°C. corrected for the weight change to be expected from the oxidation of the pyrite and chalcopyrite present.

* by difference.

+ modes estimated.

– less than 1%.

1. Granite, most unaltered rock available; fine granitoid texture
2. Porphyritic granite, slightly altered; porphyritic granitoid texture
3. Granite, moderately altered; granitoid texture
4. Granite, moderately altered; granitoid; 1 cm. from contact with granitized quartzite; 2 cm. from No. 5
5. Granitized quartzite, slightly altered; 1 cm. from granite contact; 2 cm. from No. 4.
6. Granitized quartzite, slightly altered
7. Granite porphyry, moderately altered
8. Granite porphyry, moderately altered
9. Actinolite syenite, slightly altered
10. Biotite-quartz latite porphyry, moderately altered
11. Quartz monzonite, Last Chance quartz monzonite, very slightly altered
12. Quartzite with feldspar network, slightly altered
13. Orthoclase from porphyritic granite, mechanical separation
14. Orthoclase from porphyritic granite, partial analysis; mechanical separation
15. Biotite from granite, partial analysis; mechanical separation

10 the granite-sediment contacts suggest that the granite extends sill-like into the sediments for a short distance, while in Sections 9 and 14 mapping shows that an interconnecting

according to the Johannsen system, all of these could be classified as a variety of granite (Fig. 4). According to the estimated modes some rocks mapped as granite may have prac-

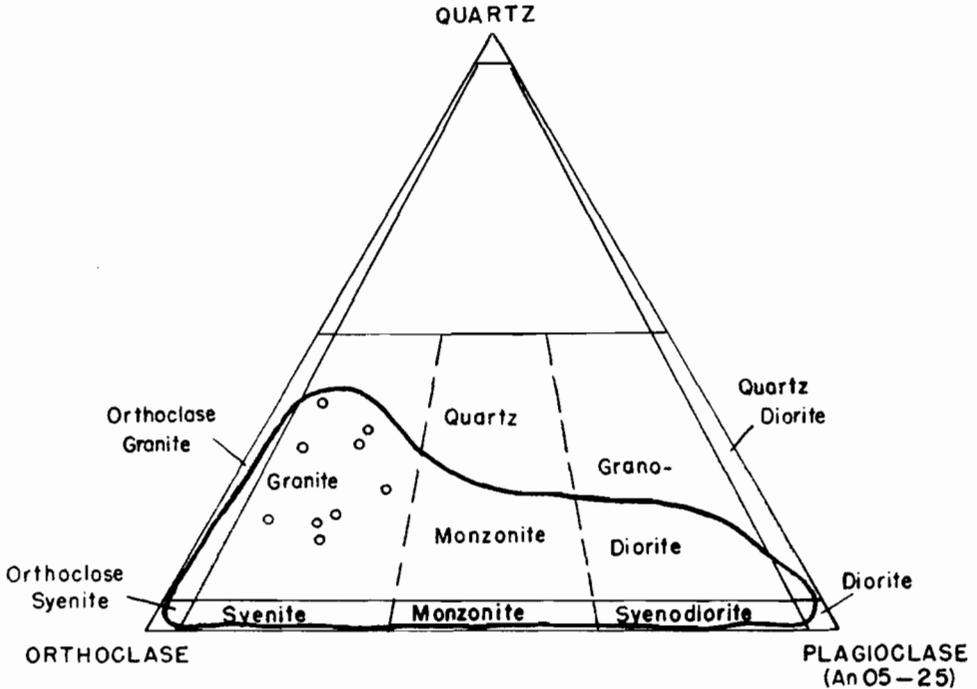


FIGURE 4.—CLASSIFICATION CHART

After Johannsen, showing the mineral composition of the granite. The nine circles represent measured modes and are true granites. Other estimated modes of the granite type rock fall within the area enclosed by the solid heavy line.

dikelike network extends deeply into the quartzite in a rather intricate manner. Granite dikes are found near all the margins of the granite and range in thickness from 2 inches to 6 and 8 feet. Many extend very irregularly with unmatched borders, often pinching out or swelling abruptly. No flow structure was found on any of these small dikes, and owing to the homogeneous character of the quartzite no sedimentary rock structures could be traced across dikes with or without offset; thus no evidence was discovered that fully and completely supports either the injection or the replacement origin of these dikes.

In attempting to classify the rock types composing the outcrop mapped as granite, estimates of the relative amounts of minerals were made on all thin sections. Nine modes were determined with the integrating stage, and,

tically no quartz, some may contain very little orthoclase, and others are essentially orthoclase and biotite, giving a range which covers the Johannsen classifications orthoclase syenite, syenite, orthoclase granite, granite, quartz monzonite, granodiorite, quartz diorite, diorite, monzonite, and syenodiorite. No attempt has been made to estimate the areal extent or relative amounts of each type, since they were all determined on microscopic preparations. However, at least 75 per cent of the slides are true granites with perhaps quartz monzonite and monzonite second in abundance. In the porphyritic types containing large amounts of pinkish-lavender orthoclase crystals, the plagioclase content usually increases while the quartz content generally decreases, placing this type generally in the monzonite group.

ACTINOLITE SYENITE

General Statement

The rocks classified as actinolite syenite are mineralogically and texturally similar to those classified as granite but are high in actinolite, epidote, and diopside. This group was mapped as a separate field unit on the presence of the readily recognized actinolite. The term actinolite syenite is used because actinolite and orthoclase are abundant in all these rocks, and quartz is usually absent or present in very small amounts. However, some rocks contain different relative mineral proportions, and other names such as actinolite-orthoclase syenite and actinolite granite are applicable.

The actinolite syenite is confined to areas on the south and southwestern intermediate levels of the pit (Sections 6, 7, 12, and 13) and forms irregular patches and dikelike masses in altered limestone, quartzite, and granite. Similar rocks are also found in the Niagara Tunnel of the U. S. Mine to the south, associated with normal biotite granite.

Megascopic Features

The overall texture of the rock is uniform and granitoid except where large patches of bladed actinolite and massive to granular diopside and epidote occur. The feldspar is gray with a very faint lavender tint and ranges in size from 0.5 to around 1.5 mm. The actinolite is always dark green and is easily recognized; it may amount to as much as 30 per cent of the rock. Biotite can occasionally be seen, but no quartz is discernible. The actinolite, diopside, and epidote, though disseminated throughout the rock in small crystals, may be present also in large (0.5-inch to 3-foot) concentrated patches, streaks, and veinlets.

Microscopic Features

The over-all microscopic features of the syenite are very similar to the granite. Orthoclase is the most prominent and persistent mineral with actinolite, diopside, and epidote very common. Plagioclase (An_8) is rare. The feldspars are roughly equidimensional, but the sizes vary markedly, even within a single thin section.

Quartz, though more often absent than present, is found, as in the granite, interstitially between

orthoclase; a number of units extinguish together in the typical sieve texture.

Orthoclase of Type I is also similar to Type I found in the granite. It is roughly equidimensional and often strongly perthitic and with boundaries so



FIGURE 5.—ACTINOLITE SYENITE

The turbid background of the whole illustration is a single optical unit of orthoclase (O). Rods and irregular patches of clear quartz (Q) in left half forms micropegmatite. Actinolite crystals are imbedded poikilitically on right. Note the actinolite crossing micropegmatite boundaries, left center. Traced from photomicrograph. $\times 50$.

irregular they resemble sutures (Pl. 2, fig. 3). Near contacts with quartzite, a structure akin to micropegmatite appears (Fig. 5; Pl. 2, fig. 4), except that the proportions of orthoclase to quartz are usually not in the eutectic proportions; the composition ranges from 90 per cent quartz and 10 per cent orthoclase to 10 per cent quartz and 90 per cent orthoclase. The large pinkish-lavender orthoclase phenocrysts similar to those found in the granite have been observed in only a very few instances.

Plagioclase is not very common, but where found it is usually euhedral with a composition near $An_{0.5}$. Plagioclase cores with orthoclase rims, as described under the discussion of granite, are very common.

The biotite in the actinolite syenite is like the biotite described in the granite but is less abundant. Crystals may be euhedral with ragged outline or may poikilitically enclose quartz and orthoclase, and there may be, in rare instances, some fine-grained biotite pseudomorphs after biotite.

Actinolite is always abundant. It is very pale green with X colorless, Y pale bluish green, Z pale bluish green, $\alpha = 1.621$, $\beta = 1.632$, $\gamma = 1.644$, $2V(-) = 72^\circ$, $ZAC = 15^\circ$. Except for a few large crystals, the sizes range from 0.2 to 2.0 mm. The larger crystals average 1–2 cm. in greatest dimension and may be present as single crystals, unoriented clumps of crystals, or arranged in rosette pattern. The actinolite relationship to the other minerals

may be classified in four ways: (1) interstitial but euhedral between orthoclase, plagioclase, biotite, and quartz; (2) poikilitically within crystals of orthoclase (Fig. 5); (3) subhedral crystals crossing boundaries of minerals and boundaries of the micropegmatitic structure (Fig. 5) without disturbing the shape of the actinolite; and (4) irregular patches and veinlets which cut all other minerals.

Epidote is not always present. Under the microscope it is yellowish, $2V(-) = 82^\circ$, $XAC = 4^\circ$. Crystal sizes range from 0.1 to about 1 mm. It occurs in precisely the same manner as the actinolite: (1) interstitial, (2) poikilitic within orthoclase (3) crossing crystal boundaries of orthoclase, quartz, etc., and (4) irregular patches and veins.

Colorless diopside (α 1.670, β 1.674, γ 1.694, $2V(+) = 52^\circ$, $ZAC = 38^\circ$) was found in several slides. It is found principally interstitially but it is always euhedral. Occasionally a large patch (3–6 cm.) of very fine-grained diopside was discovered, perhaps representing an undigested dolomite inclusion.

In all slides examined, apatite was present as disseminated crystals of various sizes, from extremely small up to as much as 0.5 mm. in length. Small euhedral crystals of sphene were found in most of the specimens examined, usually disseminated but occasionally grouped in clumps.

Special Feature

Several small crosscutting dikes of actinolite syenite were found in quartzite, having extremely irregular edges, often pinching and swelling within 1–2 inches from a dike 3 inches wide to 0.5 inch wide. The microscope showed that these dikes were rich in micropegmatite of unusual proportions of quartz to orthoclase (Pl. 2, fig. 4) and also rich in actinolite.

Chemical Analysis

Analysis Number 9, Table 1, was made on slightly altered actinolite syenite. SiO_2 and Al_2O_3 are comparatively low here, and Fe_2O_3 , MgO , and especially CaO are unusually high as compared to the granite, granite porphyry, and granitized quartzite. The K_2O and Na_2O values are near that of the granite analyses 1 and 3 and granite porphyry analyses 7 and 8. The high Fe_2O_3 , MgO , and CaO are due to the abundance of diopside and actinolite. Since this rock contains very little modal plagioclase, the high CaO (11.38) content raises the question of why basic plagioclase is not present in

large amounts. This anomaly is discussed in the section on the Origin of the Actinolite Syenite through Granitization Processes.

Contacts and Classification

All contacts of the actinolite syenite with limestone and quartzite are sharp. Small dikes extend into the quartzite, but none was found extending into the limestone. The trace of the contacts themselves are quite irregular, and wall-rock prominences extending into the syenite are common.

The contact with the granite covers 5–10 cm., and two large thin sections (3¼ by 4 inches) covering this contact show that there is no appreciable difference in the texture of the rock, from one type to the other. The only distinction is that the amount of actinolite and epidote of the syenite gradually diminishes to zero, and biotite increases toward the granite. Near the center of the contact, actinolite and epidote are altered partially or completely to aggregates of biotite. This biotite is much more greenish, in contrast to the brown color found in the secondary biotite of the granite. Nowhere along any of the contacts was there any semblance of alignment of crystals.

Only estimates were made of the relative amounts of the minerals in the actinolite syenite. The great majority of specimens contained but a very small amount of quartz and only a little plagioclase. Therefore, the term syenite is applicable in its truest sense to most of these rocks. However, in some slides quartz made up more than 5 per cent of the rock, and these could probably be called quartz syenite, nordmarkite, or perhaps even granite. A few rocks lack plagioclase and quartz and could properly be called orthoclase syenite. Since most of the rocks come under the classification of syenite, however, it seemed advisable to use the term for the group, and, since actinolite is also always present, it should be included in the name.

GRANITE PORPHYRY

General Statement

The term granite porphyry includes all the porphyritic rocks found in the pit with the

exception of the porphyritic granite and actinolite syenite, which contain large pink orthoclase crystals, and a biotite-quartz latite porphyry. The relative amount of phenocrysts to groundmass varies rather widely. If a classification based upon whether the phenocrysts constituted more or less than 50 per cent of the rock were employed, nearly one-third of the rocks could be classified as rhyolite porphyry. Compositionally two classifications are possible. In a very large majority of the rocks, orthoclase greatly predominates over plagioclase, resulting in a granitic or rhyolitic type rock. In many rocks, however, the plagioclase-orthoclase ratio is near 1, resulting in a quartz monzonite type rock.

Butler (1920, p. 352) distinguished this rock type with a generalized term "light porphyry"; this term is still in popular use.

About one-third of the total area of igneous-appearing rocks in the pit is granite porphyry. The largest uninterrupted mass is near the northwestern central part of the mine (Sections 3, 8). A large arm extends the length of the pit toward and west where it disappears under dump material (Section 1). Some medium-sized dikes and stringers extending southwestward from the main mass are found in Sections 6 and 7. One small dike here is isolated, and granite surrounds it in outcrop. In Sections 8 and 13 a medium-sized apophysis projects from the main mass toward the south. In the eastern part of the pit the main mass connects with five large dikes and several small plugs (Sections 4, 5, 9, 10, 14, 15). The two large southernmost dikes (Sections 9, 10, 14, 15) crosscut sedimentary beds at a small angle and extend to the southeast beyond the borders of the pit. The southernmost of these was not found to be connected to the main mass in outcrop (Section 9). Near the borders of the large central area are innumerable small aplite dikes which extend into all the different types of adjacent rock. Only a few of these could be shown on the map.

Megascopic Features

All specimens mapped as granite porphyry are distinctly porphyritic with orthoclase or plagioclase and occasionally biotite as phenocrysts. In some cases phenocrysts may make

up 80 per cent of the rock, and unless careful optical observation is made these types may be confused with granite. In some instances, the phenocrysts are so small and so few that the rock appears uniformly dense and may simulate some of the adjacent quartzites (Pl. 2, fig. 5). As a result, thin sections were made to determine the position of several of the contacts. In general, phenocrysts range from 0.5 mm. to 8 mm. in greatest dimension, but in a few instances some are considerably larger. The average, however, range between 1 and 5 mm.

Quartz phenocrysts are found in only a few areas, and most of them are fairly large, glassy equidimensional crystals. Orthoclase is by far the most abundant phenocryst mineral. It is usually white to pinkish, and in many places hydrothermal alteration has made many of the crystals chalklike. In some the rims only are altered. Plagioclase phenocrysts are white when fresh or only slightly altered, but most are intensely altered and then take on an earthy claylike appearance with colors near gray to tan. Biotite phenocrysts are present as brown to black euhedral crystals or in ragged patches of fine-grained hydrothermal material.

The groundmass is very dense and fine-grained, and hence the minerals are not resolvable in hand specimen except where black specks, presumably biotite, are noticed in some rocks having a slightly coarser groundmass. Depending upon the stage of alteration, the groundmass varies from very pale green to white and, where intensely altered, to tan.

Weathering and hydrothermal alteration resulted in two broad general types of changes in the typical granite porphyry.

Type I. Hydrothermal alteration not confined to fractures or other visible channels has produced considerable kaolinite, illite, biotite, and sericite. These minerals weather to montmorillonite which is yellowish brown; in the large central area these brownish-yellow phenocrysts give the rock a distinctly spotty appearance. In hand specimen the montmorillonite is pale green when wet and first collected on a fresh bank, giving the impression that the rock has a high copper content. When dry, however, the brownish yellow of the montmorillonite is seen. Where the rock has been intensely altered and later weathered, the brownish-yellow color

appears in the groundmass, and the whole rock is light tan and chalklike.

Type II. As a result of intense silicification and sericitization, which in this case follows visible channels, hard, dense, quartzose-appearing material traverses the rock in streaks, and the Type I alteration is found interstitially between the streaks. Where channels are so close together that the whole mass is altered, phenocrysts disappear, and the rock resembles dense quartzite with a few small brown patches of biotite.

Phenocrysts predominate over groundmass in the rocks of the large central mass. To the westward, and in the dikes of Section 6 and 7, phenocrysts, larger than average, make up less than 30 per cent of the rock and the groundmass is often slightly greenish. On the eastern side of the pit, in the northernmost dike and the two southernmost dikes, phenocrysts are extremely large but rather scarce. In these dikes large quartz phenocrysts become quite prominent. The groundmass here is also pale greenish. In the small plugs and stringers in Section 5 the phenocrysts are small, less than 0.5 mm. in diameter, and the groundmass is very dense, white, and sometimes chalky due to the intense alteration to sericite.

Microscopic Features

Quartz and orthoclase, which make up at least 95 per cent of the groundmass, are anhedral and equidimensional, presenting a somewhat granular appearance (Pl. 2, figs. 5, 6). The two minerals are generally about the same size. When the phenocrysts are few, the groundmass has an extremely fine texture, but the groundmass grain size grades upward to a maximum of 0.2 mm. in rocks where phenocrysts constitute 80 per cent of the rock. Groundmass plagioclase crystals, which are rather scarce, are usually slightly larger than the quartz-orthoclase aggregate and generally are subhedral. A very few small flakes of euhedral biotite about the same size as the quartz and orthoclase also appear in the groundmass. Apatite, the only accessory, is found in clumps and disseminated crystals.

Quartz phenocrysts are rather large (2-3 mm.) subhedral crystals with extremely irregular borders suggesting resorption.

Orthoclase phenocrysts present in all sections examined, make up 30-70 per cent of the phenocrysts. Most of the crystals are subhedral to eu-

hedral but exhibit very ragged borders (Pl. 4, fig. 1). Very commonly quartz and plagioclase inclusions the size of similar grains in the groundmass occur within and along the rims of the orthoclase (Pl. 2, fig. 6).

Misch (1949, p. 384; Pls. 3, 5 of Pt. II) found a somewhat similar condition in the rocks of the Sheku area, China. It is believed that such features of the phenocryst (inclusion of groundmass minerals and irregular borders) may be best explained in either of two ways: (1) The phenocryst could have continued to grow after the groundmass had largely been formed by feeding of late-stage liquid to the phenocryst. (2) The larger phenocryst has less surface energy than the smaller groundmass orthoclase crystals, resulting in an activity gradient where ions making up orthoclase migrate from the smaller crystals to the larger. This results in the growth of the larger crystals at the expense of the small groundmass orthoclase crystals. One effect of this would be ragged borders. Also, the groundmass quartz, and plagioclase originally occupying interstitial positions between similar sized randomly oriented groundmass orthoclase, would now find themselves surrounded poikilitically by orthoclase particularly near the margin. The problem of why some of the plagioclase inclusions become generally oriented with (010) parallel to the phenocryst edge (Pl. 2, fig. 6) has not been satisfactorily solved.

Plagioclase phenocrysts occur in all the porphyritic rocks and usually constitute 5-50 per cent of the phenocryst content. They are generally euhedral to subhedral with fairly straight borders, and their composition ranges between An_{05} and An_{20} . Most of the phenocrysts are so highly altered that the albite twinning is obscured. No plagioclase cores with orthoclase rims similar to those found in granite and actinolite syenite are present in the granite porphyry.

Biotite phenocrysts are not abundant but are always present, composing 10-20 per cent of the phenocryst content. The outlines of the biotite crystals are similar to the outlines of the biotite in the granite and actinolite syenite. Some crystals are euhedral or have a general euhedral outline but with ragged borders, some contain inclusions of groundmass material, and some are changed to secondary biotite (pseudomorphous after biotite). Much biotite is slightly bleached with small needles of rutile arranged within it in the commonly observed trigonal manner.

In hand specimen an alignment of crystals indicating flow is very obscure, but thin sections of a few specimens from near some of the contacts showed a strong flowage alignment parallel to the contacts.

Chemical Analysis

Aplites

Analyses numbers 7 and 8, Table 1, were made from the least altered granite porphyry specimens obtainable. The SiO₂ and Al₂O₃ con-

Small dikes and stringers related to the granite porphyry are profuse near its borders and extend out into adjacent rock as much as

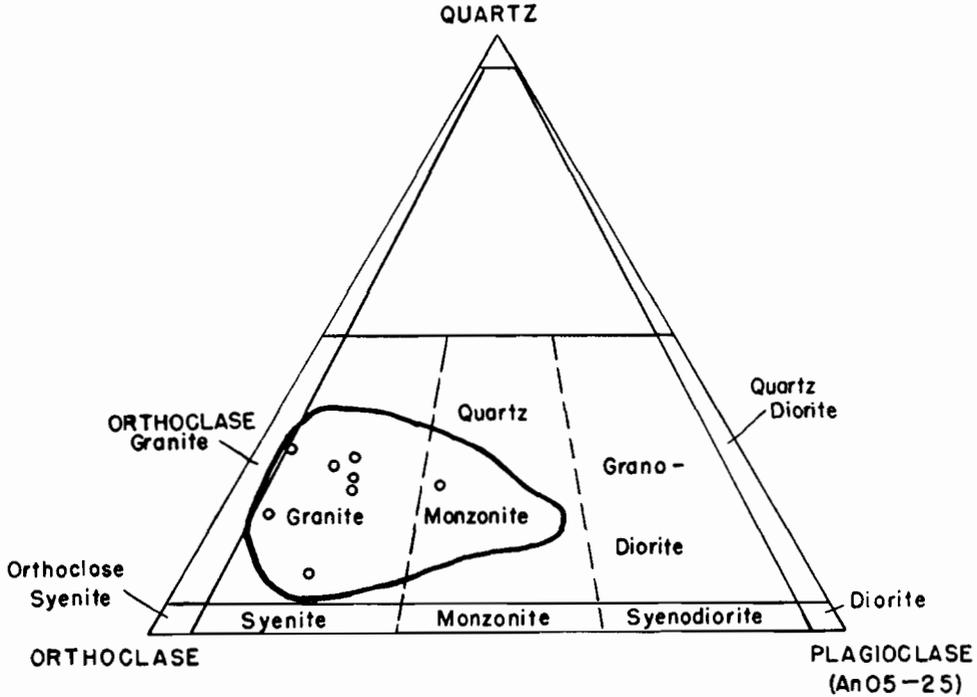


FIGURE 6.—CLASSIFICATION CHART

After Johannsen, showing the mineral composition of the granite porphyry. Of the 8 measured modes indicated, 7 fall in the granite field and one in the quartz monzonite field. All other estimated modes of granite porphyry fall within the area enclosed by the solid line.

tents do not vary much from the granite analyses 1 and 3. The amounts of Fe₂O₃, MgO, CaO, and K₂O are also very similar, and Na₂O is somewhat higher. From these four analyses (1, 3, 7, 8)—two of granite and two of granite porphyry—it seems evident that there is not much difference in the chemical composition of the two types.

Contacts

All observed contacts of the granite porphyry with granite, limestone, or quartzite are “knife edge” and quite regular when carefully traced, so that these contacts were more confidently interpolated from one level to another than were the contacts of the other rocks.

500 feet. These dikes range in width from 5 mm. to 2 feet and are found in all types of rock of the pit except the granite porphyry itself and biotite-quartz latite porphyry. In hand specimen, the aplites are slightly pinkish and rather fine-grained. They are predominantly quartz and orthoclase with a little plagioclase and a very little biotite. All the minerals are about the same size and are roughly equidimensional with fairly regular borders. Thin sections across very small dikes in granite show extremely sharp borders with a gradation in grain size from the center of the dike to the margin, the smaller crystals being next to the margin (Pl. 3, fig. 1). Many more dikes are present than are indicated on the map, and they are most abundant near the large central main mass of granite

porphyry. No offshoot aplite dikes from the dikes or plugs of granite porphyry on the east side of the pit were observed.

Classification

Eight modal measurements were made with integrating stage employing extreme caution to minimize errors due to alteration features. In all but one case these fall within the granite field; the exception is quartz monzonite. An estimation of the modes of all the other specimens showed that in a number of instances plagioclase increases to the extent that the term quartz monzonite porphyry is applicable. These measurements are plotted on a Johannsen diagram, (Fig. 6), and a field is drawn which encompasses all the estimated modal compositions.

BIOTITE-QUARTZ LATITE PORPHYRY

General Characteristics

This rock, composed of large white phenocrysts and abundant biotite phenocrysts in a pale-greenish groundmass, is distinctive in hand specimen. It occurs very sparingly in the pit. The rock forms dikes 2-30 feet wide that intrude granite, granite porphyry, and quartzite in the north-central part of the pit. Two dikes were mapped in Sections 2, 3, and 8, but the largest and most accurately outlined mass is in the northwest corner of Section 9 where the boundaries were fairly well located because banks in this part of the pit were moving rapidly at the time of mapping and several return checks could be made.

Megascopic Features

The porphyritic texture is immediately evident in all these rocks. White chalklike feldspar phenocrysts averaging about 3 mm. across are always present, together with very abundant black to brown biotite phenocrysts. The latter are commonly in alignment parallel to the walls of the dike. The groundmass is usually greenish to greenish black; its texture is very fine but in some places is coarse enough so that the grains are resolvable with a lens. Large pink orthoclase crystals, as much as 5 cm. long, occur sparingly.

Microscopic Features

All the smaller euhedral feldspar phenocrysts of the biotite-quartz latite porphyry are so altered that their true nature has been almost obscured. Probably most of them were plagioclase since the orthoclase in the groundmass has not been appreciably altered. The large pink euhedral orthoclase crystals are very slightly perthitic, and some of their borders contain inclusions of groundmass. Quartz phenocrysts with ragged edges are seen only under the microscope and are rather small and comparatively rare. They may be present as single isolated crystals or in groups. Some of the groups of quartz anheda are elongated as though they had been stretched out due to flowage. Biotite crystals are either euhedral, subhedral, or have very ragged borders, and some are completely changed to biotite pseudomorphs. Most of the biotite shows alignment due to flowage (Pl. 3, fig. 2), and many crystals appear to have been bent.

The groundmass is a granular aggregate of quartz and orthoclase with much biotite mixed with it. Alteration to a greenish biotite and chlorite is always a prominent feature, and no doubt imparts the green color. A little rutile was found as well as considerable apatite; both occur in small, disseminated crystals.

Chemical Analysis

Analysis Number 10, Table 1, is of biotite-quartz latite porphyry. Except for a high content of iron and magnesia accountable for in the profuse biotite, there is not much difference in composition from that of granite, granitized quartzite, and granite porphyry.

Contacts and Classification

All the contacts observed are quite sharp and fairly regular, and alignment of crystals showing flow is quite evident (Pl. 3, fig. 2). The direction of intrusive movement, however, was not determined in the field.

The abundance of euhedral biotite phenocrysts at first suggests that the rock is closely related to the lamprophyres. If the altered feldspar phenocrysts are all plagioclase, and the orthoclase of the groundmass is considered, the rock represents a composition near monzonite or quartz monzonite. Since groundmass always predominates over phenocrysts, the term quartz latite porphyry is probably more applicable. The profuse biotite in the groundmass as well as in the phenocrysts justifies the prefix biotite.

LAST CHANCE QUARTZ MONZONITE

The Last Chance intrusive stock is an igneous-appearing rock outcropping in a large area west, southwest, and south of the copper mine. None of the Last Chance rocks are believed to occur within the mine proper, but previous workers have made important reference to it. The Last Chance quartz monzonite is mineralized only slightly, and no appreciable disseminated copper mineralization has been found within it. Some of the early workers thought that all the igneous rocks in the Bingham District were of the same type and the same age. On his map, Boutwell (1905, Pl. XXXIII) used the same pattern for both the Bingham rocks and the Last Chance rocks. During this study approximately 50 thin sections of Last Chance specimens were observed.

Keith (1905, p. 52) classified the Last Chance rock as monzonite. The rock is medium fine granitoid with grain sizes averaging usually 1–2 mm. in diameter. Average mineral composition ranges as follows: quartz 5–15%, plagioclase (An_{26-40}) 30–40%, orthoclase 20–30%, biotite 5–10%, augite and hornblende 20–30%, and the accessories, magnetite, rutile, and apatite. In augite $\alpha = 1.685$, $\beta = 1.690$, $\gamma = 1.704$, $2V(+)$ = 60° $ZAC = 47^\circ$, it is faintly pleochroic from colorless to very pale green. The hornblende showed X pale green, Y green, Z green, $ZAC = 15^\circ$, $2V = 84^\circ$. The texture and mineral composition are much more uniform in the Last Chance rock than in the Bingham granite; the only exception is in some specimens from small dikelike bodies and along the edges of the mass which are porphyritic. Plagioclase is generally euhedral, and orthoclase and quartz interstitial. In several instances hornblende rims augite (Fig. 7). Analysis No. 11, Table 1, shows higher CaO and lower SiO_2 than any of the Bingham rocks other than the actinolite syenite. Evidently the CaO in the Last Chance stock has gone into the making of plagioclase as contrasted with the CaO in the actinolite syenite (Analysis 9), which went mainly into actinolite, epidote, and diopside.

The question as to whether the Bingham rock and the Last Chance rock are the same or not has been a matter of debate for a number of years, but from the evidence the writer

believes that the Last Chance rock is distinctly different from Bingham rock.

FELDSPAR NETWORK

Microscopic Features

Early in this study it was noted that in sections across granite-quartzite contacts the



FIGURE 7.—LAST CHANCE QUARTZ MONZONITE

Large crystal in upper left is augite with a hornblende rim. Twinned plagioclase, orthoclase, a small amount of quartz (clear), and three crystals of biotite are present. Opaque is magnetite. Tracing from photomicrograph. $\times 40$.

quartzite always contains orthoclase and plagioclase (An_{06} to An_{12}) interstitially, replacing the edges of quartz grains. Not until it was noted that thin sections of specimens taken as much as 300 feet from the granite contact also contain such introduced feldspar was the wide extent and full significance of this feature realized. Because of a late start on this problem and the monumental task of outlining the quartzite areas containing the feldspar through multitudinous thin sectioning, only a beginning on the problem of its areal extent could be attempted.

Although the hand specimen containing feldspar network looks no different from the normal quartzite, the characteristics observed in thin section are very unusual and striking. In many specimens the quartz grains interlock in the conventional manner, but between many grains are irregular stringers and patches of feldspar (Pl. 4, fig. 2). Only occasionally does feldspar cut quartz anheda, and this is usually in a pattern suggesting that the quartz was once fractured. The feldspar is otherwise interstitial, interweaving, and connecting one patch with another. Some replacement patches of orthoclase are up to 2 mm. across. The individual feldspar anheda are usually quite small with sutured borders, but occasionally a single optical unit of feldspar may surround several quartz grains. Stringers may extend from these patches through the interstices of the quartzite

to other patches, supporting the belief that all or most of the network may be interconnected. Under crossed nicols most of the sections appear to be normal quartzite; it is only when nicols are uncrossed, the light cut down, and the microscope set slightly out of focus that the network shows up well. Where feldspar is present in large amounts, quartz anheda may be surrounded. Also, in some cases where orthoclase is abundant, quartz-feldspar boundaries may become fairly straight (Pl. 4, fig. 2), but feldspar-feldspar boundaries are always sutured.

An unusual feature appears in many of these isolated or nearly isolated quartz grains. Their shape is euhedral to subhedral with rhombic shapes predominating and occasionally other short edges appearing (Pl. 4, fig. 2). Bayley (1893, p. 85-96) found a similar condition in the mottled quartzites near the Pigeon Point

PLATE 2.—PHOTOMICROGRAPHS

FIGURE 1.—FINE-GRAINED GRANITE, X NICOLS

Least altered granite observed. Light areas mainly quartz, and darker minerals largely orthoclase. Note a typical patch of sieve quartz (isolated anheda with unit extinction) within outlined area.

FIGURE 2.—PLAGIOCLASE WITH ORTHOCLASE RIM IN GRANITE, X NICOLS

FIGURE 3.—ACTINOLITE SYENITE, X NICOLS

The predominant mineral is perthitic orthoclase (darker gray) with suturelike boundaries. Very few small grains of quartz (white) present.

FIGURE 4.—ACTINOLITE SYENITE FROM NEAR QUARTZITE CONTACT, X NICOLS

Micropegmatitic structure well developed with quartz (light gray) greatly predominating over orthoclase (dark gray)

FIGURE 5.—GRANITE PORPHYRY (RHYOLITE PORPHYRY) SHOWING VERY FINE TEXTURE, X NICOLS

Phenocrysts are altered feldspar in a groundmass of quartz and orthoclase.

FIGURE 6.—TYPICAL GRANITE PORPHYRY, X NICOLS

Quartz, orthoclase, plagioclase (An_{12-15}), and little biotite compose the groundmass. Phenocrysts are orthoclase. Note the oriented inclusions of plagioclase and the small islands of quartz in the large orthoclase phenocryst (lower center).

PLATE 3.—PHOTOMICROGRAPHS

FIGURE 1.—CONTACT OF APLITE DIKE (UPPER) AND GRANITE (LOWER), UNCROSSED NICOLS

Orthoclase is turbid with low relief. Note sharp contact and gradation in grain size of quartz (clear and higher relief) toward the contact. Opaque is sulfide.

FIGURE 2.—BIOTITE-QUARTZ LATITE PORPHYRY, X NICOLS

Aligned biotite phenocrysts are in a groundmass of quartz, orthoclase, and plagioclase.

FIGURE 3.—PORTION OF FELDSPAR CRYSTAL ALTERED ENTIRELY TO KAOLINITE AND ILLITE

(ALTERATION STAGE I), X NICOLS

Dark-gray to black areas kaolinite. Lighter-gray to white flakes illite, roughly oriented in grid pattern.

FIGURE 4.—PLAGIOCLASE CRYSTALS IN GRANITE PORPHYRY PARTIALLY ALTERED TO FLAKY SERICITE (WHITE), X NICOLS

Note grid arrangement of sericite flakes with fresh feldspar between.

FIGURE 5.—VEINLET OF HYDROTHERMAL BIOTITE (B) (ALTERATION STAGE II)

Traversing a felted mass of kaolinite and illite (alteration stage I), X nicols.

FIGURE 6.—LARGE ORTHOCLASE CRYSTAL (O), IN GRANITE (Gr)

Cut by a Stage IV alteration band (IV) composed of quartz and sericite, X nicols.



FIGURE 1

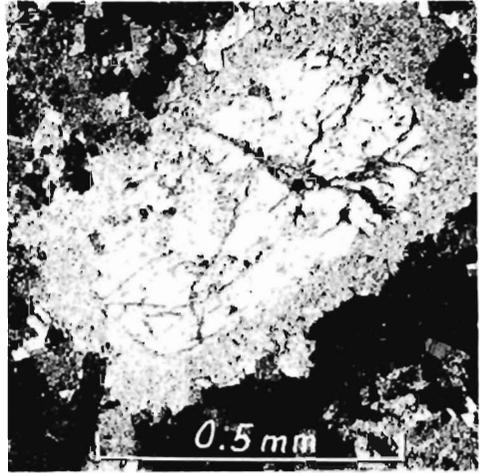


FIGURE 2

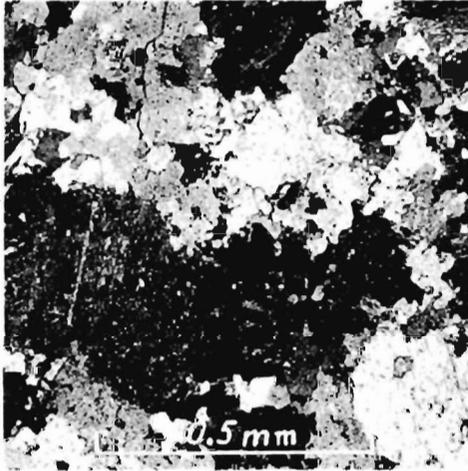


FIGURE 3

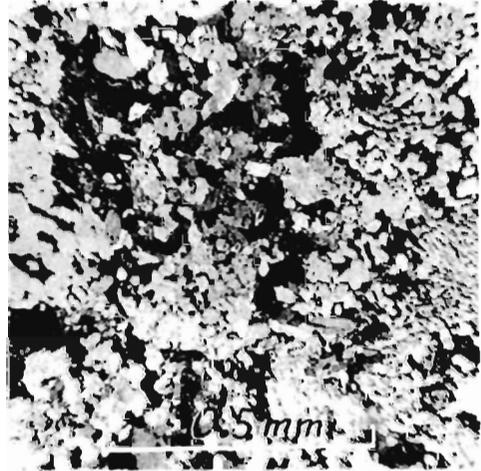


FIGURE 4

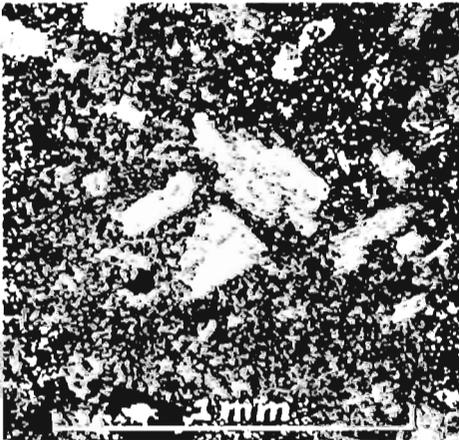


FIGURE 5

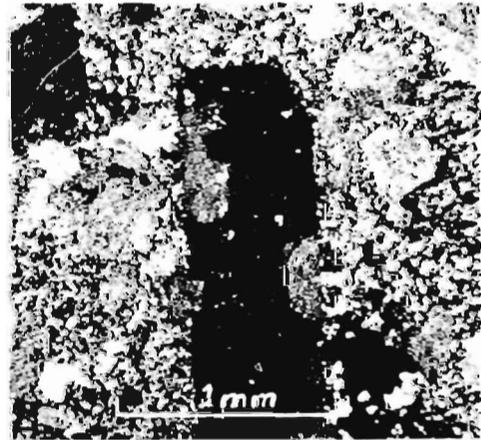


FIGURE 6

PHOTOMICROGRAPHS

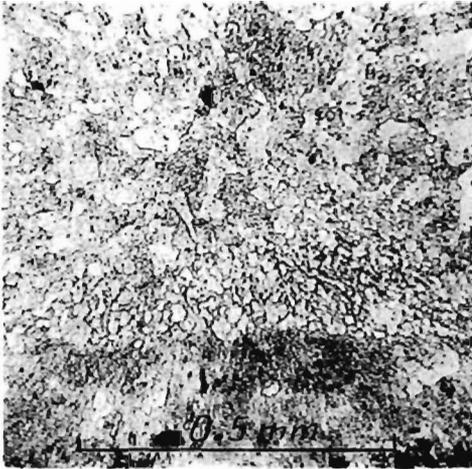


FIGURE 1



FIGURE 2

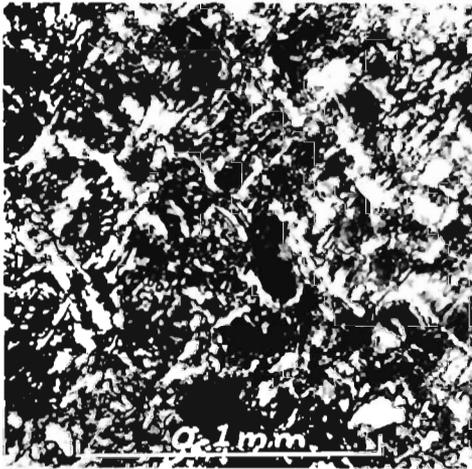


FIGURE 3

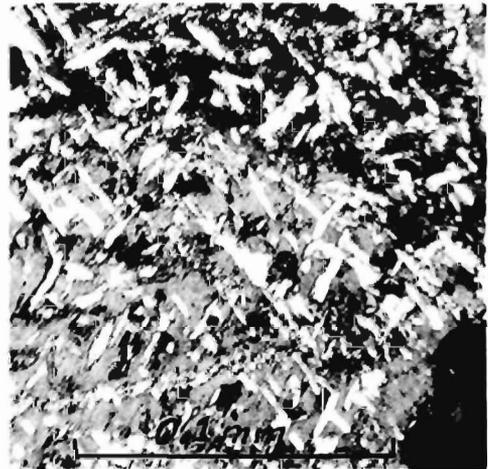


FIGURE 4

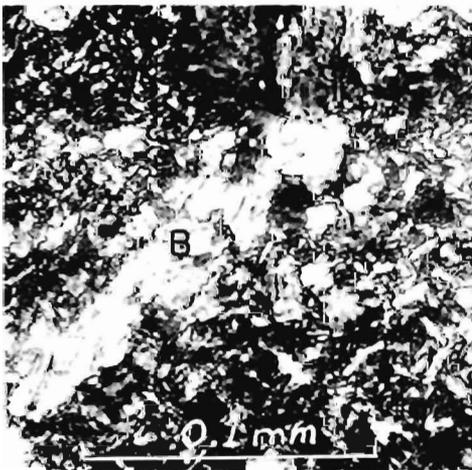


FIGURE 5

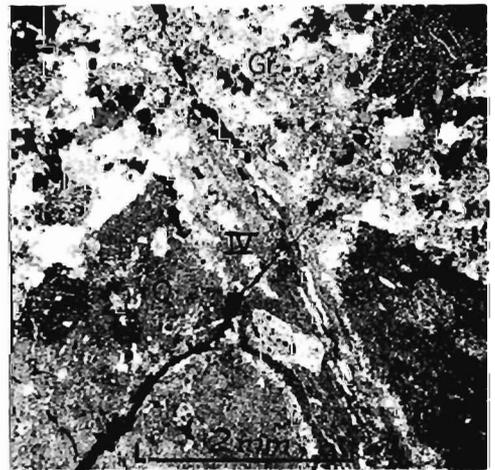


FIGURE 6

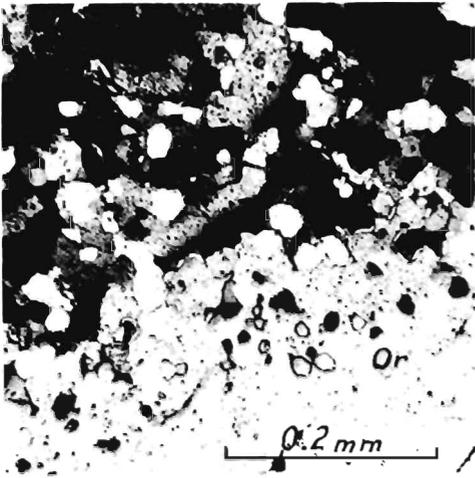


FIGURE 1

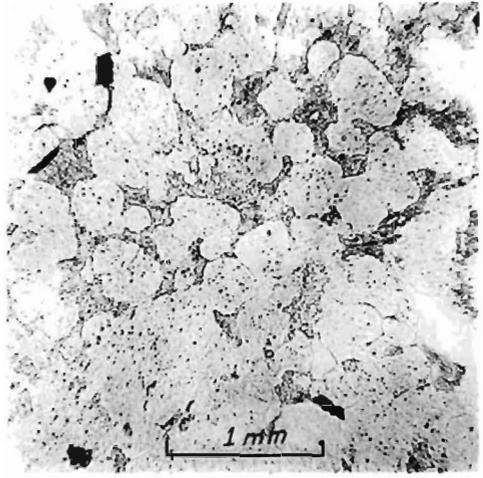


FIGURE 2

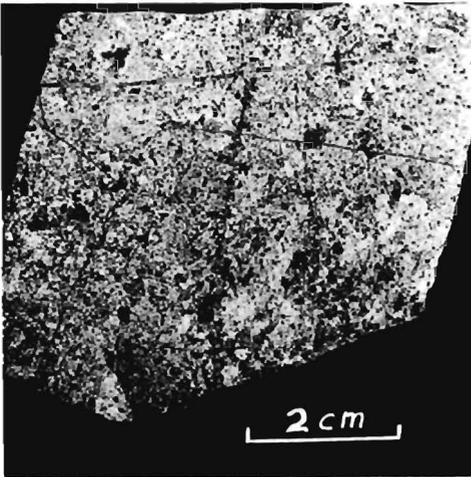


FIGURE 3

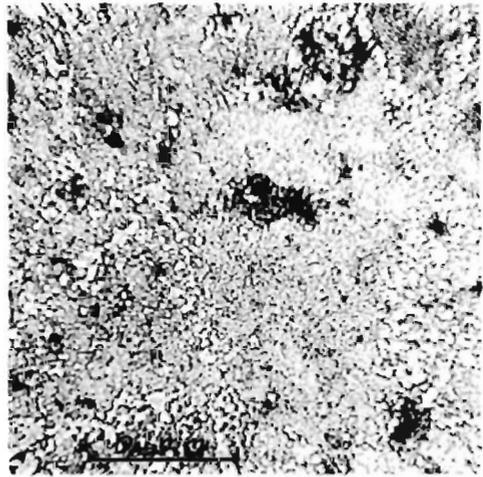


FIGURE 4

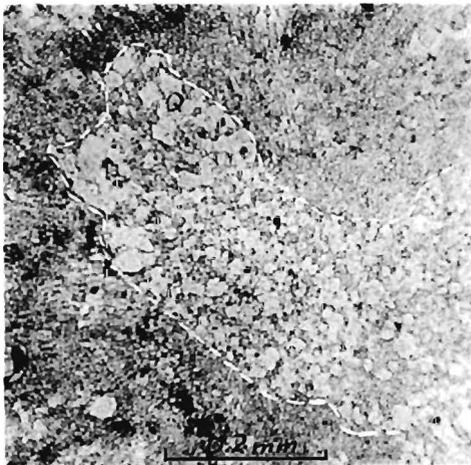


FIGURE 5

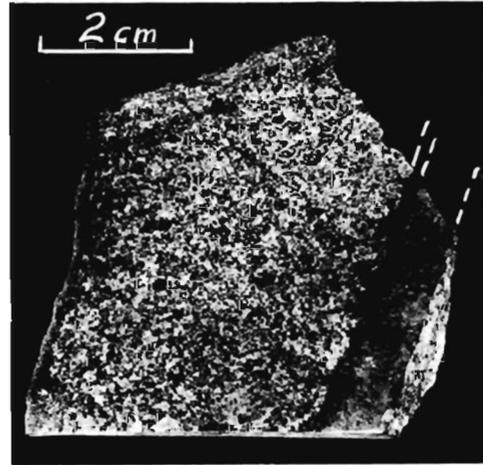


FIGURE 6

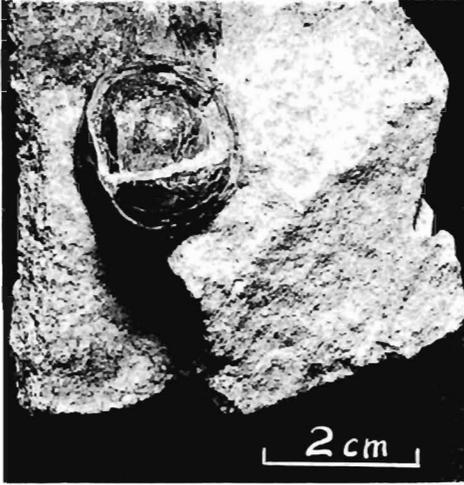


FIGURE 1

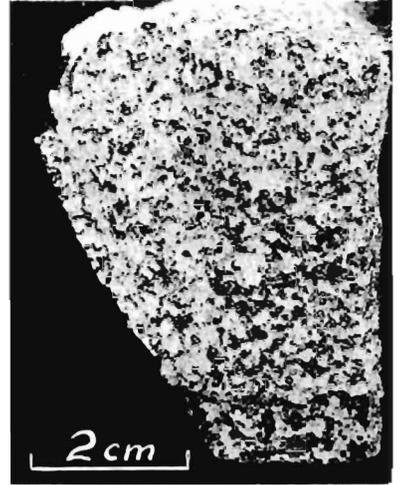


FIGURE 2

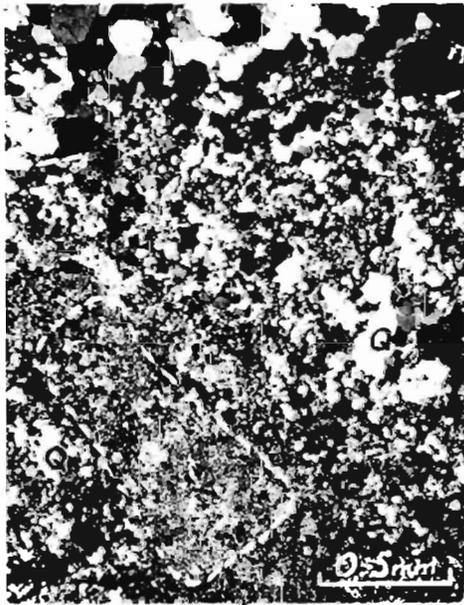


FIGURE 3



FIGURE 4

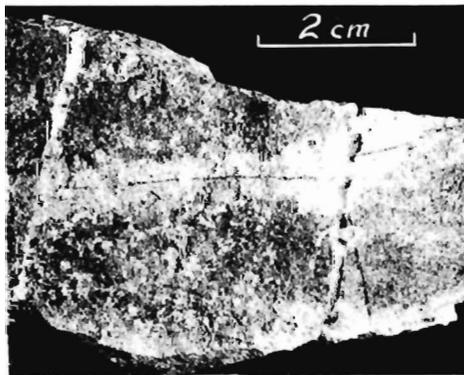


FIGURE 5

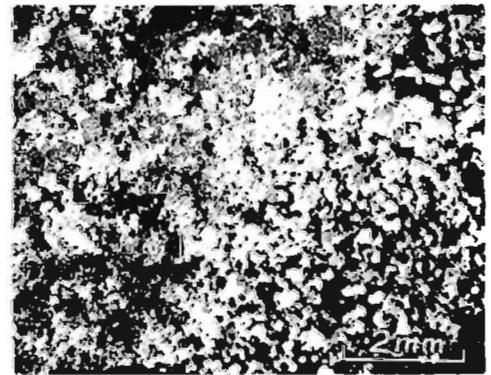


FIGURE 6

Sill, Minnesota. Here, however, some of the interstitial material was micropegmatitic. This crystal orientation based on outlines could nearly always be checked by noting the extinction position in relation to the above faces, and often the *c* axis of the quartz could be predicted before confirming with the gypsum plate or quartz wedge. Irregular fragments of some crystallized substances, when allowed to dissolve in certain solvents, are dissolved in par-

ticular crystallographic position; after a time the fragment, if extracted from the solvent, exhibits crystal faces (Buckley, 1951, p. 304). Where feldspar replaces along the irregular edges of quartz grains of the quartzite, the crystal structure of the quartz grain controls to some extent where replacement will take place, and irregularities and prominences are preferentially replaced until a fairly flat plane parallel to the rhombohedron or some other crystal face

PLATE 4.—PHOTOMICROGRAPHS: GRANITIZED QUARTZITE AND ALTERED GRANITE

FIGURE 1.—EDGE OF ORTHOCLASE PHENOCRYST (Or) IN GRANITE PORPHYRY, X NICOLS

Groundmass (upper part) composed of granular orthoclase and quartz. Note extremely irregular outline of edge of phenocryst and quartz inclusions near rim entirely surrounded by orthoclase phenocryst.

FIGURE 2.—FELDSPAR NETWORK IN QUARTZITE, UNCROSSED NICOLS

Light-gray high-relief mineral is quartz, and turbid darker-gray mineral is orthoclase. Lower part is quartzite only slightly replaced, but grading upward orthoclase becomes more abundant until some quartz grains are isolated. Orthoclase replaces principally along quartzite grain boundaries. Several replaced quartz boundaries show straight borders some of which prove to be parallel to the more common quartz crystal forms.

FIGURE 3.—PHOTOGRAPH OF POLISHED SPECIMEN OF GRANITIZED QUARTZITE

Shows the very fine texture with the light and dark patches. Veinlets of clear quartz.

FIGURE 4.—GRANITIZED QUARTZITE, UNCROSSED NICOLS

Small, white, high-relief minerals are quartz. Turbid (grayish) low-relief areas are fine aggregates of feldspar (orthoclase + plagioclase (An₅₋₁₀)). Dark minerals are biotite. Near center is a trapezoidal area of feldspar aggregate, probably a former quartzite breccia fragment.

FIGURE 5.—GRANITIZED QUARTZITE, UNCROSSED NICOLS

Quartz grains (Q) imbedded in fine aggregate of feldspar (turbid). Area containing high concentration of quartz is believed to represent an incompletely replaced fragment of quartzite.

FIGURE 6.—GRANITE MODERATELY ALTERED BY HYDROTHERMAL STAGE II (BIOTITE-SERICITE)

To extreme right of specimen may be seen half of a Stage IV alteration band (quartz-sericite) with a dark streak of hydrothermal biotite between it and the main mass of the rock.

PLATE 5.—ALTERED GRANITE: GRANITE AND GRANITIZED QUARTZITE CONTACT

FIGURE 1.—CHLORITE ORBICULE

Showing onionlike structure, developed in granite during alteration Stage III (biotite-chlorite).

FIGURE 2.—POLISHED SPECIMEN OF GRANITE WITH MEDIUM-GRAINED TEXTURE

Darker spots are biotite, lighter areas are either orthoclase, quartz, or plagioclase.

FIGURE 3.—PHOTOMICROGRAPH OF CONTACT BETWEEN QUARTZITE (EXTREME UPPER) AND GRANITIZED QUARTZITE (LOWER), X NICOLS

Lower left is oblong aggregate of relatively pure feldspar. Unreplaced quartzite fragments (Q) appear in the granitized quartzite area.

FIGURE 4.—LARGE THIN SECTION ACROSS CONTACT OF FINE-GRAINED GRANITIZED QUARTZITE

(LOWER) AND GRANITE (UPPER), X POLAROID

Note that outlined contact is sharp and very irregular.

FIGURE 5.—ALTERED GRANITE

Main portion of rock (dark) is granite altered by Stage II (hydrothermal biotite-sericite). Lighter horizontal streak is a Stage IV (quartz-sericite) band with chalcopyrite and pyrite in the center fracture. Vertical veins are vuggy clear quartz of Stage V, with no adjacent alteration, cutting through the Stage IV band. Small sulphide crystals are present in the vugs as well as disseminated throughout the rock.

FIGURE 6.—PHOTOMICROGRAPH OF GRANITE-QUARTZITE CONTACT, X NICOLS

Contact extends diagonally from upper right to lower center. Quartzite with feldspar network (does not show under X nicols) right. No flow alignment of minerals found in the granite.

has been developed. This face will then be replaced uniformly and the crystal eventually disappears¹.

Much of the feldspar of the network is masked by alteration minerals. In almost all cases one can see a few flakes of fine biotite or sericite as alteration products in the feldspar. Quite often it may be almost completely changed to a solid mat of fine biotite or fine sericite, and very careful observation is necessary to detect the orthoclase that remains. Many quartzite slides, where feldspar network has not been proved, exhibit large interstitial uninterrupted patches of the alteration minerals, but from their sizes and outline it is believed that feldspar network was once present and its original outline represents the present outline of these alteration minerals.

Classification and Distribution

The appearance of the interstitial feldspar in the quartzite gives the over-all impression of a network, and that term is used here.

The determination of the areal extent of the rock containing feldspar network is based on random locations of the thin sections of quartzite examined and thus is of limited reliability. The feldspar network is always found in quartzite and impure quartzite near the granite contact, including all the quartzite and impure quartzite inclusions in the granite. It was also noted in several rocks up to 300 feet from the contact but is more common in specimens located nearer the contact. A few sections of quartzite adjacent to the granite porphyry show no feldspar network, but sampling here is inadequate to conclude that it is absent. Because it cannot be seen in the field, it is not known whether this feature is confined to cross-cutting streaks, certain beds, or is distributed uniformly. The dashed line on the map representing the outer margin implies the probable extent of the orthoclase network. Much further work is necessary to establish the true nature of its distribution. It is surely present, however, and must be reckoned with in any hypothesis regarding the origin of the rocks at Bingham.

¹ Since this paper was written a study of these crystal faces which have developed through replacement has been undertaken, and the report, now in press, will be published in the American Mineralogist.

Chemical Analysis

Analysis number 12, Table 1, of the quartzite with feldspar network, as expected, shows extremely high SiO₂ content. The iron and magnesia is contained in a little biotite which is present as an alteration product. The high K₂O indicates that in this specimen orthoclase predominates over the plagioclase.

Origin

The sedimentary nature of the original quartzite and the evident replacement relationship between the quartz and feldspar indicate that feldspar and small amounts of biotite have been introduced into the quartzite. The possibility was considered that arkosic feldspar grains may be the source of the network feldspar and that it has simply been recrystallized and redistributed. All the true arkoses observed in thin section were definitely low in feldspar content as compared with the feldspar content of much of the feldspar network type rock. Of course if arkosic orthoclase grains were present, they probably were recrystallized and redistributed when feldspar was introduced, since no clastic grains were found in this rock. The amount of feldspar in much of the network exceeds in amount the orthoclase grains found in the most arkosic quartzites. Further, no plagioclase grains were seen in the arkosic types, and plagioclase is abundant in the network. These two features strongly indicate that most of the feldspar of the network has been introduced.

GRANITIZED QUARTZITE

General Statement

Owing to a circumstance in mapping, the true nature of the peculiar rock classified here as "granitized quartzite" was not fully realized until late in the study. Its origin has now been well established, and this may offer a clue to the origin of the granite and actinolite syenite at Bingham. Earlier workers in the district did not notice this granitized quartzite for apparently two reasons: the writer believes that either there was only a very small outcrop of it at these earlier dates and it was therefore easily missed, or, more likely, it was not exposed at all

but has been uncovered by recent excavation. To the writer's knowledge, no identical rock has previously been described. Details of the rock vary markedly in different specimens, and the mine was revisited many times to try to secure every type.

The granitized quartzite was found near the lower intermediate levels on the southwest side of the pit, specifically in the southern parts of Sections 7 and 8. This area is directly north of some large quartzite bodies which extend into the granite on higher levels (Sections 12 and 13). Contacts mapped are quite accurately located, but interpolation between levels is a matter of judgment, and the true shape of the exposure may not be exactly as drawn. Subsequent location checks, as much as 2 years later, reveal that contacts now (1952) are in somewhat different positions (due to excavation), but the granitized quartzite rock is abundant in this same general area.

Megascopic Features

All the rock in the granitized quartzite area has been so fractured without recementation that rarely can a solid specimen be secured large enough to make a large ($3\frac{1}{4}$ by 4 inches) thin section. To observe the true nature of the rock in the field it must be painstakingly chipped along edges to eliminate the masking effect of innumerable quartz veinlets and expose a fresh surface of the rock. The over-all color is a gray, with white chalklike spots and patches, and brownish spots (Pl. 4, fig. 3). Intensive hydrothermal alteration resulting in abundant biotite has produced a few rather dark rocks. No minerals can be determined megascopically, but in places, particularly where brown spots (presumably biotite) are abundant, the grain size appears slightly coarser. The rock can be best observed on a polished specimen where irregularities in grain size are readily apparent. Streaks and patches of light fine material are seen adjacent to streaks and patches of darker material. These patches may range in size from 0.1 mm. to 1-2 cm., and the borders of most of them appear to be fairly even and straight, giving a superficial appearance of a replaced or strongly recemented brecciated rock. However, the impression is gained that the rock fragments were not fully

rotated and separated, but that the fragmentation was more the result of intensive fracturing without much movement.

Unreplaced quartzite fragments or skialiths (Goodspeed, 1948a, p. 520) which range from approximately 1 mm. to several yards in diameter, are very common. Superficially the boundaries of these fragments appear quite sharp, but on the polished specimen, where quartz takes a better polish than the other minerals, it is seen that most of these contacts are gradational. Distributed through the granitized quartzite are many small late quartz veinlets as well as some very small (2 mm.-2 cm. across) discontinuous more coarsely crystalline, irregularly shaped patches and veinlets which have distinct gradational borders with the main rock. The latter are not to be confused with the thicker aplitic dikes which have very sharp borders. Frequently irregular streaks and bands, 2 mm.-3 cm. wide, having a chalcedonic appearance, occur in most of the granitized quartzite rocks examined. Thin-section observation showed that these are due to a late hydrothermal sericitic alteration which spreads more or less symmetrically on either side of small fractures.

Microscopic Features

MINERALS: Quartz grains ranging from .01 to 0.2 mm. in diameter were found in all slides examined. They are euhedral to subhedral and in many cases exhibit at least two straight and presumably rhombohedral edges and often what appears to be a prism edge. High-power magnification revealed that many of the smallest quartz grains have some semblance of crystal outline.

Where orthoclase is adjacent to orthoclase, the borders are always very irregular, but, where it borders quartz, boundaries are fairly straight. The orthoclase grains are slightly larger than the quartz grains, ranging from approximately .02 to 0.4 mm. in greatest dimension. Most of the orthoclase observed was untwinned and only slightly perthitic.

Plagioclase ($An_{0-6}-An_{12}$), with the conventional albite twinning (010) and an index near orthoclase or slightly higher, is distinguished from orthoclase principally by the presence of repeated twinning. Most of the plagioclase crystals are slightly larger than the orthoclase anhedral and are more or less euhedral against orthoclase but anhedral against quartz.

There are two types of biotite. One type, believed to be hydrothermal, consists of very fine

flakes scattered somewhat evenly or occasionally concentrated in small clumps within the feldspar areas. The most abundant type, however, is much larger (up to 0.1 mm.) and is believed to have been formed by the same processes that formed the orthoclase and plagioclase. This latter biotite is generally quite ragged in outline. In some cases several ragged and individually isolated crystals have unit extinction; in other cases many crystals may be grouped together with random orientation.

A very small amount of rutile is scattered through the rock, but the crystals are so fine they are detectable only with the highest magnifications. Some biotite, which shows slight bleaching, may contain considerable rutile. Apatite, found throughout the granitized quartzite, forms crystals less than .02 mm. in length. These crystals may at times be concentrated in areas associated with biotite.

The very fine and varied texture usually found in these rocks made it extremely difficult and impractical to make quantitative mineral measurements. Since it was estimated that there is a considerable range in relative amounts of minerals in all the slides, it was reasoned that perhaps a measured mode would not give a true picture of the mineral composition of the rock. Estimations indicate the following: quartz 10–20%, orthoclase 30–60%, plagioclase 20–35%, biotite 5–50%, and rutile and apatite combined comprise no more than 1 per cent of the rock.

TEXTURES AND STRUCTURES: The grain sizes of quartz and feldspar vary from .01 to 0.4 mm. The texture at first suggests an evenly distributed aggregate. Various aggregate sizes may be present within 1.5 mm. of each other. Quartz grains are usually detached equidimensional crystals distributed in various concentrations in the feldspar groundmass. Though most of the slides show gradual changes in grain size, many unusual patterns and odd shapes outlined by abrupt grain-size changes are discovered. For instance, quartz, occurring as isolated crystals, may be present in an unusually high concentration in areas covering a small angular patch 0.5 mm. in diameter or perhaps larger (Pl. 4, fig. 5). These areas have fairly straight or regularly curved edges and may be roughly triangular, oblong, or completely irregular. They are considered to represent quartzite fragments partially replaced by feldspar. Quartz, still as detached crystals, is found in straight or regularly curved stringers which often widen into larger angular patches (Pl. 4, fig. 4).

Orthoclase and plagioclase are always interstitial between quartz grains. In no area is plagioclase or orthoclase particularly dominant over the other. Very often an area composed of an aggregate of only feldspar will be bounded by fairly straight or

broadly curved sides whose outlines may also resemble triangles, oblongs, or trapezoids (Pl. 4, fig. 4). These are thought to be quartzite fragments completely replaced by feldspar. Most of the hydrothermal biotite occurs in these relatively pure feldspar areas. In addition to these breccialike features, large areas are found in which quartz and feldspar are uniformly distributed. In two slides, quartz and orthoclase were intergrown in a micropegmatitic structure, but the relative amounts of quartz and feldspar are not in the eutectic proportions.

Recognizable quartzite fragments are common, irregularly distributed throughout the rock (Pl. 5, fig. 3), and show the feldspar network. Some of the slides indicate that the quartzite apparently was so crushed that fractures traverse individual quartz grains and replacing feldspar has penetrated these cracks.

Three types of "veinlets" traverse the granitized quartzite, in addition to the aplites related to the granite porphyry: (1) discontinuous patches and stringers of slightly coarser orthoclase, plagioclase, and quartz, having gradational borders; (2) megascopally visible veinlets composed of a chalcedonic-looking material which under the microscope is seen to differ from the bulk of the rock only in having slightly more hydrothermal sericite; (3) definite sharp-bordered very small veinlets of colorless quartz.

Contacts

There is a very evident gradational contact between quartzite with feldspar network and granitized quartzite. This gradation is seen in many of the granitized quartzite slides containing recognizable quartzite fragments (Pl. 5, fig. 3). Around the borders of these fragments, which always contain feldspar network, the quartz and feldspar proportions vary with the distance from the contact. Near the quartzite, quartz predominates, while farther from it feldspar becomes more prominent until the usual proportions of quartz to feldspar in granitized quartzite is reached.

Except for the gradational contact with quartzite and the sharp contact with aplitic dikes, granitized quartzite is found in contact only with the granite. In the field this contact appears sharp but irregular, and thin sections across it show that it is very sharp and very irregular, the small grains of the granitized quartzite abutting against the larger grains of granitized quartzite (Pl. 5, fig. 4). In all the

slides studied, no essential mineralogical difference was recognized between the granite and granitized quartzite. Grain size, therefore, is the principal difference between the two, with the granite being the coarser.

Chemical Analysis

Two samples of granitized quartzite were analyzed (Table 1, Nos. 5, 6). Number 5 was taken 1 cm. from the contact with the granite shown in the large thin-section illustration (Pl. 5, fig. 4). The granite specimen, analysis 4, was taken 1 cm. from the same contact. Hence, analyses 4 and 5 represent rock about 2 cm. apart, with a contact between. The range of composition between the two is very slight. Analysis 6 is of a specimen taken some distance within the granitized quartzite area; except for a slightly lower silica content there is not a great deal of difference in the compositions of numbers 5 and 6. Thus the composition of the granitized quartzite seemingly is near that of the high-plagioclase granite (analyses 2 and 4).

Origin and Classification

The original rock from which the granitized quartzite was derived is believed to be either quartzite or impure quartzite. Presumably this rock was intensely fractured, but little rotation of fragments or slipping along fractures occurred. The original rock probably contained much SiO_2 and perhaps a little Fe_2O_3 , Al_2O_3 , CaO , K_2O , Na_2O , and MgO . From the abundance of the minerals of the granitized quartzite the introduced substances must have included much Al_2O_3 , K_2O , and Na_2O with perhaps a little FeO , MgO , and CaO , and a very little P_2O_5 and TiO_2 . Of the constituents now in the rock, quartz may be considered residual as well as possibly a small amount of orthoclase of the arkosic quartzite and a very little clay, calcite dolomite, and iron. The new minerals are orthoclase, plagioclase, biotite, rutile, and apatite.

The substances which formed these minerals are believed to have been introduced along the innumerable small fractures and grain boundaries. The fragments were to a certain degree selectively replaced; some were completely changed to feldspar, while others were changed only partially to feldspar and considerable quartz remained. The reason for this selectivity

is not known. Much of the rock, where original fracturing was probably not intense, shows the more or less uniform texture of much of the granitized quartzite.

During the later stages of the replacement process, solutions may have become less concentrated in introduced substances causing minerals in localized portions of granitized quartzite to grow larger, resulting in the patches and stringers of coarser minerals.

The term microgranite adequately describes the mineral composition and fine texture of this rock but does not convey the replacement origin or peculiar structure. Since the rock is believed to have been made by a replacement process the name granitized quartzite is considered suitable.

ORIGIN OF THE IGNEOUS-APPEARING ROCKS

General Statement

If a conventional intrusive origin for all the igneous-appearing rocks in the Bingham pit—granite, actinolite syenite, granite porphyry with related aplite, and biotite-quartz latite porphyry—were the only hypothesis to be considered, the origin of the feldspar network and granitized quartzite could perhaps be explained as magmatic "fringe effects." Many unusual features of the granite and actinolite syenite, however, need further explanation. Hence, two ideas, origin by igneous activity and by granitization or replacement, are offered here with criteria for each, and the reader may judge the validity of either hypothesis. The writer attempts to present all the arguments on both sides. As the criteria as now set up by proponents of each process do not apply completely, for either case, to the rocks at Bingham, this method of analysis may have merit.

Origin by Igneous Action

Validity of evidence.—Evidences for the sequence of intrusion of the igneous rocks at Bingham, excluding the Last Chance stock, are quite clear except for the granite-actinolite syenite relationship. If the Last Chance rocks are included, there have been either four or five periods of igneous activity, depending upon the origin thought most probable for the actinolite syenite.

Last Chance quartz monzonite.—The position

of the Last Chance rock in the sequence of intrusion has not been definitely established, and this rock does not crop out in the map area. For the purposes of clarity and completeness, its features were discussed previously. Early authors have related it directly to the Bingham rocks. The writer concludes that the Last Chance stock was intruded independently. It is further indicated that the Last Chance magma, of intermediate composition, may have been implaced by stoping and assimilation. Many dikes and offshoots are observed around the periphery of the main intrusive, and in a number of slides taken from these smaller masses a definite alignment of crystals is seen, indicating flowage. The boundary relationships between the minerals in this quartz monzonite indicate that the sequence of crystallization follows essentially the conventional Rosenbusch sequence in that hornblende and augite are nearly always euhedral as is also plagioclase, but the boundary of the latter yields to the boundaries of the dark minerals, and orthoclase and quartz are always interstitial. The fact that hornblende often rims augite may be regarded by some students to mean that magmatic processes have more than likely been operative. The over-all constant uniformity of texture and composition of the quartz monzonite mass and the abundance of a plagioclase of intermediate composition (An_{25-40}), accounting for the higher Na_2O and CaO in the analysis, further strongly suggests that this rock is magmatic. The petrographic and chemical criteria, as interpreted according to the classical petrology, together with the structural relationships, are fairly convincing evidence that the Last Chance quartz monzonite is magmatic.

Actinolite syenite.—The position of the actinolite syenite in the intrusive sequence could not be positively established, but contacts on Plate 1 suggest that dikes of actinolite syenite seem to be cut off by the granite. Structural evidence on the relative ages of the Last Chance rock and the actinolite syenite is not forthcoming since the two have not been found together. However, petrographic features relate the actinolite syenite more closely to the Bingham granite than to the Last Chance quartz monzonite. In this respect, the high content of orthoclase with sutured boundaries, the low amount of albite-oligoclase, and the sieve texture of the quartz

are all similar to the Bingham granite and quite dissimilar to the Last Chance rock.

There are several possible modes of origin for the actinolite syenite all of which are based upon a strict magmatic interpretation.

(1) The actinolite syenite may have been intruded early and independently as plugs and dikes in areas within or adjacent to a large bed of dolomitic limestone, the dark minerals actinolite, diopside, and epidote being original orthotectic material.

(2) The actinolite syenite may originally have been a part of a large granite magma. Contamination as a result of assimilation of the dolomitic limestone carrying abundant MgO and CaO could result in a silica-poor granitic-type rock containing enough calcium and magnesium to make actinolite, diopside, and epidote. Serious objection to this idea, however, is that the plagioclase in the actinolite syenite is near albite and not high in An , and, further, it is not at all abundant.

(3) The actinolite syenite may have been originally independently emplaced as a basic gabbroic magma with a chemical composition near the present rock. A gabbroic-type rock may originally have crystallized, but subsequent contact-metamorphic action has recrystallized the rock to actinolite syenite. The writer considers this possibility quite remote.

Metamorphism of the near-by dolomitic limestone may have been accomplished either at the time of the intrusion of the actinolite syenite or at the time of the granite intrusion.

Granite.—The next magmatic stage was the intrusion of the large body of granite which was emplaced in the main by stoping and assimilation of country rock. Since the sedimentary beds are disturbed but very little along the margins of the granite, the intrusion was probably not injected very forcefully. However, as expected along the periphery of a large body of magma, many dikes and small bodies have been intruded into the country rock. Upon examination of the representative dike patterns on the map, one could well imagine that, since many of these dikes interconnect, the stoping process is well illustrated. Inclusions of all sedimentary rock types are common in the granite, and these could be thought of as detached fragments which "floated" downward into the magma from the roof of the magma

"chamber." The crystallization history of the granite could be interpreted to be that of a typical magmatic rock. Biotite is the first and principal dark mineral to develop. The plagioclase crystallized early and was later rimmed by orthoclase. Orthoclase was formed still later with mutual crystal boundaries which are extremely sutured, and quartz crystallized last, occupying interstitial positions. Thus the rock follows the ideal conventional sequence for crystallization from a magma. The wide variations in texture and composition found throughout the granite mass may be explained by local contamination, segregation, or a lack of thorough mixing of the chemical constituents, while the magma was still liquid.

On magmatic reasoning, the feldspar network and granitized quartzite may be explained as a type of fringe effect around a magmatic body where magmatic material to form feldspar and biotite seeps into the country rock and replaces it to varying degrees. The contact metamorphism noted around the edges of the granite could have been the result of the granitic intrusion. The megascopically very sharp borders of the granite with country rock suggest strongly that this was once a solid-liquid contact. Most important of all, the absence of continuous relic country rock structure—in this case bedding—through the magmatic rock further substantiates the intrusive idea. These are felt to be very strong evidences in favor of the magmatic theory.

Granite porphyry.—Following the emplacement of the granite, the large mass of granite porphyry was intruded. This porphyry was probably emplaced chiefly by stoping and assimilating the surrounding granitic and sedimentary rocks. Along the sharp contacts of the granite porphyry are found flow structures which, together with a crosscutting relationship of large granite porphyry dikes, seem to prove that the granite porphyry is distinctly the result of magmatic activity. There are more phenocrysts near the center of the outcrop than toward the edges, which should agree with the ideal crystal distribution of a cooling magma. Since small aplite dikes are found in all rocks except granite porphyry and the later biotite-quartz latite porphyry, the aplite dikes are probably offshoots from the granite porphyry.

Biotite-quartz latite porphyry.—Following the

emplacement of the granite porphyry there was a recurrence of magmatic activity resulting in the intrusion of small dikes and irregular pipes of slightly more basic material. Many of the phenocrysts in this porphyry are aligned, showing flow structure, and undoubtedly this rock is truly magmatic.

Origin by Granitization

Actinolite syenite and granite.—The following discussion is more or less confined to features which favor origin by granitization for the granite and the actinolite syenite. The relationship of the Last Chance rock to the granitization process has not yet been fully established, and hence discussion of it is omitted.

It is generally considered that one of the best criteria for the granitization process is an obvious gradation between true igneous-appearing rock and the surrounding unchanged country rock. If this concept is true it is then one of the weakest points favoring granitization of the granite and actinolite syenite at Bingham since borders with sedimentary rocks here appear to be sharp. The feldspar network in the quartzite, though having a sharp juncture with the granite, may be regarded as distinctly a gradational feature between ordinary quartzite and granite. Furthermore, it is a question whether a gradational contact is absolutely necessary for a replacement boundary since many replacement ore bodies exhibit very sharp borders. Also, along the granite contact no flow arrangement of crystals or inclusions has been recognized, either in the field or through a petrofabric analysis of thin sections of granite from areas near contacts.

Perhaps the most convincing criteria favoring granitization is the continuation of relic country rock structures such as bedding, schistosity, etc., from wall rock into or through the igneous-appearing rock. Any such conclusive evidence is lacking in the Bingham granite, but the following could satisfactorily explain its absence. Except for one fairly thick bed of dolomitic limestone, the country rock is largely quartzite with only a few thin limestone lenses. Therefore, sedimentary structures which could be preserved as relics in the granite are practically absent except for the quartzite bedding. If some strong shale beds were present, the

chances for their relic preservation would be fairly good. Since only a few limestone beds are present in the quartzite, possibly this material could be either entirely moved out into the country rock as a sort of feeble basic front where it would be so thoroughly distributed that it would be difficult to detect, or it may have been incorporated and so thoroughly diffused in the replacing material that its identity was lost. Backlund (1946, p. 111) lists rocks in order of their susceptibility to the granitization processes. This is based principally on the chemical dissimilarity of the replaced rocks to the granitizing material. He lists arkose as first and easiest to transform, followed by shale or hornfels, quartzite, limestone, and last, basic rocks. The northwest corner of Section 9 illustrates this, in that quartzite beds have been preferentially changed to granite while altered limestone beds project into the granite for approximately 100 to 200 feet. In some drilling operations an altered limestone was occasionally encountered having granite both directly above and below and its position when projected is consistent with known limestone beds on the surface. This suggests strongly that Backlund's sequence of the susceptibility to granitization of different standard rock types is perhaps operating here and further that the altered limestone extensions occur either as connected unsupported thin beds or isolated undisturbed remnants, and are still in place, not blocks floundering in a magma. Since quartzite bedding is very obscure near the granite, an effort was made to correlate and compare petrofabric information taken from undisturbed quartzite country rock and from isolated quartzite inclusions to see if a common orientation was forthcoming. No convincing preferred quartz diagrams were obtained. The large bed of limestone and adjacent quartzite masses in Sections 12 and 13 are surrounded by granite, and yet their position seems to be fairly conformable to the regional attitude of the country rock. This bed and accompanying group of inclusions could, however, be interpreted as the lower portion of an attached pendant as could also the apparently undisturbed isolated blocks in the lower part of Section 9.

Relationships of wall-rock quartzite to the smaller dikes of granite showed no structural

proof of replacement or dilation origin (Goodspeed, 1940, p. 175), but their extreme irregularity, rapid pinching and swelling, and the unmatched wall configuration strongly suggest a replacement origin.

The space problem could be solved better for the granite at Bingham by a replacement process rather than by magmatic intrusion. The structure of the sedimentary beds surrounding the granite show a remarkably uniform continuity except for one small area in the lower right center of Section 3, the disturbance of which is believed to be due to pre-granite faulting. No crushing or brecciation of country rock is evident near the granite, and there seems to have been no major doming or pushing aside of country rock to make room for the magma. Stopping, melting, and other methods of assimilation then are the principal processes to explain the magmatic emplacement.

The concept of a basic front, wherein parts of the material composing the country rock in the area now occupied by the granitized mass have been moved to the adjacent country rock, was first applied (Reynolds, 1947, p. 205) where the removed constituents were somewhat basic. A true basic front is absent at Bingham, but the replaced rocks are quartzite. A silicic front would then be expected to develop, and at Bingham this type of front is thought to be expressed in the silication of the limestone beds and near the granite the introduction of silica into quartzite which has transformed them into rather glassy massive rocks. The true outer limits of this silicic front are difficult to detect in the quartzite, but silication of the limestone proceeds with lesser intensity away from the granite borders.

The extreme suture of the orthoclase boundaries are not what might be expected in a rock which has crystallized from a melt by growth from nuclei, as theoretically in such a case straight boundaries should result (Dan McLachlan, Jr., Personal communication). The sutured texture, then, would appear to be more crystalloblastic than magmatic. Also the extreme variation of mineral distribution even within one section suggests further that the mineral constituents were not uniformly distributed throughout the mass. Some may regard as good granitization evidence the fact that the varia-

tion in grain sizes is in no way related to proximity to the borders of the granite. The ratios of K to Na, which vary markedly in different parts of the Bingham granite, further suggest a nonuniform distribution of the alkalis.

A reasonable explanation of the features of the actinolite syenite is probably one of the best arguments for a replacement origin. The larger outcrops of this rock are close to the large bed of dolomitic limestone in Sections 12 and 13, while the smaller bodies in Section 7 are within or adjacent to quartzite and granite in a region approximately where this limestone projects. All the various textures and mineral assemblages in the actinolite syenite, except the actinolite, epidote, and diopside, are especially similar to the granite. Thus the actinolite syenite could have formed as the result of replacement by the same materials which formed the granite, except that they were contaminated with the CaO and MgO of the dolomitic limestone they were replacing. The capture of SiO₂ originally in the granitizing materials or the replaced rock to make the abundant actinolite, epidote, and diopside, all of which contain high MgO and CaO, might explain the low quartz content of the syenite. Actinolite, epidote, and diopside, associated with orthoclase and a small amount of acidic plagioclase, is a low-temperature mineral assemblage and definitely a peculiar one for an igneous rock. If the rock is magmatic, one wonders why a gabbro-type mineral assemblage did not crystallize, rather than a syenitic type, and why the high CaO was not accounted for in basic plagioclase rather than in the dark minerals. TiO₂ is found as rutile in practically every specimen of granite, yet the TiO₂ of the actinolite syenite is largely tied up in sphene. This could mean that the solutions that formed the granite found a source of CaO in the limestone and formed sphene instead of rutile. Further, the actinolite, epidote, and diopside may be poikiloblastic within orthoclase as well as interstitial between the feldspar, quartz, and biotite, as though they were formed fairly early. Yet these same three minerals are found as euhedral crystals crossing boundaries of quartz, orthoclase, and plagioclase, and also in solid monomineralic patches and veinlets as though they were formed

at a late stage as well. This unusual feature is very difficult to explain from a magmatic viewpoint.

In small actinolite syenite dikelets in quartzite where there may have been an oversupply of SiO₂, micropegmatitic structure of unusual orthoclase quartz proportions is abundant. Since this structure is regarded by Drescher-Kaden (1948, p. 205) as a reaction phenomenon, its presence further contributes to the argument for replacement.

Summary.—The above evidences against and in favor of a granitization origin for the granite and actinolite syenite are summarized as follows:

Against Granitization

- (1) No prominent continuous relic country rock structures in granite or actinolite syenite.
- (2) Sharp megascopic boundaries between granite and wall rock.

In Favor of Granitization

- (1) The feldspar network may be considered a transitional zone along the contact.
- (2) Limestone extensions and skialiths in granite, aligned with limestone beds of undisturbed country rock. Obscure quartzite bedding would likely not be preserved as a relic in replaced granite.
- (3) Periphery dikes very irregular with prominent pinch and swell features. Wall-rock borders largely unmatched.
- (4) No flow structures along contacts, even of smallest dikes.
- (5) Silicic front present near contacts (glassy quartzite with obliterated bedding, limestone silicated).
- (6) Wide variation of textures and rock types in granite.
- (7) No miarolitic cavities.
- (8) Grain-size variations bear no relation to contacts.
- (9) Crystalloblastic nature of microtextures.
- (10) Fairly wide variation in K-Na ratios in different areas.
- (11) High CaO rock (actinolite syenite) only near large limestone skialith. (a) CaO makes actinolite, diopside, and epidote rather than

plagioclase. (b) Actinolite, diopside, and epidote formed late as well as early.

(12) Strong micropegmatitic structures of unusual orthoclase-quartz proportions suggest replacement.

Granitization history.—If granitization is regarded as a possible origin for the granite and actinolite syenite, the subsequent intrusion of the granite porphyry with associated aplite, and biotite-quartz latite porphyry must be explained.

All the igneous-looking rocks of the area may be explained by two granitization hypotheses: (1) pure granitization, and (2) granitization related to magmatic action.

According to (1) granite-forming materials were transported upward from a source at depth, possibly by hot solutions or vapor rich in water. The quartzite and limestone areas now occupied by the granite were slowly replaced, and the granite and actinolite syenite were formed. Part of this process was the development of the feldspar network and silicic front in the country rock ahead of the advancing granitization front. In one place the replacement was perhaps only partial, and the granitized quartzite rock remaining represents an intermediate stage between the formation of the feldspar network and the normal Bingham granite.

With continued heat, temperatures of the rock in some areas were elevated until the granite became mobile through partial or complete melting forming a neomagma (Goodspeed, 1948b, p. 72). This gave rise to the large mass of granite porphyry which, around its borders, moved into cracks and openings in the granite and quartzite and formed dikes. Differentiation was taking place at depth in this molten mass, and after a portion of the granite porphyry had solidified the slightly more basic biotite-quartz latite porphyry was intruded. The

porphyritic nature of the granite porphyry could have developed in two ways. If only a portion of the rock were melted and some remnants of the larger minerals were still solid, upon cooling they would form nuclei for recrystallization causing them to grow to extraordinary sizes and the interstitial melted material would crystallize as groundmass. The alternative hypothesis would be that the granite was completely melted and the phenocrysts developed in the conventional magmatic manner. In either case the question could not be convincingly settled since, under equilibrium conditions, there would be no difference between two magmas of duplicate composition, one of which had been cooled from a liquid until there was 10 per cent of the whole present as crystals in the liquid, and the other which was formed by gradually heating and melting the solid rock until only 10 per cent remained as crystals in the liquid. The textures, subsequent crystallization sequence, etc., would be identical. The more uniform chemistry and mineralogy of the granite porphyry could perhaps be explained by the stirring action which would accompany movement and the chance for more thorough diffusion of chemical constituents afforded by the fusion.

Hypothesis (2) involves granitization resulting from magmatic action. From a magma at depth would develop granite, actinolite syenite, granitized quartzite, and feldspar network as above, but the whole action would be a wide fringe effect around the upper periphery of the magma. Later, the parent magma could have stopped or assimilated its way into and beyond the granitized rock forming the granite porphyry and later the biotite-quartz latite porphyry.

Evidence for either hypothesis is lacking, and the reader must fall back on his beliefs for his selection.

PART II.—HYDROTHERMAL ALTERATION

INTRODUCTION

Following the formation of the igneous-appearing rocks in the Bingham deposit, secondary processes in the form of hydrothermal

alteration and mineral introduction became operative. The alteration and mineralization took place in seven distinct stages, all of which can be clearly delineated. The separation and paragenetic sequence of all but the first two are

established on recognizable structural cross-cutting field relationships, while the first two are separated on the basis of crosscutting structure seen under the microscope. During the first four stages the original minerals in the rocks were altered, while the last three stages represent mineralization through introduction essentially without accompanying alteration. In Stage I, rock in a restricted area near the north-central part of the pit was altered with kaolinite and illite forming principally at the expense of the feldspars. Stage II saw the extensive development of sericite and hydrothermal biotite in essentially all the rocks within the mine. The alteration minerals of both these stages are disseminated throughout the rocks and do not follow fractures or other recognizable channels. The amount or intensity of alteration varies widely. These effects may be thought of as having been accomplished by solutions which more or less soaked uniformly through the rock. During Stage III, profuse chlorite and hydrothermal biotite were formed within rather restricted areas of granite and are found in wide bands, the positions of which were obviously controlled by fractures. In Stage IV, quartz and sericite were formed on either side of fractures and appear as bands and streaks in all the rocks in the area. Quartz, the only mineral formed in Stage V, is found in sharp bordered veins with no accompanying alteration. In Stage VI disseminated sulphides were developed in all the rocks within the mine. No alteration in the strict sense accompanied this mineralization stage. Sericite and allophane of Stage VII were introduced into cracks and vugs in somewhat restricted areas.

CHEMICAL ANALYSIS

The chemical analyses of the altered rock presented in Table 2 were made by precisely the same analytical methods as were used with the unaltered rock samples. These figures represent results obtained from rocks observed to be the most intensely altered specimens of their type. The same caution in evaluation of the analytical figures is imposed here as for the unaltered rocks, in that large representative bulk samples were not obtainable. With many analyses of altered rocks, authors have been able to present analytical data that showed

progressive alteration intensity (Lovering *et al.*, 1949, p. 41-60). The essential absence of fresh rock, the rather wide compositional variation of rock types, and the complexity and over-

TABLE 2.—CHEMICAL ANALYSES OF ALTERED ROCKS FROM BINGHAM

Walter J. Savournin, Analyst
University of Utah

| | 1 | 2 | 3 | 4 | 5 |
|--------------------------------------|-------|-------|-------|-------|-------|
| SiO ₂ | 68.19 | 63.06 | 61.60 | 74.19 | 73.61 |
| Al ₂ O ₃ | 14.67 | 15.83 | 14.29 | 14.41 | 15.76 |
| Fe ₂ O ₃ | 1.93 | 3.74 | 5.10 | .06 | 1.08 |
| MgO | 3.26 | 4.12 | 7.44 | .77 | .89 |
| CaO | .34 | 1.48 | .74 | .45 | .45 |
| Na ₂ O | 1.96 | 4.05 | 1.13 | 1.00 | .78 |
| K ₂ O | 6.25 | 4.68 | 5.69 | 5.60 | 3.58 |
| TiO ₂ | .63 | .72 | .99 | .58 | .42 |
| H ₂ O | 2.06 | 1.76 | 2.49 | 2.17 | 2.65 |
| Total | 99.29 | 99.44 | 99.47 | 99.23 | 99.22 |
| Sp.Gr. | 2.54 | 2.61 | 2.70 | 2.46 | |

1. Altered granite porphyry. Stage I, Illite-kaolinite
2. Altered granite. Stage II, Hydrothermal biotite-sericite
3. Altered granite. Stage III, Hydrothermal biotite-chlorite
4. Altered granite porphyry. Stage IV, Quartz-sericite
5. Altered granite. Stage IV, Quartz-sericite

lapping of the numerous alteration stages at Bingham prevented use of this valuable technique.

HYDROTHERMAL STAGE I—KAOLINITE-ILLITE

General Statement

The earliest hydrothermal activity following the formation of the igneous-appearing rocks resulted in the development of kaolinite and "a poorly organized mica possibly in the illite² group" (W. F. Bradley, Personal communication). This alteration effect is found only in the granite, granite porphyry, and biotite-quartz latite porphyry. The very small sizes (.001-.003 mm.) of these minerals and the small patches (.05-2.0 mm.) in which they

² The name illite will be used hereafter to designate this mineral.

TABLE 3.—HYDROTHERMAL STAGES AT BINGHAM

| | Alteration Stages | | | | | Mineralization Stages | |
|-----------------------------|--|-------------------------------------|-------------------------------------|--|-----------|--|--|
| | Disseminated | | Channels | | | Disseminated | Channels |
| | Stage I | Stage II | Stage III | Stage IV | Stage V | Stage VI | Stage VII |
| <i>Minerals developed</i> | Illite Kaolinite | Hydrothermal biotite Sericite | Hydrothermal biotite Chlorite | Quartz Sericite | Quartz | Chalcopyrite Bornite Digenite Enargite Molybdenite Pyrite Gold Silver | Sericite Allophane |
| <i>Paragenetic evidence</i> | Petrographic | | Field | Field | Field | Field | Field |
| <i>Introduced materials</i> | | Fe Mg | Fe Mg (much) | Si | Si | Cu Mo Fe S As (little) Au Ag | K Al SiO ₂ H ₂ O |
| <i>Rocks affected</i> | Granite Granite por- phyry Aplite Biotite-Quartz Latite Por- phyry | All rocks | Granite | All rocks (ex- cept sedi- ments) | All rocks | All rocks | All rocks |

Time →

occur make it impossible positively to distinguish this type of alteration in the hand specimen, except in a superficial way where a brown chalky appearance is present caused by abundant brownish montmorillonite which has developed through weathering of the alteration minerals. In some granite porphyry rocks intense alteration is represented on a fresh-cut bank where altered phenocrysts may break out readily from the altered groundmass. However, in all cases a thin section was necessary to distinguish this alteration type positively.

Microscopic Appearance

Under the microscope the kaolinite and illite are intimately mixed in almost all instances. Only in a few cases and under high magnification, was one mineral observed without the other. Optically the kaolinite is readily identified by a low birefringence (.007) (Pl. 3, fig. 3). The individual crystals of some aggregates of kaolinite are so small that they often appear isotropic. In most of the kaolinite aggregates, the individual crystal units are roughly equidimensional, but some typical wormlike structures with transverse flakes are present (Ross and Kerr, 1931, Pl. 41). The relief is slightly higher than the relief of quartz.

Illite is readily distinguished from kaolinite under crossed nicols, by its slightly higher birefringence, with colors in first-order yellows. It has a distinctly flaky habit with individual flakes length slow and a relief slightly higher than kaolinite, the lowest index being about 1.569. Almost all the flakes of illite are intimately mixed with kaolinite, and many are arranged or oriented in a somewhat crude pattern with the angle of the grid being about 90° (Pl. 3, fig. 3). No large patches of pure illite were discovered, and hence it was not possible to work out its precise optical properties. Because of the intimate mixture of the two minerals, it was impossible to obtain a pure enough sample of either one for chemical analysis. Positive identification of the two minerals was made by W. F. Bradley of the Illinois State Geological Survey who x-rayed some completely altered phenocrysts of the granite porphyry. He states that, from his powder pattern, he would judge the material to be "about 50 per cent kaolinite and 50 per cent a

poorly organized mica, possibly in the illite group."

The two alteration minerals have formed at the expense of all the primary minerals in the rocks except apatite and rutile. Plagioclase is usually most nearly completely altered, but orthoclase is quite often altered, and quartz is affected around its borders only in the most intensely altered rocks. Biotite is altered only rarely and then also very lightly around its borders.

Wherever a Stage I alteration patch is found it is composed of practically 100 per cent alteration minerals. In only rare cases are these alteration minerals scattered with fresh unaltered mineral between. Where alteration has been very slight, the kaolinite-illite patches may be quite irregular and occupy only a portion of a crystal. With more intensity, a whole feldspar crystal may be affected, and the outline of the alteration patch is that of the crystal.

Distribution

The first alteration stage is most intense near the north-central portion of the pit in Sections 2, 3, 4, 7, 8, and 9 (Pl. 1). The outer boundary of this area was determined by observing thin sections from well-located samples. Within the boundary are rocks altered as much as 75 per cent, but most of them have been altered much less. An arbitrary figure of 15 per cent was selected to determine the outer boundary of the alteration area which appears on Plate 1. Thus, if the rock showed less than 15 per cent kaolinite and illite, it was not included in the altered area. The boundary thus drawn is therefore not absolutely accurate, but its position should be a fairly good approximation of the outer limits of the alteration.

Character of Altering Solutions

Since kaolinite forms principally in an acid environment below 350°C., its presence as an alteration product here would definitely place the pH of the altering solutions of Stage I in the acid category and at temperatures below 350°C. The field of formation of illite is not so well known, but the intimate association between illite and kaolinite would suggest that they were formed at the same time.

Analyses No. 1, Table 2, was made of a specimen of granite porphyry composed of about 60 per cent Stage I alteration minerals. Comparison of these figures with the analyses of moderately altered granite porphyry, Nos. 7 and 8, Table 1, shows that there is very little

HYDROTHERMAL STAGE II—HYDROTHERMAL BIOTITE-SERICITE

General Statement

The alteration produced during the second stage of hydrothermal activity resulted in the

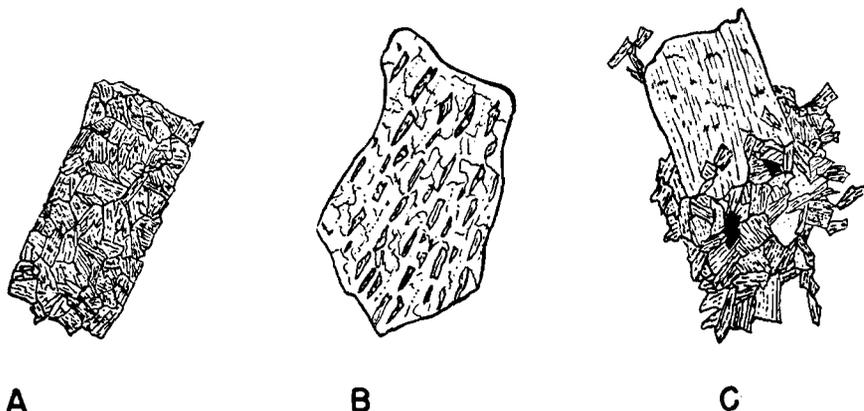


FIGURE 8.—PSEUDOMORPHS OF HYDROTHERMAL BIOTITE

(A) former biotite crystal completely changed to variously oriented small hydrothermal biotite flakes. (B) former biotite crystal altered to quartz and hydrothermal biotite. (C) biotite crystal altered to hydrothermal biotite on lower end. Note the ragged and distended border of the hydrothermal biotite. Camera lucida drawing, $\times 32$.

significant chemical difference between unaltered rock and altered rock of Stage I type. The K_2O and CaO are slightly lower than the unaltered rock, while SiO_2 is slightly higher. Thus it may be stipulated that the altering solutions of the first stage only effected mineral changes, and very little material was added or taken away from the rock.

The alteration follows no obvious channels which can be noted in the field or thin section. The solutions evidently penetrated the rock along mineral boundaries or through microscopic fractures. Since there is no pattern of the latter, it is believed that the solutions resulting in the first stage of alteration penetrated the rock as a "soaking action."

Paragenesis

Stage I is definitely the earliest alteration stage and occurred after the primary minerals in the rocks were formed. The alteration minerals of Stage I are all cut by veinlets or replaced by all other types of secondary mineralization in the pit.

profuse development of fine flaky biotite (here called hydrothermal biotite) and sericite. These alteration minerals are disseminated throughout the rock and are rarely found in concentrated clumps, patches, or veinlets. Both minerals generally occur in the same rock but are rarely intermixed. Sericite, however, is absent in some specimens, and in one area on the east side of the pit some of the small dikes and plugs of granite porphyry contain abundant sericite but no hydrothermal biotite. On the whole, however, hydrothermal biotite is by far the more widespread and abundant. In the field the hydrothermal biotite-rich rock without sericite is difficult to distinguish from sericite-rich rock without hydrothermal biotite; consequently, they were not mapped separately. All the igneous-appearing rocks and a few of the sedimentary rocks in the pit have been affected to varying degrees.

The fine flaky dark mica occurring profusely throughout the Bingham mine as an alteration product is biotite, as determined by x-ray, but, since it is believed to have been formed under different conditions from the coarser biotite,

the term hydrothermal biotite is used. The only difference between the two is the size and form of the crystals.

The boundaries of many patches or clusters of randomly oriented hydrothermal biotite flakes have a shape resembling a biotite crystal (Fig. 8A). The edges of many of these pseudomorph patches are quite regular, but some are ragged (Fig. 8C). Occasionally, they are composed of biotite and quartz (Fig. 8B), and some pseudomorphs may contain as much as 80-90 per cent quartz.

The intensity of the development of sericite was not mapped because sericite could not be distinguished in hand specimen. However, the ease of recognizing hydrothermal biotite in the field made it possible to note two areas (not mapped) where it is profusely developed. In an area on the intermediate levels in Section 7, the rock was so rich in hydrothermal biotite (50-60 per cent) as to appear black, and, on the upper levels in Section 12, it is developed to a slightly greater degree than in the rest of the pit. The various rock types show some variations in the general effects that alteration Stage II had upon them; hence, each type is described.

Granite

Hydrothermal biotite is developed best in the granite. The small patches of concentrated flakes of hydrothermal biotite and its characteristic dark color make it fairly easy to detect in the hand specimen. The sericite of this stage, however, cannot be detected without the microscope. The dark mica flakes are found in clumps and clusters occasionally with ragged borders, disseminated throughout the rock; the size approximately equals the grain size of the original rock and may vary widely as the grain size of the granite varies. Most of the patches appear rather massive, presumably due to the very small size and random orientation of the small mica flakes. Though usually ragged in outline some of these patches which have been developed from pre-existing biotite may be quite regular. Where the patches are fairly large, they are blackish, but, where they are small, a brownish color is most prominent imparting a peculiar speckled salt and pepper appearance (Pl. 5, fig. 2). In some cases where

the patches are fairly large, they seem to be interconnected and exhibit irregular and ragged borders. Some fairly coarse-textured dark rocks contain as much as 50 per cent hydrothermal biotite while most of the extremely fine-textured granite has a very small amount of it. No streaks, veinlets, or large areas of concentrated hydrothermal biotite are seen.

The sericite is confined principally to the feldspars and, where present in large amounts, colors them earthy white or tan. The kaolinite-illite development of Stage I also usually resulted in an earthy white or light brown color, and no field test was devised with which to distinguish confidently the presence of Stage I minerals from the sericite of Stage II.

The hydrothermal biotite is readily identified under the microscope by its prominent pleochroism, its high birefringence (intense first-order colors up to second-order red), and the cedar grain or birds-eye structure characteristic of mica. The flakes, usually slightly larger than those of the sericite, are near .01 mm. to 0.1 mm. across, and various sizes may be found within one patch of hydrothermal biotite. It is found on or within all the minerals except quartz, and this includes the alteration minerals of Stage I (Pl. 3, fig. 5). In many instances the flakes cross mineral boundaries. Pseudomorphs of hydrothermal biotite after biotite are discovered with straight boundaries on all sides, but more often a portion of the boundaries are ragged (Fig. 8). Some are entirely ragged. Occasionally the brown mica flakes composing the rims of pseudomorphs are either coarser or finer-grained than those of the core. Very often fine-grained quartz accompanies the brown mica in the pseudomorphs, and in some instances as much as 90 per cent of the area may be quartz (Fig. 8B).

Up to half the original biotite in a specimen may be unaltered, and in many cases an unaltered biotite crystal is adjacent to thoroughly altered biotite. Most of the fine-grained dark mica areas are extremely irregular in outline; the individual flakes have no particular alignment or arrangement. These patches may be either isolated or interconnected, with individual flakes extending in irregularly shaped stringers from one area to another. The sizes of hydrothermal biotite flakes vary throughout the

rock, and there seems to be no relationship between intensity of alteration and the size of the mica flakes.

Sericite is found in practically all specimens, accompanying the hydrothermal biotite. It is distinguished microscopically by its lack of color, high birefringence (intense first-order colors up to second-order red), flaky form, and its intermediate relief with the lowest index around 1.56. The sericite is found only in the feldspars and not intimately mixed with hydrothermal biotite. However, it is often present on or in a kaolinite-illite alteration area of Stage I. In the feldspars the sericite flakes are commonly spaced wide apart with unaltered feldspar between (Fig. 9); several characteristic arrangements of the flakes are seen. For instance, a "train" of randomly oriented sericite flakes crosses an otherwise unaltered feldspar crystal (Fig. 9A) as though the solution effecting the alteration had proceeded through a microfracture in the feldspar and the alteration has occurred only near the fracture. Several of these "trains" of sericite flakes may criss-cross within a single crystal. Many feldspars have altered only in part to sericite, while the rest of the feldspar crystal is clear and unaltered (Fig. 9B). The sericite flakes are frequently arranged with the long dimension of the shreds or flakes oriented in two directions forming a grid pattern over a feldspar crystal (Fig. 9C; Pl. 3, fig. 4). However, more commonly the sericite flakes have a completely random or feltlike arrangement with an even distribution throughout the crystal (Fig. 9D). With increasing intensity of alteration the amount of sericite increases, and the unaltered feldspar between the flakes decreases. In all the granite observed there was never more than 20 per cent of the rock changed to sericite, and except in a very few instances hydrothermal biotite always accompanied it.

Actinolite Syenite

The actinolite syenite was altered to a minor degree by Stage II type. The hydrothermal biotite and sericite are found in the same relationships and proportions and affecting the same minerals as in the granite but are not so abundant. Around the borders of the actinolite

syenite areas where it is in contact with granite some actinolite and diopside, have been altered to a fine flaky greenish mica rather than brown mica. The most intensely altered actinolite syenite contained about 10 per cent of Stage II alteration minerals.

Granite Porphyry

As in the granite, sericite is not detectable in hand specimen except for the alteration found in the small dikes and plugs of Section 5 and the upper part of Section 10 where hydrothermal biotite is essentially absent and a silky luster on intensely altered feldspar phenocrysts distinguishes the sericite. In the rest of the granite porphyry, hydrothermal biotite is abundant, but it generally amounts to about one third of that present in the granite and occurs principally as pseudomorphs after biotite. Only about one third to one half of the total biotite phenocrysts in the granite porphyry (which are readily observed in the hand specimen) are changed to pseudomorphic patches which generally have a regular outline but show a very dense structure.

Under the microscope about 90 per cent of the hydrothermal biotite in the granite porphyry is found in large patches with regular or irregular outlines and is believed to have developed largely from previously existing biotite. About 10 per cent of the hydrothermal biotite occurs in the quartz-orthoclase groundmass or in the feldspar phenocrysts distributed in small disconnected patches. Many of the pseudomorphs here contain considerable accompanying alteration quartz similar to that found in the granite. Some biotite phenocrysts have been bleached with the accompanying development of many oriented rutile needles. The sericite is found here in precisely the same manner as in the granite, being derived entirely from the feldspar and found in similar relationships (Figs. 9A, B, C, D).

Both second stage minerals are distributed throughout the granite porphyry. Where a later stage (Stage IV) has altered large areas in the granite porphyry, the hydrothermal biotite and sericite of Stage II have been obliterated, and identity of Stage II in these areas is therefore lost.

In aplite the alteration minerals of Stage II have been developed to about the same extent and intensity as within the granite porphyry proper.

are 0.5 mm. across and are believed to have been formerly occupied by feldspar. In some specimens the feldspar is partially altered only to sericite.

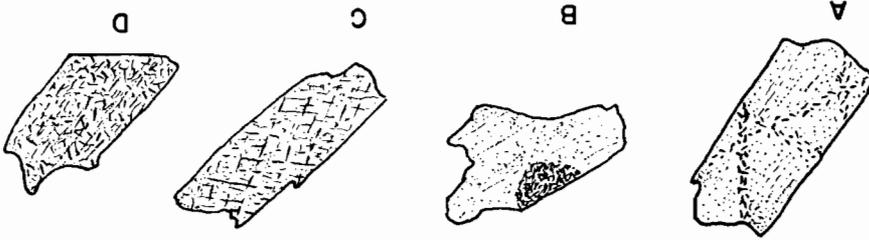


FIGURE 9.—SERICITE IN FELDSPAR

(A)—aligned in "trains." (B)—present only in part of a crystal. (C)—flakes oriented in a grid pattern. (D)—flakes in felt-like or random arrangement. Camera lucida drawing, $\times 26$.

Biotite-Quartz Latite Porphyry

In practically all the dike rocks classified as biotite-quartz latite porphyry most of the feldspar phenocrysts have been completely changed to sericite, whereas hydrothermal biotite occurs principally on the fringes of the biotite and to a slight extent in the groundmass.

Granitized Quartzite

The typical granitized quartzite contains but a very little hydrothermal biotite, and no well-developed dark mica pseudomorphs were found. In only one or two specimens was hydrothermal biotite present in sufficient quantity to give the rock a brownish appearance. The smaller biotite flakes are more or less randomly oriented and disseminated. The sericite in the very fine feldspar aggregates is usually in such small flakes that very high magnification was necessary to resolve them. When observable, however, they are found to be present in an open disconnected manner similar to that found in the feldspar of the granite porphyry and granite.

Feldspar Network

In practically all cases quartzite having the feldspar network contains very fine-grained unmixed hydrothermal biotite and sericite both of which are present only in the feldspars. The flakes are generally quite small and randomly oriented, but occasionally some areas or patches

Sediments

Some hydrothermal biotite was found in a few unfeldspathized quartzites. It is recognized in hand specimen by the presence of some very small (0.5 mm.) widely spaced, brownish-looking spots disseminated throughout the rock.

In the limestones hydrothermal biotite is generally restricted to the edges of some of the xenoliths, or skialiths. In some places enough dark mica has been introduced to make up as much as 50 per cent of the rock, and occasionally the individual flakes become so large that cleavage units can be discerned megascopically.

Relations between Hydrothermal Biotite and Sericite

In many slides, hydrothermal biotite and sericite adjoin, and the boundary relations suggest that the dark mica is later than the sericite. However, there are no crosscutting veinlets or other visible structural features to show that the two minerals were developed at separate stages, and it is therefore believed that the two are closely related in time and environment of formation.

Character of Altering Solutions

It has been fairly well established (Gruner, 1944, p. 587) that true sericite (fine muscovite) probably forms in acid solutions above 350°C. and in alkaline solutions below 350°C. The field of formation of biotite is not so well known.

However, one might extrapolate that, since biotite is so similar to sericite, both might have approximately the same general environment of formation. There is no critical mineral accompanying this stage of alteration which would place the temperature of formation above or below 350°C. or the pH of the solution above or below 7. Therefore neither the pH nor the temperature of the solution can be determined.

Chemical analysis Number 2, Table 2, is of an intensely altered (50 per cent alteration minerals) granite containing hydrothermal biotite and sericite. This analysis is not radically different from an analysis of the comparatively unaltered rocks, Numbers 2 and 4, Table 1. The greatest difference is in the Fe_2O_3 content, which jumps from 1.88 per cent to 3.74 per cent in the altered rock. All other figures remain within a reasonable and expectable range considering the wide variation in composition of the original rock. The introduction of iron was no doubt responsible for the profuse formation of biotite. Analogous percentages for silica, alumina, magnesia, soda, and potash in the analyses indicate that not much if any of these materials were introduced.

Paragenesis

When Stage I minerals, kaolinite and illite, were found with Stage II minerals, the hydrothermal biotite and sericite frequently formed on the Stage I minerals, and occasionally veinlets of Stage II minerals traversed Stage I minerals (Pl. 3, fig. 5). This evidence is admittedly purely petrographic, but it is fairly conclusive that Stage II followed the development of illite and kaolinite of Stage I.

HYDROTHERMAL STAGE III—CHLORITE- HYDROTHERMAL BIOTITE

General Statement

Alteration Stage III, resulting in the development of profuse chlorite and hydrothermal biotite in granite, is readily recognizable in the field. The dark mica is of the same type as that found in Stage II though the individual flakes are generally much smaller. The term chlorite here is used to cover several mineral species of the chlorite group. At the beginning

of the study seven chlorites—penninite, antigorite, clinocllore, delessite, diabantite, jenkinsite, and prochlorite—were distinguished optically. However, there seemed to be no spatial or areal relationship of these chlorites to one another, and in the present report it seemed proper to use the general term chlorite rather than any of the species names.

The granite which has been intensely altered to chlorite and hydrothermal biotite of Stage III appears very dense, nearly black, and when wet resembles black limestone. Where the alteration is less intense, the original granitoid texture may be discerned, though the granite is still quite dark. Alteration is best developed near the western margin of the pit (Sections 1 and 6) where it is readily seen as dark streaks. These streaks range in width from a few millimeters to slightly over 200 feet. Three irregular areas were mapped on the southern middle and upper levels (Sections 7 and 12), but the specimens in this region show less intense alteration than do the rocks to the west. Many additional small pods or patches of this alteration type are found everywhere within the granite area, but because of their small size they were not mapped.

Microscopic Features

Under the microscope, the hydrothermal biotite and chlorite always occur in a fine flaky form often intimately mixed. In the most intensely altered rocks no feldspar or biotite has been left unaltered, and the quartz units have been replaced principally on their edges. In less intensely altered rock some of the feldspar and original biotite may be unaffected. The alteration minerals occur either as very fine-grained felted irregular solid mats or, in less intensely altered rocks, as fine flakes scattered through feldspar and biotite.

Chlorite Orbicules

Of special note are some chlorite orbicules which have formed in granite as a result of Stage III alteration. In these orbicules the chlorite has formed with spherically curved cleavages, giving a distinct onionlike structure to the mass. The largest orbicule seen was 22

mm. in diameter (Pl. 5, fig. 1), but the average size is around 10 mm. with some as small as 2 mm. in diameter. The chlorite orbicules appear to have grown by replacing the minerals which surrounded it. It is not yet known why these orbicules have developed in such a unique manner.

Character of Altering Solutions

The minerals of the chlorite group have not been investigated extensively, and very little is known of the hydrothermal physico-chemical conditions under which they form. However, it is thought (T. S. Lovering and J. W. Gruner, Personal communication) that chlorite probably forms in neutral to slightly alkaline solutions at temperatures that range from near 100° to about 400° or 500°C. The intimate mixture of fine biotite and chlorite suggests they were formed at the same time and hence from the same type solutions. If biotite forms under similar conditions to sericite (alkaline solutions below 350°C.), then it may be argued that, since chlorite probably forms in alkaline or neutral solutions, the temperature at the time of Stage III alteration was probably lower than 350°C.

Chemical analysis Number 3, Table 2, was made of an altered rock of Stage III. The only significant chemical difference between this rock and the more or less unaltered granite (Table 1, Analyses 1, 2, 3, 4) is the expected higher magnesia and iron content. The percentages jump from a maximum of 2.7 for iron in unaltered rock to 5.1 and 4.1 for magnesia to 7.44 in the altered rock.

Paragenesis

The position of Stage III in the hydrothermal paragenetic sequence is very clear from structural evidence. In the field alteration streaks or bands of Stage III minerals cut through alteration Stage II, thus definitely dating the chlorite-hydrothermal biotite alteration.

HYDROTHERMAL STAGE IV— QUARTZ-SERICITE

General Statement

The fourth alteration stage finds quartz and sericite extensively developed along variously oriented fractures in granite, actinolite syenite,

granite porphyry, and granitized quartzite. The alteration has developed symmetrically on either side of the fractures producing bands easily recognized in the field. Where the bands are so wide and numerous as to coalesce leaving no unaltered rock between, as is common in the granite porphyry, the resultant rock somewhat resembles quartzite.

Field Features

The quartz-sericite alteration type clearly follows fractures in all cases. It colors the rock gray and converts it to a very dense chalcedonic-appearing material. Where the dark granite and actinolite syenite have been affected, these alteration areas appear as light streaks and bands (Pl. 5, fig. 5), but where they traverse the light-colored granite porphyry they appear darker than the host. It is difficult to recognize them in the granitized quartzite since the colors and textures are similar.

The alteration is always symmetrically developed on either side of a fracture, and the band or streak maintains a more or less constant width for a given fracture. The width of these bands ranges from 2 mm. to 10 cm. with most falling between 5 mm. to 3.5 cm., and the outer margins always appear as sharp contacts with the host rock. Along some outer borders in the granite a concentration of hydrothermal biotite formed, producing a darker streak on either side of the alteration area. Some fractures are open and empty, but most of them are filled either with glassy quartz of Stage V or sulfides of Stage VI, and frequently with both.

There seems to be no particular relation between the width of the alteration band and the width of the fracture. The fractures controlling the alteration are not preferentially oriented and are distributed entirely at random. They are usually fairly straight but may criss-cross one another at various angles in an intricate network. Because they are so easy to detect in the dark granite, some of the wider alteration bands (2-3 inches) have been traced in the field as far as two or three levels (200 or 300 feet).

Microscopic Features

Under the microscope the most intensely altered rocks of this stage are found to be com-

posed entirely of quartz and sericite in about equal amounts. The sericite, which occurs in irregular patches, is fine-grained, and the flakes are usually arranged in a feltlike manner, forming solid mats. The quartz is medium-grained with interlocking boundaries. Some of the alteration bands show less intense alteration, but this is also found to have quartz and sericite. Sericite is much less abundant and is found only in the position of former feldspars, biotite, and hydrothermal biotite. Some unaltered feldspar may remain. Where alteration has been less intense, the porphyritic texture of the granite porphyry is still readily determinable. Where an alteration band cuts large pink feldspar phenocrysts, the alteration seems to be predominantly sericite with sharp outer boundaries and contains quartz only near the center of the alteration band (Pl. 3, fig. 6).

There seems to be no particular gradation in the intensity of the alteration from the center of an alteration band to the outer margin; the whole band shows either intense alteration or moderate alteration. Although in most rocks the outer border of a band appears very sharp in hand specimen, under the microscope it is seen to be fairly gradational over a distance of 0.1 to 0.2 mm. Of special interest are bands of a dark mineral which sometimes occur just beyond the border of the alteration bands in granite (Pl. 4, fig. 6). Under the microscope this dark border is observed to be composed of hydrothermal biotite in greater concentration than in the granite, and within the alteration band itself are many bleached biotite crystals and hydrothermal biotite aggregates. This suggests that the altering solutions removed the iron and magnesia from the dark mica within the band to the position just beyond its border and there formed the dark mica. This condition may be somewhat similar to that commonly thought of as a "basic front."

Distribution

The alteration bands, though observed over the entire open pit, seem to be more concentrated in the western part of the mine. The amount of the altered rock generally ranges between 2 and 20 per cent of the whole, but, in many cases where alteration bands are wide

and frequent, these figures may grade up to 100 per cent. The areas mapped as Stage IV on Plate 1 indicate the areas where alteration constitutes 25 per cent or more of the rock. Some fairly large areas of 100 per cent altered rock are found principally in the granite porphyry on the higher levels to the west in Sections 1, 2, 6, and 7. Only a few small patches of 100 per cent altered rock are found in the granite. The intensely altered specimens often closely resemble quartzite, and a thin section was necessary in many instances to determine the true nature of the rock.

Character of Altering Solutions

The solutions that accomplished the Stage IV alteration evidently obtained access into the rock along fractures and soaked symmetrically into the walls on either side of the fracture. The only significant chemical addition was SiO_2 since the material to form sericite is present in the feldspars and biotite. The solutions extracted MgO and FeO and perhaps a little K_2O from the biotite and hydrothermal biotite and either removed them or deposited them nearby as disseminated material or as dark mica streaks along the edges of the alteration band. No diagnostic hydrothermal mineral was developed during this alteration stage by which to estimate the temperature or pH of the solutions. It is believed that quartz may form under all types of physico-chemical environments and, as stated elsewhere, sericite is formed either in acid solutions above 350°C . or in alkaline solutions below 350°C . There is no evidence to indicate which condition existed at the time of the alteration.

Analysis numbers 4 and 5, Table 2, are of rock showing alteration Stage IV. Of significance is the fact that the SiO_2 has jumped from 60–68 per cent to approximately 74 per cent and that Fe_2O_3 and MgO have declined rather markedly. Analysis number 3, Table 1, is of a comparatively unaltered granite and was taken from rock approximately 3 mm. from an altered band. Analysis number 5, Table 2, is of the altered band. Note that SiO_2 rises from 66.71 per cent in unaltered rock to 73.61 per cent in the altered band and that the MgO and Fe_2O_3 and Na_2O significantly decline.

Paragenesis

The sequence of formation of Stage IV is very clear from field evidence. These alteration bands traverse or cut through the hydrothermal biotite-sericite rock of Stage III, the hydrothermal biotite-sericite rock of Stage II, and the kaolin-illite rock of Stage I and are in turn cut by barren quartz veins of Stage V.

HYDROTHERMAL STAGE V—QUARTZ

The quartz of Stage V occurs in sharp-bordered veins which obviously filled fractures, and no minerals are altered as a result of its formation, hence stage V cannot be strictly called an alteration stage (Pl. 5, fig. 5). The quartz is clear to milk white and glassy and often contains vugs. The veins traverse all the rock types of the pit with random orientation and range in width from 0.5 mm. up to 10 cm. with the average near 1 to 7 mm. They are generally so widely spaced that no mapping of them was attempted. Sulfide crystals are found in many of the vugs.

As quartz is not diagnostic of temperature and pH of depositing solutions, no evidence as to the environment of formation of the Stage V quartz is possible. Study of the liquid inclusions in the quartz (not attempted here) could reveal information regarding the temperature of the quartz formation. In the field these veins cut through alteration bands of Stages III and IV (Pl. 5, fig. 5) and in turn are cut by sulfide veinlets, thus placing Stage V as definitely pre-sulfide and post-Stage IV.

STAGE VI—SULFIDES

General Statement

Although the presence of sulfides in the copper deposit at Bingham is the most important economic consideration, intensive study of the sulfide minerals was not attempted here for various reasons. This study was confined to the relationships of the stage of sulfide development to the overall hydrothermal history of the deposit. Evidence is conclusive that all the sulfides were formed during one clear-cut period in the hydrothermal sequence, but earlier work shows that the different sulfide minerals were

probably deposited at different times within this period, and it is recognized that these features deserve special study. Beeson's (1916) early work on the sulfide minerals at Bingham shows a picture of the sulfide problem at that time, but perhaps a new study is now warranted because of new and deeper exposures. The large and extensive problem of oxidation and enrichment of the ore body, though also important, would not materially add to the present study and was therefore neglected.

Sulfide Minerals

Sulfide minerals believed to have been deposited by hydrothermal solutions have been determined as digenite (x-ray determination), chalcopyrite, bornite, enargite, molybdenite, and pyrite.

The digenite occurs in very small (0.1 mm. diameter) individual units disseminated throughout the deposit. It usually is accompanied by one or several other sulfides. Chalcopyrite is the most widespread ore mineral and occurs predominantly as small (1.0 mm. maximum diameter) units also disseminated throughout the rock, but occasionally small veinlets of it are noticed. In one instance, a veinlet of chalcopyrite, about 6 inches long and 2 cm. wide was found in granite. Chalcopyrite is also found in many instances as well-shaped crystals in vugs within the quartz veins of Stage V.

Most of the bornite is present in the lower levels of the pit. It occurs in a manner similar to the chalcopyrite—that is, as small disseminated grains and rarely as small and disconnected veinlets.

Enargite is rare in the mine but, where found, is present in the vugs of the Stage V quartz.

Molybdenite occurs in very small units distributed throughout all the rocks in the mine; it is almost universally associated with the copper minerals. The largest molybdenite crystals are obtained, however, where it has crystallized in vugs in the quartz of Stage V.

Pyrite is by far the most abundant sulfide mineral in the mine. It forms small crystals disseminated throughout the rock, small veinlets, and very often well-developed crystals in vugs in the quartz of Stage V (Pl. 5, fig. 5).

Pyrite is also abundant in the sediments around the periphery of the igneous-looking rocks and in some cases may replace fairly large masses, particularly in the limestone.

Distribution

Pyrite is found in small crystals or large replacement bodies in all types of rock within the pit. Enargite occurs only in vugs of Stage V quartz while chalcopyrite, pyrite, bornite, and digenite are found in varying amounts in all the igneous-looking rocks and to a minor extent in some of the quartzites and limestones near the granite and granite porphyry.

The copper, iron, and molybdenum sulfide minerals do not seem to favor in occurrence any special alteration type or fundamental rock type within the mine except that they are generally more sparse in quartzite and limestone.

The sulfide minerals disseminated in the igneous-appearing rocks seem to favor positions within or adjacent to biotite (Schwartz, 1947, p. 326).

Alteration

The sulfide minerals in the pit were formed by (1) replacement in the solid rock, and (2) precipitation in the vugs of the quartz of Stage V. No rock-alteration effects were found which could be related to the development of the sulfide minerals.

Nature of Depositing Solutions

Available data indicate that none of the minerals formed during the sulfide stage are diagnostic of the physico-chemical nature of the depositing solutions. The question is raised as to just how the sulfide minerals were disseminated so uniformly throughout the rocks at Bingham. Many instances are found where quartz of Stage V containing large vugs may have only a few sulfide crystals deposited on the quartz, whereas, in the solid rock adjacent to the quartz vein, disseminated units of sulfide minerals in the usual concentration are present (Pl. 5, fig. 5). If the sulfide-bearing solutions traveled through the rock in a soaking manner, the connected vugs in the quartz veins would probably act as channels, accelerating the movement of the solutions. It might be expected

then that the vugs, having a more constant and fresh supply of sulfide-depositing solutions, ought to be filled with sulfides. This is true only rarely, and the vast majority of quartz veins which show vugs contain but a small amount of sulfides. When the overall spatial distribution of the sulfides in the rock is observed, the sulfide minerals are about equally spaced whether there is a vein with vugs in the area or not.

From this it is suggested that perhaps a new explanation of the mechanism of the sulfide introduction and deposition might be forthcoming. The sulfide-bearing solutions could have penetrated the rocks at Bingham and more or less come to rest without any deposition. This penetration when completed would soak not only through the pores of the rocks but also through the vugs in the quartz. Then, a more or less uniform concentration of sulfide material would be accomplished through diffusion throughout the soaked-up rock. At some time when conditions were right, crystallization of sulfides began with nucleation at more or less equally spaced points in the rock whether in a vug or not. The nuclei then grew, being fed by diffusion from the solutions in the immediate neighborhood of the growing crystal. Hence it might be thought that each crystal or unit represents the deposition of all the sulfide material from the solutions which were present just before precipitation. This would necessarily imply a rather concentrated ore solution. For example, if the total porosity of the rock (and hence volume of the ore solution) is assumed to be 10 per cent, this formed 1 per cent copper sulfide ore by this process, the rock density is taken as 2.6. The solution would have to contain 0.26 gm each of sulfur and copper per cc—*i.e.*, it would contain 26 weight per cent each of Cu and S if it had a density of 1.0. At this stage, local cracks may have formed resulting in the streaming in of sulfide-bearing solutions forming occasional small solid veinlets of sulfides. This whole process could thus be thought of not as a dynamic one but rather a comparatively stagnant soaking action.

There is a possibility that the uniform disseminated distribution of sulfides may be the result of an original uniform disseminated distribution of magnetite in the original igneous

rock and that the magnetite crystals, when the sulfide-bearing solutions traversed the rock, simply formed nuclei for sulfide replacement (Boutwell, 1905, p. 168). The present position of each crystal of sulfide then would largely be in the position of a former magnetite crystal. Magnetite was discovered in the limestones of the upper middle levels on the south side, but, in all the sections of the ingeous-appearing rock examined, not a single magnetite unit was found. If the above process is correct, some magnetite crystals should have been left unreplaced.

HYDROTHERMAL STAGE VII— SERICITE-ALLOPHANE

Following the deposition of the sulfides, sericite and allophane were formed in cracks and fractures. The two minerals have not yet been found together. The sericite occurs in veins up to an inch wide, principally on the east side of the pit. It is dense, white, with a satiny appearance and a very soapy feel. The allophane is quite widespread. One area near the middle levels on the south side contains so much allophane that the rocks appear white from a distance. The allophane is white, dense, and porcelainlike and forms in veins, the same as the sericite. Both minerals have been deposited on top of sulfide minerals, thus establishing their age as post-sulfide.

SUMMARY OF THE HYDROTHERMAL ALTERATION AND MINERALIZATION STAGES

In the first alteration stage following the formation of the rocks, kaolinite and illite were formed as an alteration product from feldspars in an area more or less confined to the north-central part of the pit. The temperature of the depositing solutions was probably below 350°C, and the solutions were acid. No appreciable amount of material was added to or extracted from the rock as a result of this stage.

Stage II finds sericite and hydrothermal biotite extensively developed in all the igneous-appearing rocks in the pit. Petrographic evidence separates Stage I from Stage II; microscopic veinlets of sericite and hydrothermal biotite are found in kaolinite and illite. Iron and

magnesia were introduced by the solutions, but not enough is known regarding the field of formation of hydrothermal biotite or sericite to state confidently the temperature and pH of the solutions. On the basis of the presence of sericite, the solutions either were at temperatures above 350°C and acid or below 350°C and alkaline.

Stage III is found principally in the granite as dark streaks and bands consisting of an intensive development of chlorite and hydrothermal biotite. These streaks cutting the granite establish this alteration as post-Stage II. Chlorite is believed to form in solutions which are neutral to slightly alkaline, and the hydrothermal biotite, so closely associated with the chlorite, probably forms in neutral to alkaline solutions which are below 350°C. Therefore, the alteration Stage III might have been accomplished by slightly alkaline solutions below 350°C.

The quartz and sericite bands of Stage IV cut Stage III alteration as well as Stages I and II, thus establishing its age. Sericite or quartz are not diagnostic of any particular environment, and nothing can be said regarding the temperature and pH of the solutions. Silica was introduced in profuse amounts.

Stage V saw the development of quartz only in veins and is not an alteration stage. In the field the veins cut the quartz sericite alteration of Stage IV as well as all earlier alteration stages, and it is therefore later. Quartz is believed to form in all types of solutions at all temperatures, hence no statement can be made regarding the temperature and pH of the solutions. Silica was the only substance introduced at this stage.

Sulfide crystals of Stage VI are in vugs in the quartz of Stage V, and small sulfide veinlets cut the quartz veins. Thus the sulfide stage is separated from the quartz mineralization of Stage V. Since various sulfides may be formed in all types of solutions in all ranges of temperatures, no interpolation can be made regarding the temperature and pH of the solutions. Copper, iron, sulfur, molybdenum, a little arsenic, silver, and gold were introduced by these solutions.

The minerals of the last hydrothermal stage, allophane and sericite, coat sulfide crystals, thus establishing that the allophane-sericite

stage is post-sulfide. Neither sericite nor allopahane is diagnostic of any hydrothermal environment of formation, and the temperature and pH of these solutions remain unknown. Potash, alumina, silica, and H₂O were introduced.

The solutions of the first four stages definitely altered some of the minerals in the rocks, and the solutions of Stages I and II soaked through the rock more or less uniformly. The solutions of the third and fourth stages traversed the rock through fractures and altered the rock adjacent to them. The solutions of the last three stages introduced material, and no alteration in the above sense was effected. Solutions of the fifth and seventh stages followed fractures, while, in the sixth or sulfide stage, solutions penetrated the rock uniformly, suggesting a soaking action.

ORIGIN OF SOLUTIONS

The problem rises as to the origin of the post-magmatic or post-granitization solutions and the localization of these solutions within the Bingham copper mine area. The solutions evidently came from depth, being derived as a differentiate of the original magma or the neomagma, which ever view is taken. The broader geographic localization may be due to the presence of a deep-seated channel in the vicinity of Bingham through which the solutions moved from a fairly deep source. The local position of the alteration stages and introduced minerals in the rock is probably the result of: (1) the original higher porosity of the igneous-appearing rock plus the intense fracturing which was localized in these same rocks and occurred concurrently with the entrance of at least the later solutions; (2) the original composition of the rocks for some reason caused the deposition of minerals from the solutions to favor the igneous-appearing rocks. The specific distribution of alteration types among the rock types is thought to be more a matter of spatial coincidence than a result of specific chemical "affinities".

It is not within the province of this study to speculate on the separation of the solutions from the magma or to offer reasons for the several distinct stages of mineralization; these

problems will be left to others. Perhaps when the entire Bingham or whole Oquirrh Mountain area has been intensively studied, some of the problems along these lines will be solved satisfactorily.

GENERAL CONCLUSIONS

The studies of the hydrothermal alteration at Bingham have resulted in the recognition of seven distinct mineralization periods. From this information interpretations have been made regarding the temperature and pH of the altering solutions of Stages I and III. Perhaps a reasonable and acceptable hypothesis could be made regarding the pH and temperature of Stages II and IV, but similar information regarding the last three stages would be purely guesswork.

The geologic and mineralization features of the Bingham disseminated copper deposit could be compared with other similar deposits, but no new information would be forthcoming since an adequate comparison has already been made by Schwartz (1947, p. 323-346), Kerr (1951, p. 478-480), Anderson (1950, p. 621-625), and others. A review of the hydrothermal studies of porphyry copper deposits by Kerr (1951) and Kerr *et al.* (1950) at Silver Bell and Santa Rita; Anderson (1950) at Bagdad; Gilluly (1946) at Ajo; Peterson *et al.* (1946) at Castle Dome, and Schwartz (1947) at San Manuel shows perhaps as many dissimilarities as similarities to the hydrothermal features at Bingham.

One may take the similarities of the group such as the argillic (illite and kaolinite at Bingham), biotitic, sericitic, and silicic alteration and propose that these features will likely be present to some extent in all "porphyry copper" deposits and that they might be used confidently in further exploration. At Bingham, however, the ore and protore mineralization extends practically to the full limit of the altered area making the alteration target there essentially no larger than the ore target; therefore the hydrothermal alteration is of little practical use as a guide to the ore finder at Bingham. This condition may not be true for all deposits, and the characteristic alteration above mentioned may be of great value to the ore finder in other areas.

The granitization and the feldspar network halo associated with the Bingham ore body possibly offers a new or different line of thought to the student of porphyry copper deposits.

There is a possibility that some of the dissimilarities of the various deposits mentioned above may be more apparent than real, due to the differences in background of the different workers and the time and intensity of the studies.

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