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Igneous Rocks and Hydrothermal Alteration at Bingham, Utah

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Abstract

Igneous rocks in the Carr Fork area of Bingham Canyon belong to the multiple-intrusive Bingham stock, the Last Chance stock, and the Carr Fork dikes. The Bingham stock includes, in order of emplacement, granite, granite porphyry, gradational granite porphyry, Type "A" porphyry, and quartz-latite porphyry. The undifferentiated Last Chance stock is an augite quartz monzonite, which is interpreted to be of the same intrusive system as the Bingham granite stock. The Carr Fork dikes are of three types that range from rhyolite porphyry to latite porphyry and correlate with porphyritic rocks of the Bingham stock.

The methods of emplacement of the igneous rocks have been interpreted. These methods include several forceful intrusions, one passive intrusion, one permissive intrusion, and one phase of recrystallization.

In the Carr Fork area hornblende and augite, with their alteration products, and magnetite and sulfide minerals are distributed zonally. They are indicators of the direction and distance to the center of the Utah Copper orebody. The alteration products of hornblende and augite, in general sequence toward the center of the orebody, are calcite, chlorite, quartz, actinolite, sericite, secondary biotite, and orthoclase. The most prominent magnetite-sulfide minerals in the same sequence are magnetite, pyrite, chalcopyrite, and bornite.

Significant results of this study include the recognition of several new igneous rock types, determination of the zonal distribution of some significant alteration products, and correlation of the Last Chance stock and Carr Fork dikes with phases of the Bingham stock.

Conclusions pertaining to the Carr Fork area are that (1) all the igneous rocks are the result of differentiation of one magma; (2) hornblende or augite, and magnetite were originally present in all the igneous rocks; (3) the sulfide minerals are not syngenetic; and (4) a period of hydrothermal activity immediately followed each of the porphyritic intrusions.

Introduction

Bingham Canyon, Utah, contains the major portion of the Bingham mining district. Through 1960 (Hammond, 1961), the district produced $4,250,000,000 in metal values. The majority of the values are from the Utah Copper porphyry orebody; underground operations conducted around its periphery account for the remainder.

The Utah Copper orebody is centered on and largely contained within the multiple-intrusive Bingham stock. It contains values in copper, molybdenum, gold, silver, selenium, rhenium, tellurium, and other trace elements. Lead-zinc-silver orebodies are zonally arranged around this stock as replacement bodies in sedimentary rocks and as fissure fillings.

In addition to the Bingham stock, four other groups of igneous rocks are present in the Bingham district. They are the (1) Last Chance stock, (2) Carr Fork dikes, (3) Butterfield sills, and (4) a volcanic complex.

The area of this study (Fig. 1) is a rectangle 4,000 feet wide that extends outward from the center of the Utah Copper orebody for 18,000 feet to the southwest. It includes half of the Bingham stock and orebody, part of the Last Chance stock, and almost all of the Carr Fork dikes (and minor sills). Igneous rocks comprise one-fourth of the area; sedimentary rocks of Pennsylvanian age occupy the remainder.

The method of study consisted of geologic mapping of outcrops and underground exposures. More than 400 samples were collected and 266 thin sections examined. Previous geologic work was utilized where applicable.

Field and laboratory work was conducted from 1963 to 1966.

Acknowledgments.—This paper includes a large part of the material in a thesis presented to the University of Utah as a partial requirement for a Master of Science degree in Mineralogy with Dr. Matthew P. Nackowski as the thesis committee chairman.

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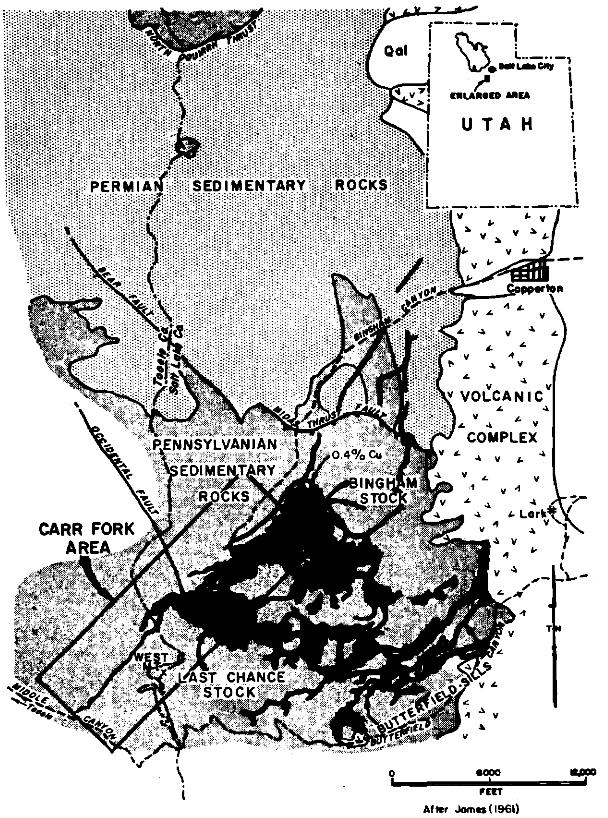

FIG. 1. Index map, Carr Fork Area.

was completed under Herman L. Bauer, Jr., Division Geologists of the Utah Copper Division.

The writer, in addition to his own original field work, made use of the previous detailed geologic map of the open pit mine by R. Eldon Bray and A. Paul Mogensen (unpublished) and district mapping by Allan H. James, John E. Welsh, and Wilbur H. Smith (1961).

General Geology of the Carr Fork Area

The surface geology of the Carr Fork area is shown on Figure 2. The principal geologic features include the Bingham stock, the Last Chance stock, and the southwesterly-trending Carr Fork dikes. Pennsylvanian quartzites with the intercalated Jordan and Commercial limestone beds dip moderately to the north and are the most abundant type of rock in the map area. The Occidental fault and a set of northeasterly-striking faults are shown. The outline of the porphyry copper orebody is represented by the 0.4% copper boundary centered on the Bingham stock.

The Bingham stock covers two-thirds of a square mile and is roughly triangular in plan. The base of the triangle lies off the eastern margin of the map and the apex points toward the southwest. The Bingham stock contains 75 percent of the exposed porphyry copper orebody—the remaining 25 percent is in the immediately-adjacent sedimentary rocks. The Last Chance stock forms an exposure of one-fourth square mile in the map area southwest of the Bingham stock. The Carr Fork dikes extend from the southwest apex of the Bingham stock in a southwesterly direction for more than 12,000 feet. They are generally subparallel to each other and are quite narrow.

Quartzite with minor limestone beds is the host for the igneous rocks in the Carr Fork area. The quartzite and limestone beds are Pennsylvanian and extend from the Upper Butterfield formation to the Upper Bingham mine formation of the Oquirrh group (Welsh and James, 1961; James, Smith, and Welsh, 1961; Hansen, 1961). In general the sedimentary rocks strike northeasterly and dip moderately to the northwest. Near the north edge of the Bingham stock the beds dip more steeply, are locally overturned, and the strike changes from east-west to northwest and again to east-west.

Faults are numerous in the Carr Fork area. The normal Occidental fault strikes north-northwest and forms the western boundary of the Bingham horst (James, Smith and Welsh, 1961). Dikes offset by this fault show right-lateral displacement suggestive of renewed right-lateral or reverse movement. The horst contains the Bingham and Last Chance stocks. The flat-lying Roll fault, 1,000 feet east of the Occidental fault, offsets the Jordan and Commercial limestones but does not offset the dikes. Northeasterly-striking faults are most numerous. They dip from 75°NW to 75°SE. They parallel the porphyritic dikes, apparently control the northwest edge of the Bingham stock, offset the limestone beds with either right or left-lateral displacement and are the site of important veins. Faults and fractures increase in number toward the Bingham stock. The Bingham stock is intensely broken by a multitude of minor faults but the Last Chance stock is relatively unbroken.

The ore deposits of the Bingham district are zoned around the granite porphyry of the Bingham stock. Copper and molybdenum of ore grade concentration occur in veinlets and as disseminated grains in all the granite porphyry exposed and extend laterally 2,000 feet to the south in the granite but extend only a few hundred feet into the sedimentary rocks to the north. A pyritic zone from 1–2,000 feet wide lies between the porphyry copper orebody and the peripheral lead-zinc-silver replacement and fissure zone. The outer margin of the lead-zinc-silver zone extends roughly 9,000 feet from the center of the porphyry copper orebody. The Carr Fork area includes a large sector of all the ore zones.

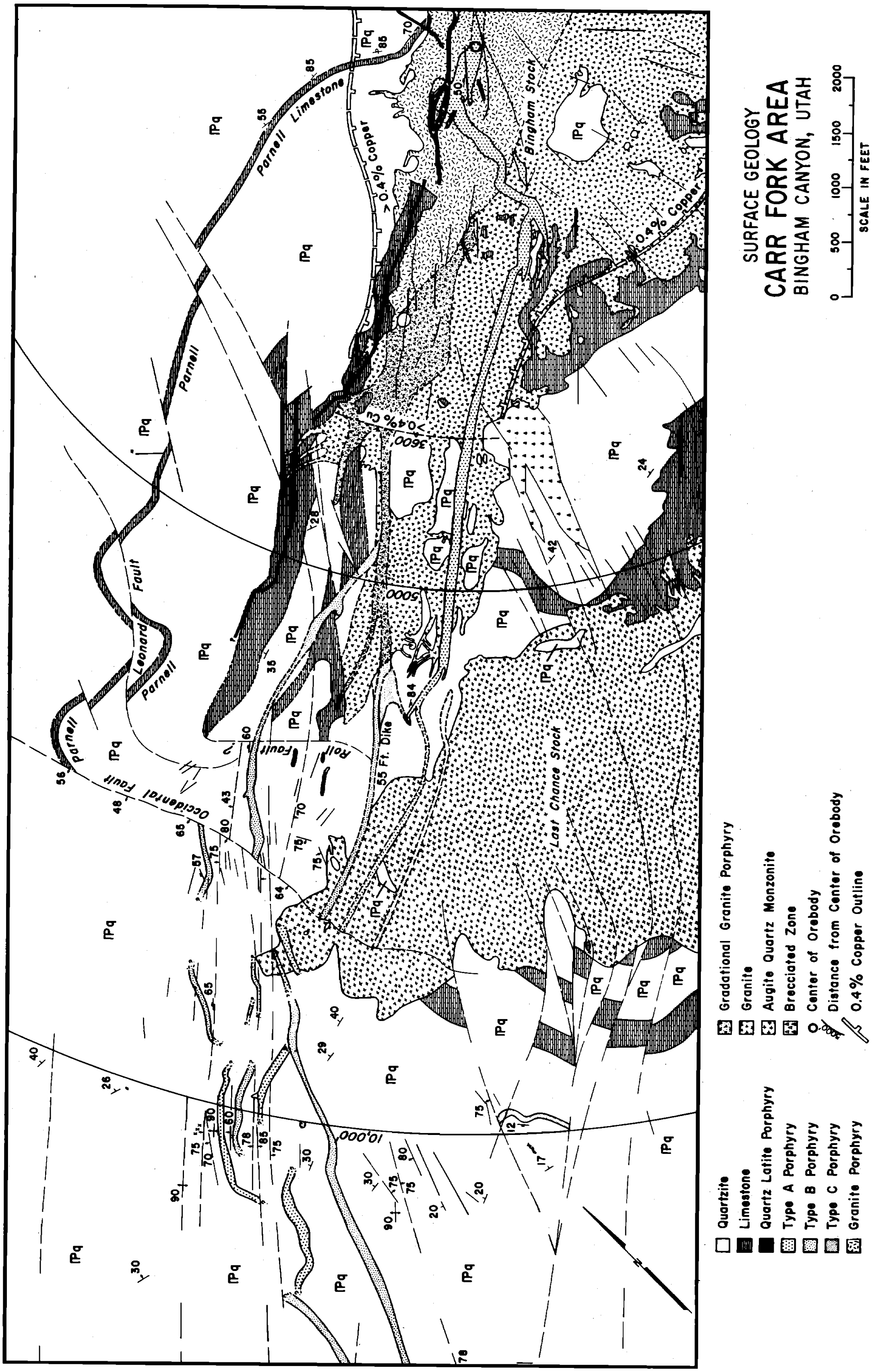
SURFACE GEOLOGY
CARR FORK AREA
BINGHAM CANYON, UTAH
0 500 1000 1500 2000
SCALE IN FEET
Quartzite
Limestone
Quartz Latite Porphyry
Type A Porphyry
Type B Porphyry
Type C Porphyry
Granite Porphyry
Gradational Granite Porphyry
Granite
Augite Quartz Monzonite
Brecciated Zone
Center of Orebody
Distance from Center of Orebody
0.4% Copper Outline
Parnell Limestone
Parnell
Leonard Fault
Occidental Fault
Roll Fault
55 Ft. Dike
Bingham Stock
Last Chance Stock
>0.4% Copper
>0.4% Cu
0.4% Copper
3600
5000
10,000

FIG. 2.

Hydrothermal alteration effects are evident from the center of the orebody outward for more than 15,000 feet. The effects are most obvious in igneous rocks. The distribution and spatial-genetic relationships of hornblende, augite, and their alteration products and of magnetite and sulfide minerals form zones and change significantly as the center of the porphyry copper orebody is approached.

Igneous Rocks of the Carr Fork Area

Igneous rocks present in the Carr Fork area are the composite Bingham stock, the Last Chance stock, and the Carr Fork dikes. The Bingham stock includes five rock types, the Last Chance stock one, and the Carr Fork dikes three. The geometric form of the outcrops of the several igneous rock types in the Carr Fork area varies from broad triangular forms to narrow elongated dikes. The nature of the contacts ranges from gradational to sharp. Crosscutting relationships give reliable indications of the relative ages of most of the rocks. The various igneous rocks of the Carr Fork area represent forceful, passive, and permissive (emplaced without force) types of intrusion as defined by Stringham (1960). Unpublished potassium-argon age determinations by Fred McDowell of Columbia University and by the U. S. Geological Survey indicate the igneous rocks were emplaced over a short time interval approximately 36 to 39 million years ago.

Description and Classification

The nine types of igneous rocks in the Carr Fork area range from granite to latite porphyry in composition. Photomicrographs of the Bingham stock and the Last Chance stock rock types are shown on Figure 3. Stringham (1953) conducted the only previous detailed study of the igneous rocks in the area.

Bingham Stock.—The Bingham stock contains granite, granite porphyry, gradational granite porphyry, Type "A" porphyry, and quartz-latite porphyry.

The granite (Fig. 3A) is a medium gray, equigranular rock made up principally of 0.9 mm orthoclase, oligoclase, and quartz grains. It has a uniform texture in which the grains are randomly oriented and distributed. Near the granite porphyry the granite is coarser grained and commonly contains orthoclose phenocrysts. Megascopic aggregates, mostly of secondary biotite, replace hornblende and augite and comprise 12 percent of the rock. Books of primary biotite comprise 6 percent of the rock. Actinolite is present in amounts up to 15 percent near the south and west edges of the ore-body where it is only partially replaced by secondary biotite. Disseminated sulfides and veinlets of quartz and sulfides are common. The granite is distinguished from all other rocks of the Carr Fork area by its relatively larger grain size, generally equigranular texture, medium-gray color, and abundance of hornblende-augite replacement aggregates.

The granite porphyry (Fig. 3B) is light gray and contains 30 percent 0.5 mm to 5.0 mm feldspar phenocrysts scattered randomly through a light gray aphanitic groundmass. Books of primary biotite make up 3 percent and secondary biotite shreds in replacement aggregates make up 6 percent of the rock. No quartz phenocrysts are evident. Disseminated sulfide minerals and quartz veins with associated sulfides total 6 percent. Microscopic examination shows that the groundmass is saccharoidal and composed of 0.05 mm orthoclase and quartz grains and some trace minerals. The granite porphyry is distinguished from all other rocks of the Bingham stock by its light color, presence of feldspar phenocrysts, absence of quartz phenocrysts, and a groundmass composed of 0.05 mm orthoclase and quartz grains.

The gradational granite porphyry (Fig. 3C) is medium gray and porphyritic with an aphanitic groundmass. This classification includes two indistinguishable rock types; one is a textural gradation from granite toward granite porphyry and the other is a textural and mineralogic gradation from granite porphyry to Type "B" porphyry. The amount of groundmass in the rock gradational from granite varies from zero at the granite contact to 50 percent at the granite porphyry contact. The rock gradational from granite porphyry to Type "B" porphyry has 45 percent groundmass. An average sample of gradational granite porphyry has a uniform texture in which 46 percent of orthoclase and 5 percent andesine phenocrysts ranging from 0.2 to 4.0 mm across are randomly distributed in a medium gray interstitial groundmass. The interstitial groundmass is composed of 0.06 mm orthoclase and quartz grains with some trace minerals. Aggregates of secondary biotite make up 9 percent and books of primary biotite make up 5 percent of the rock. Disseminated sulfide minerals are preferentially associated with the hornblende-augite replacement aggregates. The secondary orthoclase, quartz, and rutile that occur in the replacement aggregates with the secondary biotite and sulfide minerals are evident only under the microscope. Quartz-sulfide veinlets are common. Where the groundmass is less abundant this rock is similar to granite in megascopic appearance. Where the groundmass is more abundant this rock is distinguished from granite porphyry by its darker color and by its slightly coarser grained and more altered groundmass.

The Type "A" porphyry (Fig. 3D) is a medium gray porphyry with an aphanitic groundmass and a

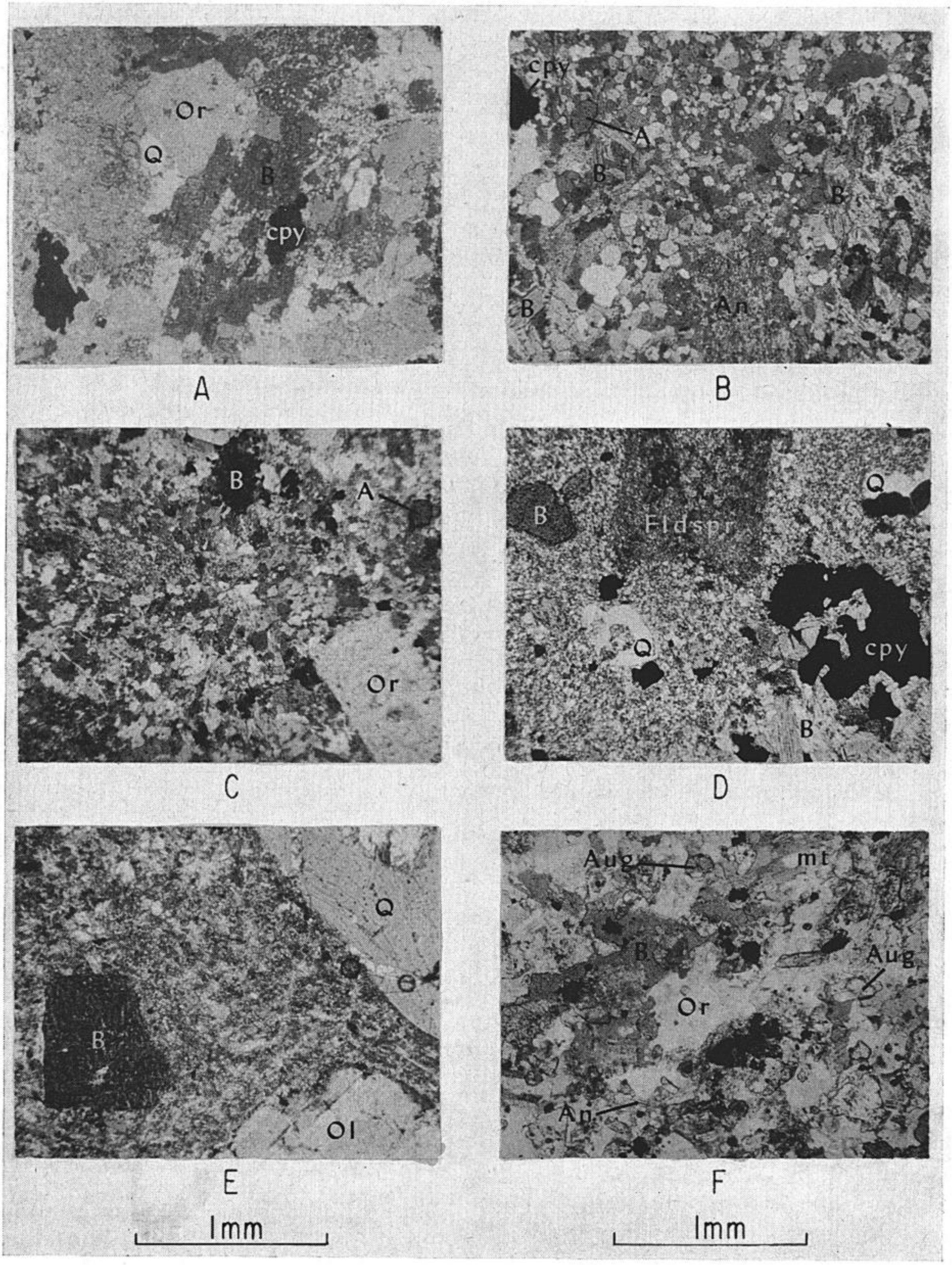

FIG. 3. Photomicrographs of Bingham and Last Chance stock rock types. A, Granite. Orthoclase (Or), quartz (Q), primary biotite (B), and chalcopyrite (cpy) are shown. B, Granite porphyry. An andesine phenocryst (An), shreds of secondary biotite (B), bornite (bn), chalcopyrite (cpy), and apatite (A) are shown in the orthoclase-quartz groundmass.

uniform texture. Dikes of Type "A" porphyry extend 12,000 feet from the center of the Bingham stock and are more basic farthest from the center. The Type "A" porphyry near the orebody center is composed essentially of 18 percent orthoclase and 11 percent oligoclase phenocrysts averaging 2.3 mm in a medium gray aphanitic groundmass. Secondary biotite in megascopic hornblende-augite replacement aggregates constitutes 12 percent and books of primary biotite constitute 4 percent of the rock. Quartz phenocrysts are sparse to absent. Copper sulfides are disseminated and are also associated with quartz veinlets. The groundmass is composed essentially of orthoclase, quartz, and biotite grains which average 0.02 mm across. Partially resorbed quartz phenocrysts average 0.6 mm across and form 3 percent of the rock. Apatite, rutile, and zircon are trace minerals. The Type "A" porphyry near the center of the Bingham stock is a rhyolite porphyry; it is distinguished from the granite porphyry by the finer grain and darker color of its groundmass.

Three stages of quartz latite porphyry intrusion occur in the Bingham stock but only one stage is found within the map area. The quartz latite porphyry (Fig. 3E) is medium gray and is composed of 25 percent feldspar and 8 percent quartz phenocrysts in an aphanitic groundmass. The feldspar phenocrysts are commonly subparallel and average 2 mm across; the quartz phenocrysts average 3 mm across. Subparallel books of primary biotite total 6 percent; secondary biotite is absent to sparse. Sulfide minerals are disseminated through the rock; veinlet-associated sulfides and quartz are sparse. The groundmass is composed of 0.05 mm orthoclase, quartz, and plagioclase grains. Chlorite commonly forms pseudomorphs after hornblende. This rock ranges from rhyolite porphyry to quartz latite porphyry in petrographic classification. It is distinguished from all other rocks of the Bingham stock by the presence of relatively large quartz phenocrysts, an absence of secondary biotite, and by the more basic character of its groundmass which is reflected by a lower quartz and a higher plagioclase content.

Last Chance Stock.—The Last Chance stock in the Carr Fork area is composed of augite-quartz monzonite. No other stage of intrusion originating within the Last Chance stock is noted but the Last Chance stock is cut by porphyritic dikes associated with the Bingham stock.

Megascopically the augite quartz monzonite (Fig. 3F) is medium gray, equigranular, aphanitic, and has a uniform texture in which the grains are randomly oriented and distributed. No phenocrysts are evident except near the margins of the stock where there are up to 3 percent feldspar phenocrysts averaging 3 mm across. Primary biotite, which makes up 6 percent of the rock, is recognized by cleavage reflections but no other minerals can be distinguished in hand specimen. Actinolite and minor pyrite do occur in the Last Chance stock but alteration features common to the Bingham stock such as secondary biotite, copper sulfides, quartz veining, and feldspar alteration products are absent to sparse. Microscopic examination shows orthoclase and andesine grains which average 0.4 mm across with augite crystals that average 0.25 mm across and 0.1 mm quartz grains. Magnetite makes up 4 percent of the rock. Less than 1 percent appatite and zircon are present as minor accessories. This rock is generally distinguishable from the granite of the Bingham stock by its smaller grain size, presence of augite, and more basic composition.

Carr Fork Dikes.—The Carr Fork dikes and one sill are of at least three petrographic types. They include Types "A," "B," and "C" porphyry. Based on feldspar ratios, total quartz, and texture, they range from rhyolite porphyry to latite porphyry. The field classifications are largely based upon groundmass textures.

The Type "A" porphyry 11,000 feet from the center of the orebody is slightly finer-grained, contains less quartz, more andesine, and has a different alteration assemblage than the Type "A" porphyry near the orebody center. It is light to medium gray and contains 29 percent andesine and orthoclase phenocrysts, which average 1.5 mm across, in a medium gray 0.02 mm groundmass. Primary biotite makes up 5 percent, altered augite 6 percent, hornblende 1 percent, and magnetite 2 percent of the rock. Calcite and chlorite are the hornblende-augite alteration products; some magnetite is replaced by pyrite. No quartz veining is evident. This rock is a quartz latite porphyry. It is distinguished from the Type "B" and "C" porphyries by its finer-grained microcrystalline and generally equigranular groundmass.

Dikes of Type "B" porphyry extend a horizontal distance of more than 13,000 feet in the Carr Fork

C, Gradational granite porphyry (recrystallized granite). An orthoclase phenocryst (Or), secondary biotite (B), and apatite (A) are shown in the orthoclase-quartz groundmass. D, Type "A" porphyry. A highly altered feldspar phenocryst (fldspr), two small quartz phenocrysts (Q), primary biotite (B) and a secondary biotite (B)-chalcopyrite (cpy) aggregate are shown in the orthoclase-quartz groundmass. E, Quartz latite porphyry. The edge of a large quartz (Q) phenocrysts, and a book of primary biotite (B) are shown in the plagioclase-orthoclase-quartz groundmass. F, Last Chance stock augite quartz monzonite. Augite (Aug), primary biotite (B), andesine (An), orthoclase (Or), and magnetite (mt) are shown.

area and are more silicic nearer the orebody. A sample 10,000 feet from the orebody center is medium light gray and essentially composed of andesine and orthoclase phenocrysts averaging 1 mm across in an aphanitic groundmass. The texture is uniform to subparallel. The rock also contains 6 percent altered hornblende and 7 percent primary biotite phenocrysts. Chlorite and calcite are alteration products of hornblende; the magnetite is unaltered. The groundmass is made up essentially of orthoclase, andesine, and quartz grains which average 0.08 mm across. This rock is a borderline quartz latite or rhyolite porphyry. It has a coarser groundmass than the Type "A" porphyry and contains less plagioclase than the Type "C" porphyry. The Type "B" porphyry probably grades into the granite porphyry of the Bingham stock.

The Type "C" porphyry is medium gray, has an aphanitic groundmass, and is quite variable in composition and texture. It is probably a contact gradation of the Type "B" porphyry but may be a separate rock type. A typical sample contains 12 percent andesine and 5 percent orthoclase phenocrysts, which average 1.5 mm across, in a medium gray aphanitic groundmass. Other megascopic features include 9 percent primary biotite, 7 percent altered augite, 3 percent magnetite, and 1 percent hornblende and quartz. Calcite and chlorite are the augite alteration products; magnetite is unaltered. The groundmass is made up of andesine, orthoclase, augite, and quartz grains which average 0.1 mm across and exhibit preferential planar alignment. The Type "C" porphyry is generally a latite porphyry. The groundmass differs from the Type "A" or "B" porphyry groundmasses by containing more andesine and less orthoclase and by having a subparallel texture.

Geometric Form of Outcrop

The form of the igneous rock outcrops in the Carr Fork area (Fig. 2) offers important evidence of the mode of emplacement (Stringham, 1960) and is defined by shape, size, and orientation.

Bingham Stock.—The triangularly-shaped Bingham stock has a surface exposure of 420 acres and is comprised of five rock types. The granite, on the south, is triangular in shape with an apex extending westward and forms an incomplete outer shell around the off-center core of granite porphyry which is also triangular with its apex pointing southwestward. The gradational granite porphyry forms a wedge-shaped septum between the granite and granite porphyry near the southwest apex of the stock. The Type "A" porphyry is a 60-foot wide dike that trends generally southwestward from the center of the orebody. The quartz latite porphyry forms narrow dikes and sills (average 12 feet) and also trends southwestward.

Last Chance Stock.—The Last Chance stock forms a triangular-shaped outcrop southwest of the Bingham stock. It covers one-fourth of a square mile. The Last Chance stock also extends beyond the map area to the south as irregularly-shaped salients that occupy an additional one-fourth of a square mile. The Last Chance and Bingham stocks are in contact to the southeast of the map area.

Carr Fork Dikes.—The Carr Fork dikes are 3 to 120 feet thick and of considerable length. They extend from the apex of the Bingham stock in a southwesterly direction for more than 12,000 feet and are subparallel to each other. They are offset an apparent distance of 600 feet right-laterally by the Occidental fault.

Nature of Contacts

The nature of igneous rock contacts in the Carr Fork area are classified as sharp or gradational and as regular or irregular and are evidence of their mode of emplacement. According to Stringham (1960) sharp, regular contacts are generally indicative of forceful emplacement whereas gradational, irregular contacts are generally indicative of permissive emplacement.

Bingham Stock.—The contacts of the several igneous rock types of the Bingham stock are varied (Fig. 2). The granite formed sharp to gradational irregular contacts against the sedimentary rocks and an undetermined type of contact with an extension of the Last Chance stock augite quartz monzonite southeast of the map area. The granite porphyry formed a sharp irregular contact against quartzite, sharp regular contacts against limestone and granite, and a gradational regular contact against the gradational granite porphyry. The gradational granite porphyry has regular contacts that grade gradually into granite on the south, more abruptly into granite porphyry on the north, and into Type "B" porphyry to the southwest. The Type "A" porphyry has moderately sharp regular contacts against the granite porphyry and very sharp regular contacts against the granite, quartzite, and limestone. The quartz latite porphyry has sharp regular contacts against all other rock types.

Last Chance Stock.—The Last Chance stock is in contact with limestone, quartzite and the porphyritic dikes of the Carr Fork group. The contact against limestone is sharp and irregular; xenoliths of limestone in the intrusive are common near the contact. The northern contact against quartzite is also quite sharp but regular.

Carr Fork Dikes.—The Carr Fork dikes, which include Types "A," "B" and "C" porphyry, have sharp, regular contacts with quartzite,, limestone, and the Last Chance stock. The Type "B" porphyry probably grades into the gradational granite porphyry of the Bingham stock. The Type "C" porphyry is probably in gradational contact with the Type "B" porphyry. No contact between the Type "A" and either "B" or "C" porphyry was recognized.

Cross-Cutting Relationships

Cross-cutting relationships between the igneous rocks of the Carr Fork area (Fig. 2) are the most positive evidence of their relative ages. Sequentially the granite, the oldest rock of the Bingham stock, is intruded by the granite porphyry, which is cross-cut by the Type "A" porphyry, which is in turn intruded by the quartz-latite porphyry. The Last Chance stock is cross-cut by the Carr Fork dikes; these dikes grade into porphyritic phases of the Bingham stock.

Bingham Stock.—The granite of the Bingham stock does not cross-cut any igneous rock types; it probably grades into the augite-quartz monzonite of the Last Chance stock southeast of the map area. The granite porphyry occupies a wedge-shaped area partly surrounded by granite; only a few small dike-like apophyses of granite porphyry cross-cut the granite. The gradational granite porphyry consists of two phases; the granite porphyry to granite gradation is cut by a small granite-porphyry dike and the gradation from granite porphyry to Type "B" porphyry cuts through the granite at the southwest apex of the stock. The Type "A" porphyry cross-cuts the granite and the granite porphyry of the Bingham stock near the center of the orebody as a wide, well-defined dike. The quartz-latite porphyry cuts the granite east of the map area as narrow dikes and plugs and cuts through both the granite porphyry and the Type "A" porphyry as narrow dikes near the orebody center.

Last Chance Stock.—The Last Chance stock is made up of augite-quartz monzonite. At its northwestern edge the Last Chance stock is cut by the Carr Fork dikes. To the southeast, beyond the map area, the Last Chance stock probably grades into the granite of the Bingham stock. It forms an undetermined contact with the Butterfield sills.

Carr Fork Dikes.—All three types of Carr Fork dikes cut through the Last Chance stock and correlate with porphyritic rocks of the Bingham stock. The Type "C" porphyry of the Carr Fork dikes grades into and is a border phase of the Type "B" porphyry which is the equivalent of the granite porphyry of the Bingham stock. The Type "A" porphyry of the Carr Fork dikes is the same as the Type "A" porphyry in the Bingham stock. The Type "A" and "B" porphyries are not found in contact with each other but cross-cutting relationships in the Bingham stock indicate the Type "A" porphyry is younger and should cross-cut the Type "B" porphyry.

Alteration of Igneous Rocks

The features of alteration and mineralization include alteration products of hornblende and augite and the relationships between magnetite and sulfide minerals. The works of Stringham (1953) and Peters, James, and Field (1966) deal chiefly with aspects of alteration other than those included here but there is some overlap. The principal alteration products of hornblende or augite (which are characterizing accessories of the igneous rocks) are calcite, chlorite, actinolite, sericite, quartz, secondary biotite, and orthoclase. This sequence broadly reflects their spatial distribution from outlying areas toward the center of the orebody. The abundance of magnetite, pyrite, chalcopyrite, bornite, primary chalcocite and covellite, secondary chalcocite and covellite, and hematite were also established. Figures 4 and 5 are photomicrographs of alteration features; the distribution of alteration products is depicted in Figures 6. The hydrothermal solutions had little effect on the Last Chance stock as compared to the porphyritic dikes at equivalent distances from the orebody center.

Hornblende-Augite Alteration

Distribution of Minerals.—The abundance, distribution, and associations of hornblende, augite, calcite, chlorite, quartz, actinolite, sericite, secondary biotite, and orthoclase are described herein.

Hornblende is consistently present in amounts up to 4 percent beyond 15,400 feet from the orebody center. The occurrences of hornblende between 8,300 and 4,000 feet from the orebody center are erratic. It is commonly associated with the low-grade alteration products chlorite, minor calcite, magnetite, and leucoxene.

Augite is consistently present beyond 14,300 feet from the orebody center in amounts up to 12 percent. It occurs between 9,000 and 3,000 feet from the orebody center probably for the following reasons: (1) samples were collected from the Last Chance stock, which was impermeable and largely unaffected by the hydrothermal solutions, (2) samples were collected from other igneous units, which were "insulated" from the hydrothermal solutions, and (3) samples were collected from igneous rocks which reacted with immediately-adjacent limestone to form more augite. Presence of limestone also apparently preserved the augite from alteration. Augite is commonly associated with its alteration products calcite, chlorite, and actinolite.

Calcite replaces augite especially, and hornblende to a minor extent. It occurs as fine-grained aggre-

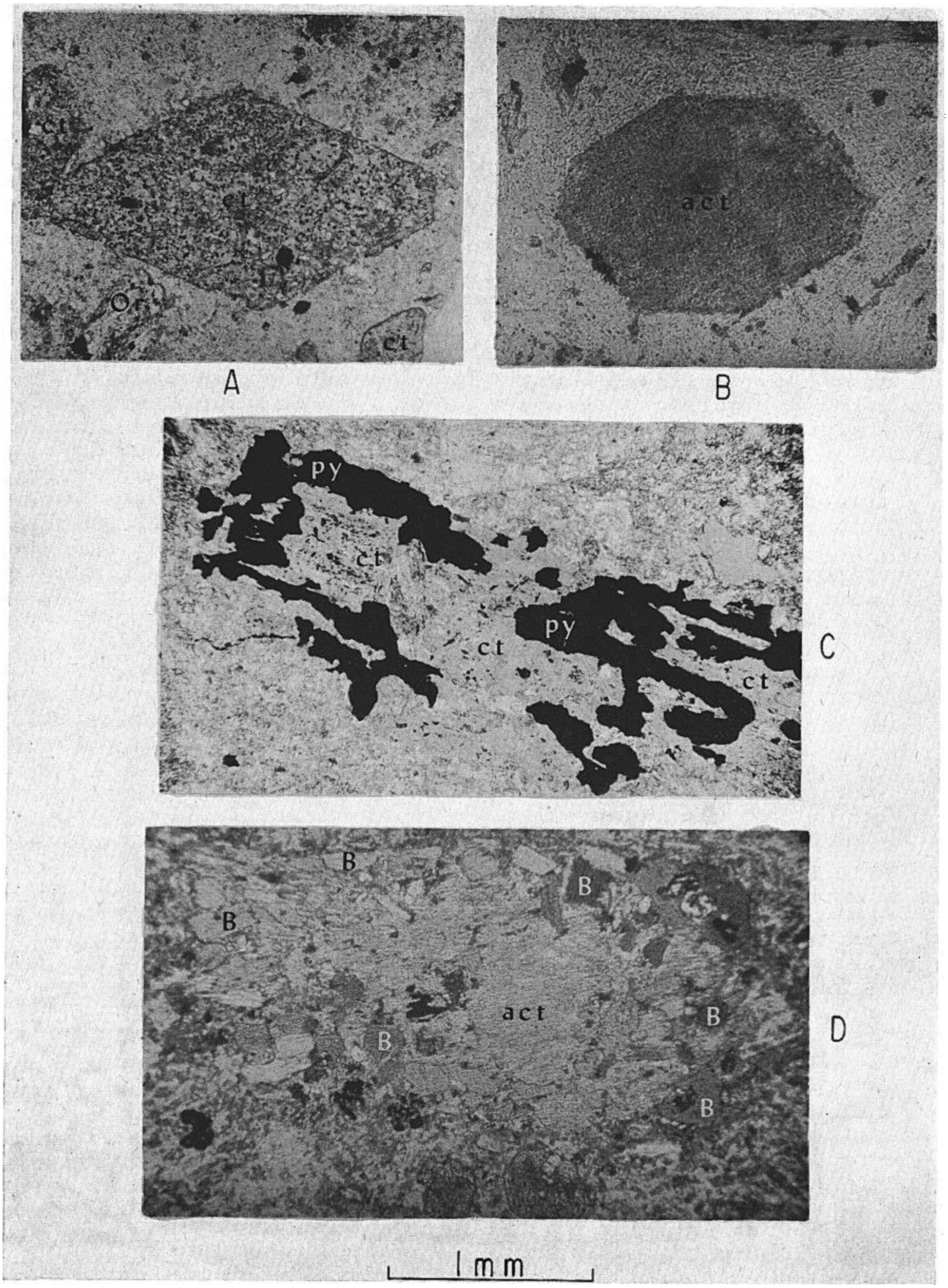

FIG. 4. Photomicrographs of alteration features in igneous rocks of the Carr Fork area. A, Three chlorite (ct)-leucoxene (tiny disseminated opaque grains) pseudomorphs after hornblende and one orthoclase (Or) phenocryst are shown in Type "A" porphyry. B, An actinolite (act) pseudomorph after a cross-section of augite is shown in Type "B" porphyry. C, Pyrite (py) and chlorite (ct) form a pseudomorph of hornblende in quartz latite porphyry. D, An actinolite (act) pseudomorph of augite is rimmed by numerous secondary biotite (B) crystals in Type "C" porphyry.

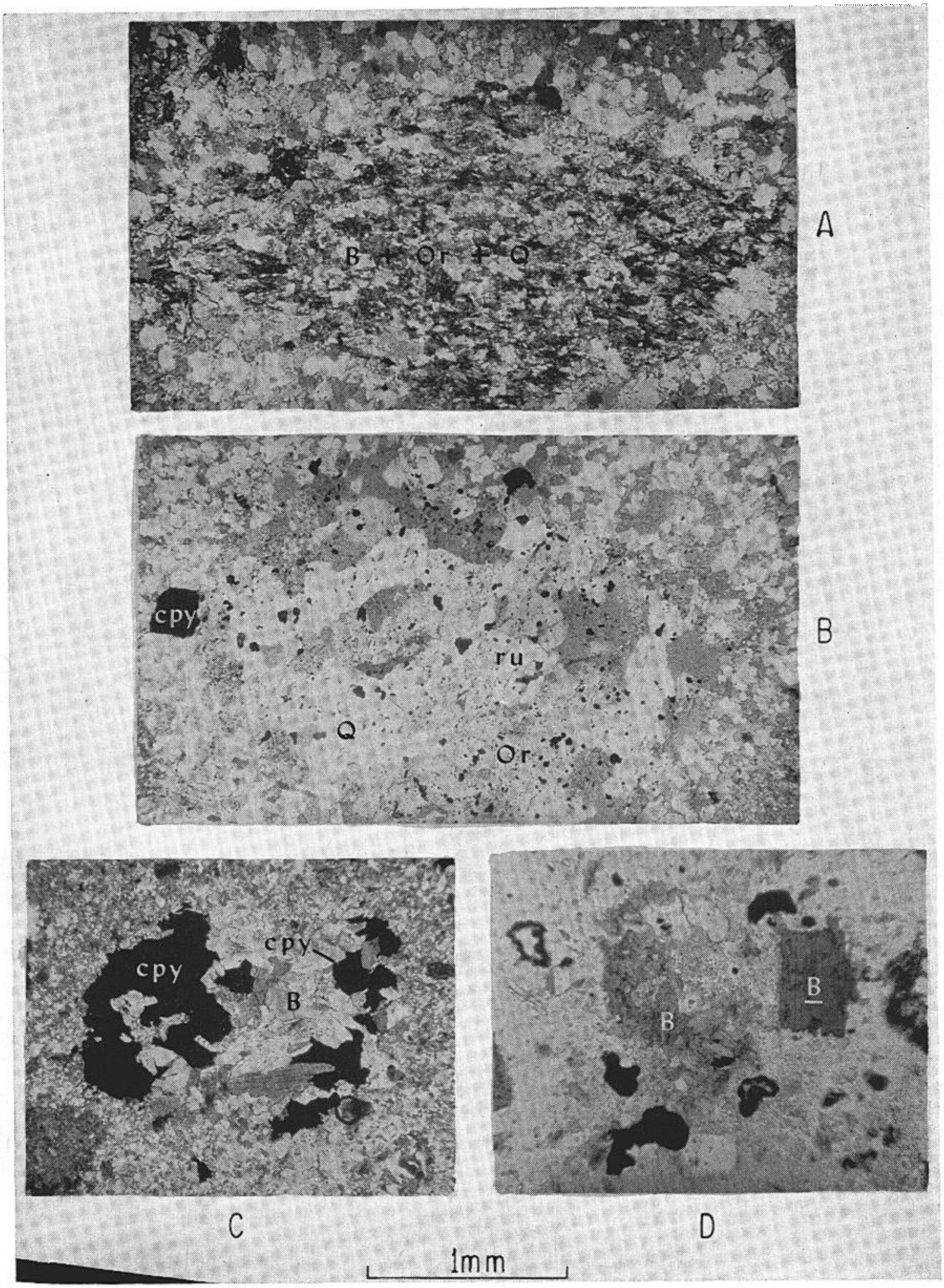

FIG. 5. Photomicrographs of alteration features in igneous rocks of the Carr Fork area. A, An alteration aggregate of secondary biotite (B), orthoclase (Or), and quartz (Q) preserves a hornblende cross-section in granite porphyry. B, Coarse-grained secondary orthoclase (Or) and minor quartz (Q) with disseminated rutile (ru) crystals form a pseudomorph of an unidentified ferro magnesian mineral in granite porphyry. C, A replacement aggregate composed of chalcopyrite (cpy) and secondary biotite (B) is shown in Type "A" porphyry. D, A book of primary biotite (*B*) and an aggregate of secondary biotite (B) shreds is shown in Type "A" porphyry.

gates within the crystals it replaces. Calcite is found from the limits of sample collection at about 17,000 feet to 7,100 feet from the center of the orebody in amounts up to 14 percent depending on the amount of augite or hornblende originally present and the intensity of alteration. Calcite and chlorite generally occur together to form well-defined pseudomorphs after hornblende or augite. Calcite is apparently not replaced by other minerals but it decreases in abundance as actinolite becomes prominent.

Chlorite replaces hornblende mostly (Fig. 4A, C) and augite to a lesser extent. It occurs as fine-grained aggregates within the crystals it replaces. Chlorite is found from the limits of sample collection to 2,900 feet from the orebody center in amounts up to 15 percent. Chlorite and calcite generally occur together farther than 7,100 feet from the orebody center and form pseudomorphs of hornblende and augite, which retain the original crystal outlines. Chlorite grades into or is replaced by secondary biotite as the orebody is approached.

Quartz replaces hornblende and augite (Fig. 5A, B) and is found within 15,000 feet of the orebody center in amounts up to 8 percent. Secondary quartz is distinguished from primary quartz by its association with other replacement products and by its intermediate grain size. The crystals average 0.12 mm across, which is coarser than the groundmass crystals of the porphyritic rocks but finer grained than the primary quartz in the granite. The secondary quartz crystals are commonly elongated parallel to the long dimension of the replacement aggregates. Secondary quartz forms replacement aggregates in association with all the other replacement products and is not a diagnostic mineral for determining distance from the orebody.

Actinolite replaces augite (Fig. 4B, D) in amounts up to 17 percent from 7,400 to 5,000 feet from the center of the orebody. It is found partially or completely replacing augite as continuous individual crystals and generally retains the augite crystal outline. Where present it is generally the major replacement product of augite. Actinolite does not replace earlier replacement products but is replaced by secondary biotite near the orebody. Actinolite is of special significance because of its proximity to the edge of the orebody, its definite correlation with hydrothermal alteration, and the link it forms between augite and secondary biotite.

Sericite replaces hornblende and augite or earlier replacement products in amounts up to 7 percent from 5,800 to 2,600 feet from the center of the orebody. The zone of sericitic replacement overlaps the 0.4 percent copper assay wall and its width is restricted, so sericite is especially significant. Sericitic alteration is commonly associated with strong pyritization. It occurs as minute shreds forming poorly-defined pseudomorphs of hornblende and augite and also of feldspar. Sericite generally replaces a major portion of the rock in which it occurs but is also associated with other replacement products. It may replace secondary orthoclase and commonly grades into or is replaced by secondary biotite.

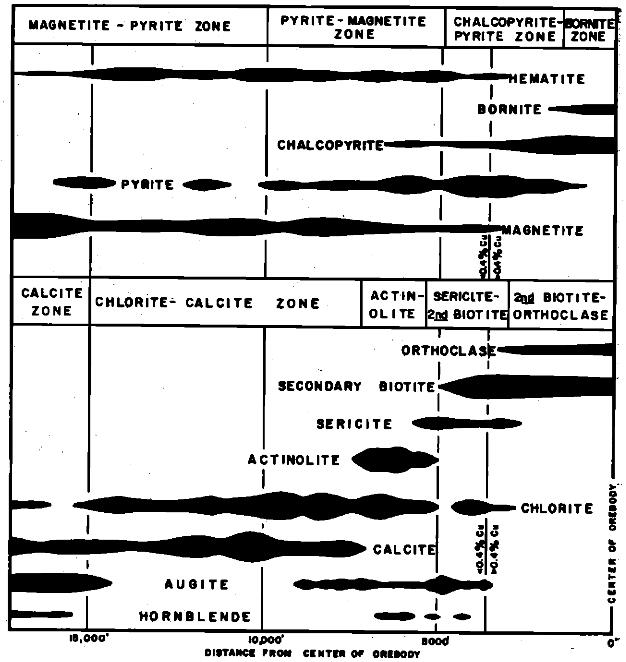

FIG. 6. Hornblende-augite alteration and magnetite-sulfide relationships, Carr Fork Area, Bingham Canyon, Utah.

Secondary biotite replaces hornblende and augite or earlier replacement products (Figs. 4D, 5A, C, D) within 4,800 feet of the center of the orebody in amounts up to 12 percent. It is found in replacement aggregates with secondary orthoclase, quartz, copper sulfide minerals, and rutile near the orebody center and with sericite, actinolite, chlorite, pyrite, copper sulfides, and rutile near the edge of the orebody. The replacement aggregates commonly retain recognizable hornblende crystal outlines. Secondary biotite also replaces actinolite, chlorite, and possibly sericite. It, and secondary orthoclase, represent the highest grade of alteration in the Carr Fork area and are confined almost entirely within the orebody.

Secondary orthoclase replaces hornblende and augite (Fig. 5A, B) within 3,200 feet of the center of the orebody in amounts up to 5 percent. Secondary orthoclase occurs in replacement aggregates with secondary biotite, secondary quartz, copper and iron sulfides, and rutile. It is distinguished from primary orthoclase by its association with other replacement products and by its intermediate grain size. The crystals average 0.12 mm across, which is coarser than the groundmass crystals of the porphyritic rocks and finer grained than the primary orthoclase in the granite. Secondary orthoclase is confined to the orebody and, with secondary biotite, represents the highest grade of hydrothermal alteration.

Leucoxene commonly results from the alteration of ferromagnesian minerals (Fig. 4A) and generally comprises less than 1 percent of the constituents of the igneous rocks. Details of its distribution were not determined. It is white and opaque and is commonly associated with hornblende-augite alteration aggregates. As the orebody is approached the leucoxene grades into rutile (Fig. 5B).

The hornblende-augite alteration pattern can be divided into five zones as illustrated in Figure 6. Progressing from the least-altered rocks toward the center of the orebody the five zones are:

(1) Calcite zone—17,300 to 15,000 feet from the orebody center.
(2) Chlorite-calcite zone—15,000 to 7,200 feet from the orebody center.
(3) Actinolite zone—7,200 to 5,400 feet from the orebody center.
(4) Sericite-secondary biotite zone—5,400 to 3,000 feet from the center of the orebody.
(5) Secondary biotite-orthoclase zone—from 3,000 feet to the center of the orebody.

Zones (1) and (2) could be combined. Difference in the original ratio of augite to hornblende probably caused the variations in the calcite to chlorite ratio.

Alteration products of hornblende differ somewhat from those of augite. Hornblende, where weakly altered, results in the formation of chlorite and minor calcite, quartz, and leucoxene; weak or propylitic alteration of augite results in the formation of calcite with minor chlorite, quartz, and leucoxene. Also, actinolite is a replacement product of augite but not of hornblende.

Characteristics of Primary and Secondary Biotite.—The distinction between primary and secondary biotite (Fig. 5D) is important for making alteration interpretations. Primary biotite is an ubiquitous mineral in the igneous rocks. Secondary biotite is a hornblende-augite replacement product resulting from intense hydrothermal alteration.

Primary biotite is present in unaltered as well as in altered igneous rocks. It occurs as medium brown pleochroic 0.6 mm euhedral books. Hydrothermal solutions affected these books only slightly, resulting in corroded crystal edges; weathering commonly bleaches the biotite light yellow-brown.

Secondary biotite is an end product of high-intensity alteration of hornblende and augite at Bingham. It occurs as aggregates of 0.06 mm shreds which form partial pseudomorphs after hornblende and augite. The color and birefringence of secondary biotite in the central part of the ore zone is very similar to that of primary biotite and cannot be used to distinguish them. Secondary biotite is commonly pale green or pale brown outside the orebody and can there be distinguished from primary biotite by color as well as habit.

Magnetite-Sulfide Relationships

Distribution of Minerals.—The distribution of magnetite and the sulfides pyrite, chalcopyrite, bornite, primary chalcocite and covellite, molybdenite, secondary chalcocite and covellite, and hematite are sequentially discussed herein.

Magnetite is a disseminated primary constituent in amounts up to 4 percent of the least-altered igneous rock in the Carr Fork area (Fig. 3F). It may also be a minor alteration product of hornblende. Both primary and secondary magnetite are progressively replaced by pyrite as the orebody is approached; only traces of pyrite or hematite weathered from pyrite are present 17,000 feet from the orebody center. The magnetite content of the igneous rocks decreases as pyrite replaces it until, at 3,400 feet from the orebody center, all of the magnetite is replaced. Magnetite is generally associated only with pyrite but near the orebody chalcopyrite commonly is found in the same rocks. The individual grains of magnetite generally are completely replaced by pyrite; partial replacement is uncommon. Indirect evidence for the replacement of magnetite by pyrite is the inverse relationship in their abundance; as the amount of magnetite decreases the amount of pyrite increases.

Pyrite is a replacement product of both primary and secondary magnetite in the igneous rocks and its abundance increases progressively from a distance of 17,000 feet toward the orebody center (Fig. 4C). Up to 4 percent pyrite is present in thin sections 3,400 feet from the orebody center where magnetite is completely replaced; much of this pyrite occurs in veinlets. From the 3,400-foot point toward the center of the orebody pyrite decreases as chalcopyrite increases in abundance and at 700 feet from the center of the orebody pyrite is absent. Pyrite is associated particularly with magnetite beyond 5,000 feet and with chalcopyrite within 5,000 feet of the orebody center.

Chalcopyrite (Fig. 5B, C) appears consistently as disseminated grains and veinlets in thin sections of samples within 6,500 feet of the center of the orebody (2,900 feet outside the 0.4 percent Cu boundary). Chalcopyrite increases in abundance toward the center of the orebody and reaches a maximum of 3 percent. Chalcopyrite apparently replaces pyrite; direct evidence is the sea-and-island texture in veins where chalcopyrite surrounds islands of pyrite. Indirect evidence for the replacement of pyrite by chalcopyrite is the decrease in the abundance of pyrite as the amount of chalcopyrite increases. Chalcopyrite is associated especially with pyrite beyond 1,500 feet and with bornite within 1,500 feet of the orebody center.

Bornite generally occurs as composite grains with chalcopyrite and primary chalcocite. It is confined to the higher-grade portion of the orebody. Bornite is first noted 2,100 feet from the center of the orebody and increases in abundance toward the center; some samples contain almost 2 percent bornite. Paragenetic relationships between bornite, primary chalcocite, and chalcopyrite have not been established.

Primary chalcocite, probable digenite, and covellite are generally confined to the higher-grade part of the orebody and occur in amounts to 0.5 percent in composite grains with bornite and chalcopyrite. The paragenesis of primary chalcocite, probable digenite, and covellite in the Carr Fork area has not been determined.

Molybdenite is associated with the more intense copper mineralization in the exposed orebody and is especially associated with quartz veins and fractures. Molybdenite does not replace other sulfide minerals. The detailed distribution of molybdenite was not noted and is not shown in Figure 6.

Secondary chalcocite and covellite are similar in appearance to primary chalcocite and covellite but differ in occurrence. The secondary chalcocite and covellite occur in very small amounts generally as coatings on pyrite grains in samples collected near the base of oxidation. Secondary chalcocite and covellite were found, in the early 1900's, overlying the present orebody but have been largely removed by mining.

"Hematite" formed from the weathering of sulfide minerals near the ground surface and commonly retains outlines of pyrite crystals. Practically no "hematite" is found in the samples collected from the open pit because the oxide zone has been removed. Yellow-brown iron oxide results from the weathering of hornblende, especially, and is not included under the heading of "hematite."

The magnetite-sulfide minerals distribution pattern has been divided into four zones as illustrated in Figure 6. In sequence toward the center of the porphyry copper orebody the four zones are:

(1) Magnetite-pyrite zone—17,300 to 10,000 feet from the orebody center.
(2) Pyrite-magnetite zone—10,000 to 4,900 feet from the orebody center.
(3) Chalcopyrite-pyrite zone—4,900 to 1,500 feet from the orebody center.
(4) Bornite zone—from 1,500 feet to the orebody center.

A correlation is drawn between the disseminated magnetite, hornblende, and augite of unaltered rocks and their altered equivalents within the Utah Copper orebody, which are disseminated copper sulfide minerals and aggregates of secondary biotite, orthoclase, quartz, rutile, and copper sulfides. However, copper sulfides also occur in sedimentary rocks most of which never contained appreciable amounts of magnetite, hornblende, or augite; this indicates that magnetite, hornblende, and augite were the preferred and major but not exclusive host or nucleus for replacement by or precipitation of sulfides. Veinlets of copper sulfide minerals also occur and may indicate remobilization of disseminated sulfides or direct crystallization of some sulfides from the hydrothermal solutions.

History of Intrusion and Hydrothermal Activity

The methods of emplacement and formation, correlation of equivalent intrusive rocks, the relative ages of intrusion, and the periods during which hydrothermal activity occurred have been determined for the Carr Fork area. These determinations suggest that a single magma differentiated at depth to form the several stages of intrusion and mineralization.

Methods of Emplacement and Formation

The methods of emplacement and formation of the igneous rocks in the Carr Fork area are classified according to Stringham (1960) and are based on the geometric form of the outcrops, the nature of the contacts, the structural attitude of the country rock, and microscopic features of the rocks. The interpretations herein agree quite well with Stringham's (1953, 1960) earlier interpretations.

Bingham Stock.—The rocks of the Bingham stock represent three different modes of emplacement and formation.

The granite is a permissive intrusion (involving very little force). It does not form any extensive dikes and its contacts with sedimentary rocks are quite irregular. The limestone beds in contact with the granite are in a relatively undisturbed position and project into the granite as shown in Figure 2. Apparently quartzite beds originally above and below the limestone have been assimilated or removed by stoping or plucking. The high ratio of meta-limestone to quartzite in contact with the granite on the pit surface is in excess of the relative abundance of these sedimentary rocks in the district. Drilling to depth on the east and south sides of the mine shows that the Jordan and Commercial limestone horizons project as relatively unbroken beds into the granite for several hundreds of feet.

Three methods by which the permissive emplacement of the granite may have taken place are suggested:

(1) Digestion of the quartzite immediately adjacent to the contact by a magma.
(2) Plucking of quartzite and its transportation from the system by the magma.
(3) Formation of an igneous rock in situ by permeation and attendant heating of the quartzite by magmatic solutions, which contributed elements required to form granite by additive replacement of quartzite.

Method (1) with (2) and (3) playing minor roles provides the most likely mechanism of granite emplacement.

The granite porphyry is a forceful intrusion as evidenced by several features. Granite porphyry and its equivalent, Type "B" porphyry, form dikes having contacts that are sharp. Xenoliths are absent in the granite porphyry and the attitude of the Parnell limestone is changed, apparently by force, near the granite-porphyry contact.

The gradational granite porphyry is probably recrystallized granite. It is located between the surface exposures of granite and granite porphyry and is largely underlain by granite porphyry. The gradational granite-porphyry-granite contact, recognized microscopically, is imperceptibly gradational; the contact with granite porphyry is more abrupt.

The Type "A" porphyry is a forceful intrusion. It forms at least one narrow dike that extends for 11,000 feet to the southwest. The contacts of the Type "A" porphyry against most other rock types are sharp and regular.

The quartz latite porphyry is a forceful intrusion as evidenced by the extensive, narrow dikes that it forms, and the sharp contacts of these dikes.

Last Chance Stock.—The Last Chance stock contains only augite-quartz monzonite and is classified as a passive intrusion because some evidence favors a forceful and some a permissive means of emplacement. Indications of a forceful emplacement include dikes formed southeast of the map area, sharp contacts with sedimentary rocks, and a relative lack of contamination of the stock by immediately adjacent limestone. Indications of a permissive emplacement are that the intruded sedimentary rocks are relatively undisturbed, limestone in the northeastern margin of the stock protrudes without deformation into the stock, and if the Last Chance stock and the Bingham stock granite are a single intrusive this implies that the Last Chance stock, as the granite, was also emplaced permissively.

Carr Fork Dikes.—The three types of Carr Fork dikes are forceful intrusions. The elongated, narrow, tabular form of the Carr Fork dikes is strong evidence of their forceful emplacement. The sharp, regular contacts with the country rock are supporting evidence.

Correlation of the Last Chance Stock with the Bingham Stock Granite

Analogous and equivalent alteration facies of the two rocks indicate the Last Chance stock augite quartz monzonite and the Bingham stock granite are of the same intrusive system. Primary mineralogical and textural differences within a single intrusion coupled with differential alteration can account for their present differences.

The portions of the augite quartz monzonite most affected by hydrothermal alteration are similar to and difficult to distinguish from the portions of the granite least affected by hydrothermal alteration.

The Bingham stock granite is slightly coarser grained and contains more orthoclase and quartz than the Last Chance stock. Primary zoning is probably largely responsible for these differences as evidenced by primary zoning relationships within all the individual igneous bodies in the area. Hydrothermal alteration further increased the quartz and orthoclase content of the granite. The augite and magnetite originally present in both rock types are at least partially replaced by actinolite and pyrite at a distance of 5,000 feet from the orebody center. In the granite nearer the center of the orebody the actinolite is replaced by aggregates of secondary biotite, orthoclase, and quartz; the pyrite is replaced by copper sulfides.

Relative Ages of Intrusion

The relative ages of all the igneous rocks in the Carr Fork area are determined by interpretation of the mode of formation of the gradational granite porphyry, cross-cutting relationships between most of the igneous rocks of the Carr Fork area, and correlation of the augite-quartz monzonite with the granite.

The relative ages of the igneous rocks of the Carr Fork area are summarized diagrammatically:

Younger

- Quartz Latite Porphyry of the Bingham stock
- Type "A" Porphyry of the Bingham stock and Carr Fork dikes
- Gradational Granite Porphyry of the Bingham stock formed by recrystallization of Granite
- Granite Porphyry of the Bingham stock and its equivalents—a fraction of the Bingham stock Gradational Granite Porphyry and the Type "B" and "C" Porphyries of the Carr Fork dikes.
- Granite of the Bingham stock and Augite-Quartz Monzonite of the Last Chance stock

Older

Age of Hydrothermal Activity

The hydrothermal activity responsible for the alteration and mineralization of the Bingham stock and surrounding area occurred as several separate stages, one stage occurring immediately after each of the porphyritic intrusions. These separate hydrothermal stages resulted in the alteration of the hornblende, augite, and magnetite originally present in each of the igneous rock types; a net result is that the oldest intrusions are the most and the youngest intrusions are the least altered and mineralized.

Near the center of the orebody igneous rocks emplaced progressively later than the granite porphyry contain progressively lower grade alteration minerals indicating that they postdate part of the hydrothermal activity. The earlier-emplaced granite and granite porphyry near the orebody center contain secondary biotite, secondary orthoclase, bornite, primary chalcocite, and chalcopyrite which are typical of the highest grade of alteration. The slightly later-emplaced Type "A" porphyry, also near the orebody center, contains secondary biotite and secondary orthoclase but less bornite and primary chalcocite than the immediately-adjacent granite or granite porphyry. Also near the orebody center the first two intrusions of quartz latite porphyry, which are younger than the Type "A" porphyry, generally contain minerals typical of a still lower grade of alteration; these alteration minerals are chlorite, only a trace of secondary biotite, and chalcopyrite and pyrite. The third, or last intrusion of quartz latite porphyry, occurs in the same locality and is the youngest igneous rock in the Carr Fork area; it contains actinolite, pyrite, and magnetite, which is the lowest-grade alteration mineral assemblage in the Bingham stock. This decreasing effect of alteration in successively younger intrusions suggests that a stage of hydrothermal activity immediately followed each of the porphyritic intrusions with the last, a weak stage, ending after the last intrusion of quartz-latite porphyry.

Magmatic Differentiation

Magmatic differentiation of a single magma at depth is proposed as the source of the igneous rocks and hydrothermal solutions in the Carr Fork area. The several stages of intrusion and hydrothermal activity in the Carr Fork area are closely related spatially and are probably structurally controlled. There is also a close chronological association of the several intrusions and the hydrothermal activity. The composition of the parent magma probably approximated that of a borderline granite or quartz monzonite.

The three or more porphyritic intrusions in the area are centered on the north side of the Bingham stock granite and are elongated to the southwest. There apparently is a structural control for these porphyritic intrusions and for the hydrothermal activity in the Carr Fork area. Numerous faults and fissures in the Carr Fork area strike in a northeast direction; very likely the porphyritic rocks were emplaced along similar planes of weakness. In turn, the mass of the granite porphyry is the apparent control for the center of hydrothermal activity.

The small differences in ages of the igneous rocks and the evidence that a stage of hydrothermal activity followed each porphyritic intrusion suggests a close genetic relationship for them. The youngest age determination, of 36 million years, and the oldest, of 39 million years, almost overlap when a 3 percent possible analytical error is considered.

The composition of the parent magma probably approximated that of the weighted average of the present composition of the several igneous rocks. The present composition includes much of the hydrothermal solutions, which immediately followed each of the porphyritic intrusions. The average weighted composition of the igneous rocks in the Carr Fork area is approximately that of a borderline granite or quartz monzonite.

Summary

The nine types of igneous rocks in the Carr Fork area are all part of or correlative with the four types of the Bingham stock. The oldest rock, granite, was emplaced permissively; the youngest three, granite porphyry, then Type "A" porphyry, and lastly quartz latite porphyry, were forcefully emplaced. Potassium-argon age determinations indicate all of these rocks were emplaced between 36 and 39 million years ago.

In the Carr Fork area hornblende and augite with their alteration products, and magnetite and sulfide minerals are distributed zonally in the igneous rocks. The mineral distributions are indicators of the direction and distance to the center of the Utah Copper orebody.

The hydrothermal activity in the Carr Fork area occurred as several stages; at least one followed each of the porphyritic igneous intrusions.

The highly mineralized igneous rocks of the Utah Copper porphyry orebody originally contained hornblende, augite, and primary magnetite but not copper sulfides. The hornblende and augite have been replaced by aggregates of secondary biotite, orthoclase, quartz, rutile, and copper sulfides. The magnetite has been replaced by copper sulfides.

Differentiation of a magma at depth resulted in the successive stages of igneous intrusion which took place over a geologically short period of time in the Carr Fork area. These successive intrusions and the hydrothermal solutions followed paths of weakness that were structurally controlled and correspond most closely to the center of the Utah Copper porphyry orebody.

Kennecott Copper Corporation,
Bingham Canyon, Utah,
May 6; September 18, 1968

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