Geology of the Copper King Uranium Mine Larimer County Colorado

GEOLOGICAL SURVEY BULLETIN 1032-D

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By P. K. SIMS, GEORGE PHAIR, *and* R. H. MOENCH

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Thomas B. Nolan, *Director*

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GEOLOGY OF THE COPPER KING URANIUM MINE LARIMER COUNTY, COLORADO

By P. K. SIMS, GEORGE PHAIR, and R. H. MOENCH

ABSTRACT

The Copper King mine, in the Prairie Divide region of Larimer County, Colo., in the northern part of the Front Range of Colorado, was opened during World War I in an unsuccessful attempt to mine copper and zinc ore. In 1949, following the discovery of pitchblende on the dump, the mine was reopened; it was worked until 1953 for uranium. A total of 652 tons of ore that contained an average of 0.28 percent U_3O_8 was shipped; 622 tons of the ore was mined from an ore shoot opened under a Defense Minerals Exploration Administration contract.

The bedrock consists predominantly of biotite granite, part of the Precambrian Log Cabin batholith, and minor metasedimentary rocks, biotite-quartz-plagioclase gneiss, amphibole skarn, biotite schist, quartzite, amphibolite, and biotite sköls. The metasedimentary rocks occur as inclusions that trend northeast, almost parallel to the prevailing foliation in the granite. In places the metasedimentary rocks are crosscut sharply by the granite and form angular, steep-walled blocks in the granite. Faults, confined to a narrow eastward-trending zone through the mine, cut all the Precambrian rocks.

Mineral deposits of two types are present at the mine: pyrometasomatic sulfide-magnetite deposits and a vein pitchblende deposit that cuts the skarn.

The sulfide-magnetite deposits are small and consist of pyrite, sphalerite, chalcopyrite, pyrrhotite, and, at places, magnetite. Alpha-helium age determinations on ore magnetite indicate that the mineral assemblage is late Precambrian in age.

The uranium deposit consists of pitchblende and associated vein-forming minerals that occur in the Copper King fault and locally in pyrite boxwork adjacent to the fault. Three black, uranium-rich phases have been identified: uraninite, coffinite, and UO_3-rich pitchblende. Colored secondary minerals are absent. The pitchblende occurs in a steeply plunging, tabular shoot that is 45 to 135 feet below the surface and that has a horizontal length of about 50 feet. Within the shoot the pitchblende occurs in pods or layers that are generally a few feet in height and length and as much as a foot thick, and that are separated by nearly barren vein. The grade of the ore within the pods ranges from 0.2 percent uranium to as much as 20 percent but averages about 1 to 2 percent. Age determinations by the Pb^{206}/U^{238} and Pb^{207}/U^{235} methods on two samples of hard pitchblende from the vein, not from the pyrite boxwork,

gave ages, after suitable common lead correction, ranging from 55 to 76 million years, corresponding to an early Tertiary age.

Diamond-core drilling and reconnaissance for radioactivity have not disclosed other uranium deposits in the Prairie Divide region; nevertheless it seems likely that other deposits are present.

INTRODUCTION

PURPOSE AND SCOPE OF REPORT

In 1949 a black radioactive mineral, later identified by Phair as pitchblende, was found by two prospectors on the dump of the Copper King mine, at Prairie Divide in Larimer County, Colo. The pitchblende on the dump was sufficiently abundant and high in grade to indicate the possible occurrence of an economic deposit of uranium underground and accordingly the mine was unwatered. R. U. King and H. C. Granger (written communication, 1951) examined the workings and found that the ore came from the 70-foot level which was worked by the earlier operators. Subsequent exploration by Cherokee Mines during 1950 disclosed uranium ore of shipping grade, and in 1951 the company requested and obtained an exploration contract from the Defense Minerals Exploration Administration to explore the vein further. Because of the economic and scientific importance of the deposit, the writers, on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission, began a detailed geologic investigation of the mine. The study disclosed that the uranium occurred in a vein that cut the massive sulfide ore, which was worked by the early operators, and in ore of boxwork type adjacent to this vein.

During September 1951, Sims and Phair mapped the geology of the surface and the mine workings. The surface geology was mapped on a scale of 40 feet to 1 inch by plane table and telescopic alidade (pl. 16); the mine was mapped on a scale of 5 feet to 1 inch, using a base map made by a transit, tape, and brunton compass survey (pls. 17 and 18). Subsequently as the DMEA exploration progressed and mining continued, the new work was mapped by Sims. To support the field investigations, 65 thin sections and 47 polished sections were studied in the laboratory.

During the course of the mining, the U. S. Atomic Energy Commission sampled the pitchblende deposit to determine grade and tonnage. From September to November 1952 the Commission conducted a diamond-core drilling project in the search for an extension of the uranium ore body indicated by mining, and the results of this exploration are given by Derzay and Baker (1953).

This report presents the results of the field and laboratory investigations carried on by the Geological Survey at the Copper King mine. The Precambrian rocks and massive sulfide ores that are present in the mine area are discussed together with the uranium ores. An interim report on the general geology of the mine (Sims and Phair, 1952), intended mainly to assist the Atomic Energy Commission in the interpretation of the exploration, and a report on the paragenesis and age of the ores (Phair and Sims, 1954) were prepared previously.

ACKNOWLEDGMENTS

This investigation was carried out jointly by Sims and Phair. The field mapping and the laboratory studies of the Precambrian rocks and ores were the responsibility of Sims; the laboratory investigations of the uranium minerals were the responsibility of Phair. Moench assisted in the study of the petrography of the rocks and ores. Most of the report was written by Sims. J. W. Adams assisted in the field work in September 1951, and several other members of the U. S. Geological Survey assisted for short periods during the course of the project. This report is based on work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

The writers are indebted to Cherokee Mines, and particularly to T. H. Sackett, for full cooperation during the survey and for permission to publish the production data. During the investigation many of the economic problems were discussed with geologists and engineers of the Denver Exploration Branch of the U. S. Atomic Energy Commission.

GEOGRAPHY

The Copper King mine is on the Black Hawk No. 1 claim in sec. 8, T. 10 N., R. 72 W., 6th principal meridian, Larimer County, Colo., in the northern part of the Front Range (fig. 41). From Fort Collins, Colo., it can be reached by following the road log below:

	Miles
From Fort Collins proceed north along U. S. Highway 287 for a distance of	23.3
Turn left (west) on gravel road and proceed to road fork	12.4
At road fork take sharp left turn on road to Red Feather Lakes; proceed along this road to Copper King mine	5.3

The mine is near the southwestern edge of Prairie Divide, a broad, gently rolling mountain flat, at an altitude of about 8,000 feet. This flat is the result of a widespread pre-Wisconsin glaciation that has been named the Prairie Divide stage (Ray, 1940, p. 1856). The plain is mantled by weathered gravel that rests on deeply weathered till. At places, rounded knobs and hills composed largely of granite protrude above the plain.

HISTORY AND PRODUCTION

The Copper King mine and several nearby shafts were opened during World War I in the search for copper and zinc ores. No ore

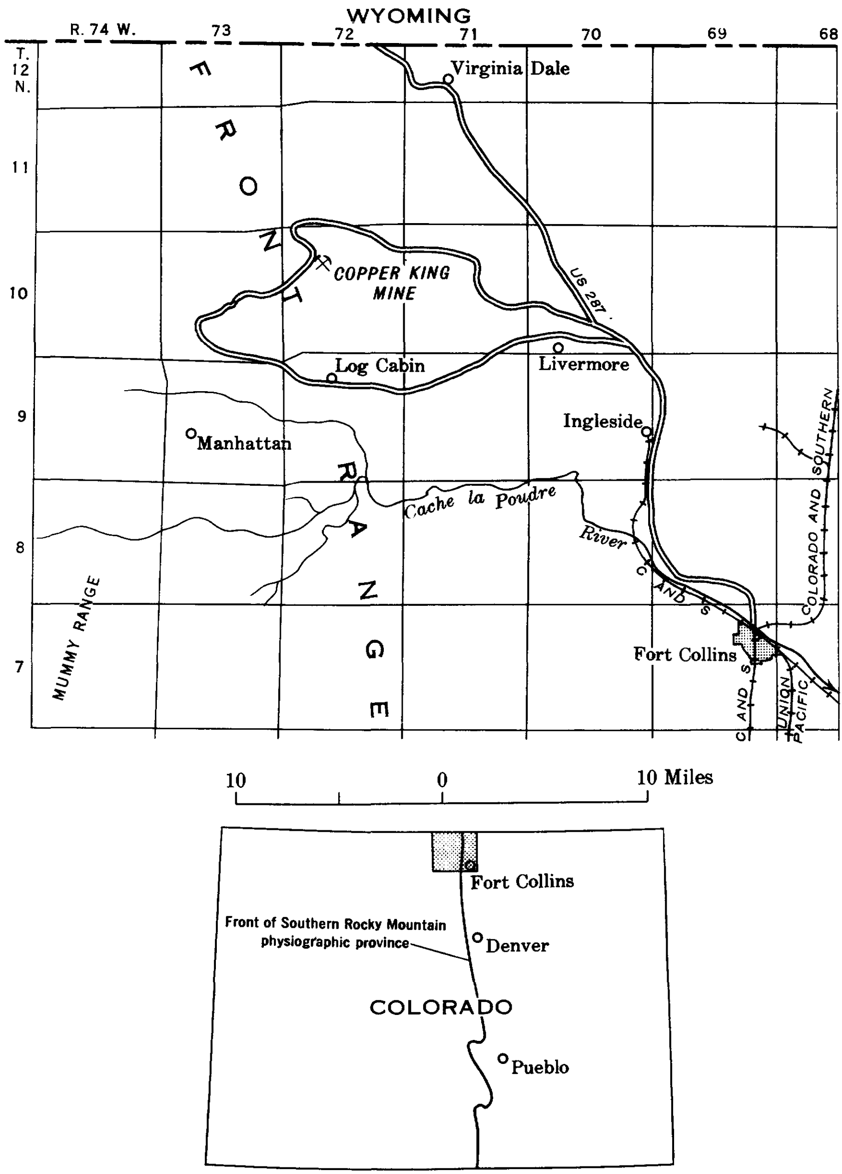

FIGURE 41.—Index map showing location of the Copper King mine, Larimer County, Colo.

is known to have been shipped, however, until 1920, when a carload of zinc ore was mined on the first level of the Copper King mine from a deposit of massive sulfides and oxides. This carload failed to pay the cost of milling and the mine and prospect shafts were abandoned. In 1936, Richard Kyle of Idaho Springs, Colo., operated the Copper King mine briefly for zinc but, so far as known, no ore was shipped.

In 1949, after finding the dump to be highly radioactive, A. H. Brown and H. G. Ismert filed claim on the Copper King mine on July 14, 1949, naming it the Black Hawk No. 1 claim. Shortly afterwards the mine workings, which consisted of a 64-foot vertical shaft, a level at a depth of 64 feet, and a 12-foot sump at the position of the present main shaft were unwatered. In 1950 and 1951 the operators extracted several tons of massive sulfide ore and some pitchblende-bearing rock from the level and sump. Fifty-five tons of hand-sorted sulfide ore that contained 18.2 percent zinc was shipped to Salt Lake City in 1951.

In 1951, Cherokee Mines, the mine operator, was granted a Defense Minerals Exploration Administration exploration contract, DMEA Docket 1702, contract Idm-E61, to sink a new 2-compartment shaft. This shaft, located 50 feet east of the old (west) shaft, was made by raising to the surface from the first (70-foot) level, and sinking below that level. During sinking, stations were cut at the 110-foot and 160-foot levels. The shaft was completed to a depth of 170 feet in May 1952. In the summer of 1952, an inclined raise was driven from the 160-foot level to the bottom of the pitchblende ore shoot, and a level at a depth of 140 feet was connected to the main shaft. Subsequently, during mining, a raise was completed connecting the 140-foot level and the 110-foot level.

As a result of Defense Minerals Exploration Administration exploration, a discovery was certified by the Government.

From December 1951 until the mine closed in August 1953 a total of 652.33 tons of ore that had an average grade of 0.28 percent U_3O_8 was shipped; 622 tons of the ore was mined from an ore shoot opened under the Defense Minerals Exploration Administration contract.

MINE WORKINGS

The mine workings consist of two vertical shafts 52 feet apart totaling 234 feet in length, 4 short levels, and 3 main raises (fig. 42). The principal manway and hoisting shaft, the main or east shaft, is a 2-compartment cribbed opening 170 feet deep. The west shaft, a single-compartment cribbed shaft, is 64 feet deep and bottoms at the first level. The drift on the 70-foot level is 118 feet long and connects the two shafts. The drifts on lower levels were driven to the east from the main shaft. All levels except the lowest were driven on ore. Raises were driven between the various levels. The main shaft and all workings below the 70-foot level were driven under DMEA contract.

ROCK UNITS

The Copper King mine is near the central part of a Precambrian batholith of Silver Plume granite known as the Log Cabin batholith.

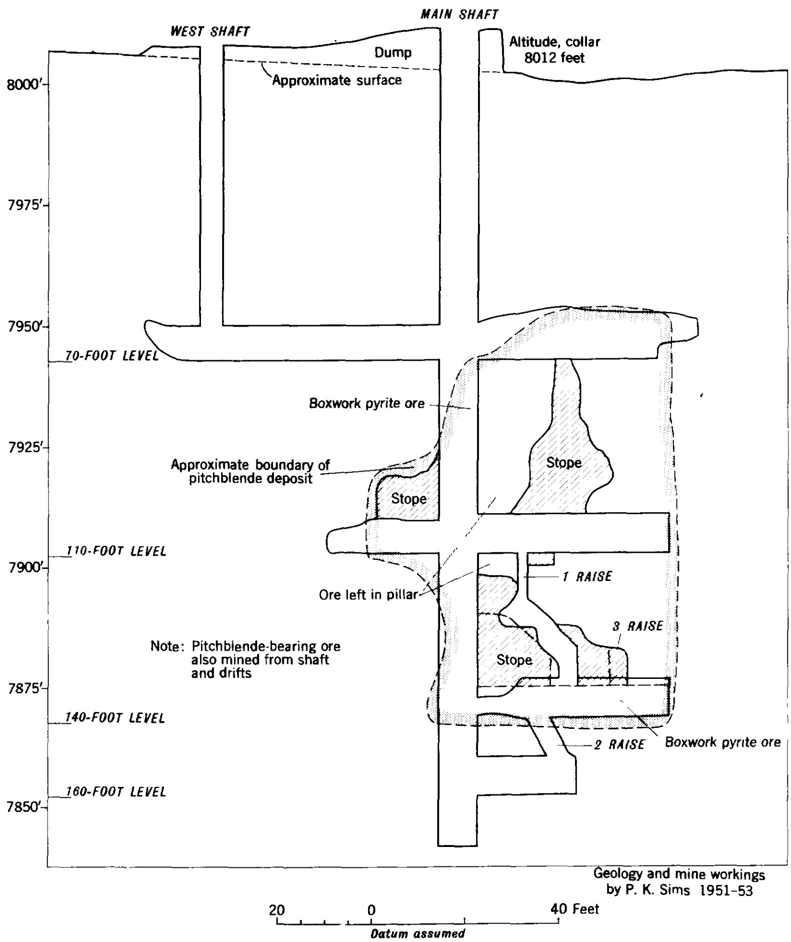

FIGURE 42.—Vertical longitudinal projection of mine workings, Copper King mine, showing approximate outline of pitchblende deposit.

Alpha/lead determinations upon zircon from the granite and isotopically corrected Pb^{208}/Th^{232} age determinations upon two monazite crystals from a pegmatite within the body, believed to be genetically related to the granite, indicate a late Precambrian age. At the mine the granite contains less mica than typical phases of the batholith and has the average composition of a leucocratic biotite granite. Within the granite are small inclusions of metasedimentary rocks, principally biotite-quartz-plagioclase gneiss and amphibole skarn.

METASEDIMENTARY ROCKS

Metasedimentary rocks constitute about 10 percent of the exposed bedrock in the Copper King mine area (pl. 16). Besides the biotite-quartz-plagioclase gneiss and amphibole skarn, which are the most abundant types, the metasedimentary rocks include biotite schist, amphibolite, and quartzite and related rocks. Approximate modes in volume percent of typical facies of these rocks, determined by Rosiwal analyses of thin sections, are given in table 1. The metasedimentary rocks are believed to represent metamorphosed alumino-siliceous, quartzose, and carbonate sediments that have been recrystallized and reconstituted; all evidences of the original textures have been destroyed. Because these rocks have been folded and then intruded by granitic rocks, the age relations among the metasedimentary rocks are unknown.

BIOTITE-QUARTZ-PLAGIOCLASE GNEISS

Exposures of biotite-quartz-plagioclase gneiss occur sporadically in the south half of the mapped area (pl. 16), and rocks of this type were intersected in some drill cores. From the surface exposures and the drill cores it is inferred that individual bodies of the gneiss are small and that many are crosscut by the granite, to form steep-walled inclusions. At the surface west of the mine small exposures of biotite-quartz-plagioclase gneiss, interpreted as parts of a larger body of gneiss which has a northeastward-striking foliation, abut against biotite granite; the contact between the two rock types strikes northwestward and dips nearly vertically. At the contact and for a distance of a few feet from it, the biotite-quartz-plagioclase gneiss has been altered to a streaked granite. (See p. 188.)

The biotite-quartz-plagioclase gneiss is a dark-gray fine-grained equigranular foliated rock that consists almost entirely of biotite, quartz, and plagioclase (table 1). Biotite constitutes 15 to 20 percent of the rock. It is pleochroic and varies from straw yellow to dark brownish green; $nY=1.685\pm.003$, but it varies within a single crystal to as low as $1.630\pm.003$. Plagioclase (An_{30}) constitutes 30 to 40 percent of the rock; single grains are uniform in composition. Quartz, which shows strain shadows, consistently comprises about 45 percent of the rock. The characteristic accessory minerals are muscovite, apatite, opaque iron oxides, and zircon.

The gneiss has a granoblastic texture. The biotite, concentrated into thin layers and wisps, has a strong dimensional and crystallographic orientation, which produces a conspicuous foliation. At places a later, weaker foliation, visible only under the microscope, is produced by biotite foliae that are partially oriented at an angle of about 30° to the dominant direction. The magnetite throughout the gneiss characteristically is surrounded by round or lenticular halos composed of quartz, plagioclase, and small quantities of muscovite and apatite. In one specimen (A-31, table 1), a magnetite crystal with a maximum diameter of 1.5 mm is surrounded by a halo 0.75–1.25

TABLE 1.—*Modal analyses of metasedimentary rocks, Copper King mine*

Mineral	*A-31*	*A-32*	*D-17-B*	*UG-9*	*UG-15*	*C-4-2*
Quartz	46	45	16	86	47	tr
Plagioclase	33	40	----	----	----	49
Microcline	tr	----	----	----	----	-----
Hornblende	----	----	----	----	10	50
Phlogopite	----	----	tr	11	----	-----
Biotite	21	15	82	----	----	1
Mica	----	----	----	----	37	-----
Muscovite	tr	tr	tr	----	----	tr
Apatite	tr	tr	2	tr	tr	tr
Opaque iron oxides	tr	tr	----	3	6	tr
Carbonate	----	----	----	----	tr	-----
Zircon	tr	tr	tr	tr	----	-----
Rutile(?)	----	----	----	tr	----	-----
Sphene(?)	----	----	----	tr	----	-----
Epidote	----	----	----	----	----	tr
Average grain diameter, in mm	0. 2	0. 24	----	0. 75	----	-----

A-31 Biotite-quartz-plagioclase gneiss. Plagioclase is An_{30}.
A-32 Biotite-quartz-plagioclase gneiss.
D-17-B Biotite schist.
UG-9 Phlogopitic quartzite.
UG-15 Quartz-mica-hornblende schist.
C-4-2 Amphibolite. Plagioclase is An_{47}; hornblende is hastingsite.

mm in diameter. In specimen A-32 (table 1) the halos are lenticular and flattened parallel to the foliation; one magnetite crystal, 1.25 by 2 mm in size, is surrounded by a lenticular halo 12 mm long and 2 mm wide. The quartz and feldspar within the halos have a granoblastic texture, similar to that throughout the gneiss.

BIOTITE SCHIST

A layer of biotite schist, 2 feet thick, crops out between granite and biotite-quartz-plagioclase gneiss, 100 feet south-southeast of the main shaft of Copper King mine, but schist is not exposed elsewhere in the area. Sparse thin layers of schist, commonly a foot or less thick, were cut in the drill cores. In drill hole BH-8, 3 feet of schist in biotite-quartz-plagioclase gneiss was intersected at a depth of 67 feet (fig. 43).

The biotite schist is a black uniform rock that contains about 80 percent biotite, 15 percent quartz, 2 percent apatite, and sparse phlogopite, zircon, and muscovite (D-17-B, table 1). The zircon occurs as inclusions in the biotite and is surrounded by conspicuous pleochroic halos. The quartz forms subrounded inclusions in the biotite. The biotite is dark brown; $n\text{Y}=1.630$. The biotite is of two generations. The first generation consists of compact aggregates of oriented laths that produce a definite foliation. The laths average about 1 mm in diameter and .1 mm in thickness. The second generation consists of much larger single crystals with a decussated texture that clearly cuts the foliation at all angles. The color and refractive index of both generations of biotite are identical.

AMPHIBOLITE

A black fine-grained foliated gneiss consisting mainly of green hornblende (hastingsite) and plagioclase of the composition An_{47} is found on the dump of shaft 8 and locally in the Copper King mine, but does not crop out at the surface. The foliation is produced by sparse streaks and lenses of plagioclase, generally less than one-fourth inch thick, and by the dimensional orientation of the hornblende and plagioclase. The rock has a crystalloblastic texture. Hornblende constitutes 50 percent of the amphibolite (C–4–2, table 1); locally it is slightly altered(?) to biotite, which occurs as small anhedral brown flakes both parallel and transverse to the hornblende cleavage traces. The hornblende is strongly pleochroic: X=pale yellow-green, Y=dark green, and Z=dark bluish green. Measurements of the refractive index indicate that $n\text{Y}=1.683\pm.003$; dispersion of the optic axes is strong, with $r>v$. The rock contains a small amount of quartz and traces of magnetite, apatite, muscovite, and epidote.

QUARTZITE AND RELATED ROCKS

Small bodies of dark-gray to black fine- to medium-grained quartzite are interlayered with amphibole skarn on the south wall of the 70-foot level of the Copper King mine, immediately east of the main shaft (pl. 17); and two bodies, each less than 2 feet thick, associated with skarn, mica sköls, and biotite-quartz-plagioclase gneiss, were intersected in drill hole BH–8. The quartzite is principally a massive, nearly equigranular, heterogeneous rock that contains about 11 percent phlogopite and sparse to abundant magnetite (UG–9, table 1). The quartz occurs as clear polygonal grains; it includes abundant euhedral apatite and subhedral phlogopite and magnetite. The phlogopite varies from colorless to pale brown; $n\text{Y}=1.610$. The mica crystals are for the most part rounded at their terminations.

Intercalated with the quartzite on the 70-foot level are gray to black, foliated to schistose rocks that are composed of variable quantities of quartz, mica, and hornblende. Magnetite is present in almost the same quantities as in the quartzite. The typical composition of this rock is given in table 1 (UG–15). The foliation is produced by alternating layers, less than an inch thick, of light and dark minerals. The dark layers consist predominantly of hornblende and quartz; the light layers consist mostly of quartz and mica. The hornblende (hastingsite) occurs as euhedral to anhedral blades, some of which are poikilitic with abundant inclusions of subrounded quartz. The hornblende is pleochroic: X=very pale yellow-green, Y=green, Z=blue-green; $Z \wedge C=28°$; $nZ=1.667 \pm .003$. The mica varies in individual flakes from a deep grass green near the margins and along some cleavage cracks to colorless in the center; the index of refraction of the green mica indicates that it is biotite with an appreciable content of iron, whereas the colorless mica is phlogopite. Mica of similar type occurs in the cummingtonite skarn. The quartz is anhedral and it contains minute inclusions of mica, hornblende, and magnetite. The texture of the rock is granoblastic; the average grain diameter is about 1 mm.

AMPHIBOLE SKARN

The rocks that consist almost entirely of anthophyllite, cummingtonite, or actinolite, and which are related to the massive sulfide deposits, are mapped as amphibole skarn (pl. 17). Although lime-rich layers or unaltered carbonate "beds" are not present, the rocks, in mineral composition, texture, and structure, resemble demonstrable skarn deposits from Fennoscandia. The writers believe, therefore, that the rock probably represents metasomatized limy layers. An alternative interpretation is that the anthophyllite skarn represents a layer originally rich in magnesia that was regionally metamorphosed to the anthophyllite-phlogopite assemblage and subsequently replaced locally by cummingtonite, green biotite, and sulfide minerals.

Thin selvages and partings of biotite occur in the skarn and sulfide ores. These selvages and partings, because they resemble one type of sköl, or shell, that has been described from Fennoscandia (Eskola, 1914, p. 226, 259) and from the Northeastern United States[1] (Sims, 1953, p. 271), are referred to as biotite sköls.

Skarn does not crop out at the surface but is present in the Copper King mine and on the dump of shaft 1. The skarn exposed within granite in the mine (pl. 16) forms a roughly tabular complexly folded steeply plunging body that has a probable stope length of more than 100 feet, a width of as much as 20 feet, and a maximum breadth of about 50 feet. The skarn body extends east of the mine workings, for it was intersected in drill holes BH–8 (fig. 43) and BH–3; where cut by hole BH–3, 80 feet east of the Main shaft, however, the skarn is less than six feet thick. The body becomes thinner as depth increases; probably it pinches out at a depth of about 170 feet below the surface. The skarn mass is generally conformable to the enclosing granite, except at its southwest end, where it is crosscut sharply by the granite (pl. 18, 70-ft. level). At places the skarn contains

[1] Leonard, B. F., 1951, Magnetite deposits of the St. Lawrence County district, New York: unpublished Ph. D. thesis, Princeton Univ.

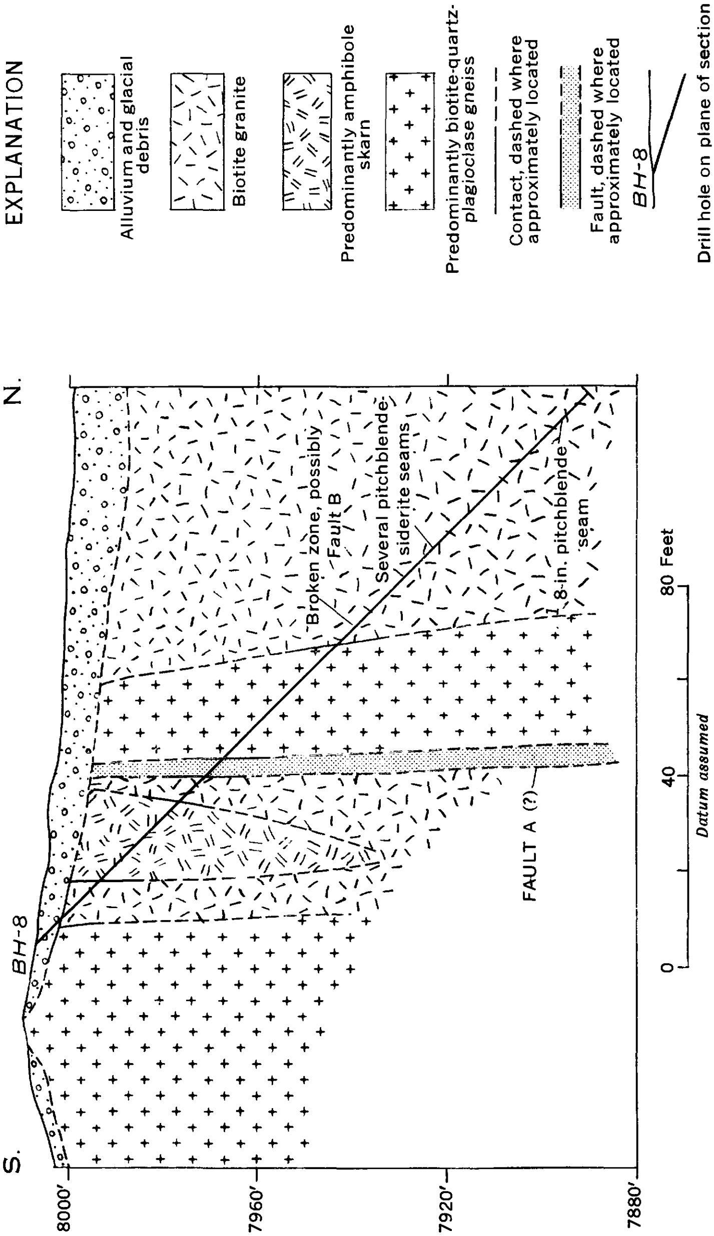

FIGURE 43.—Section through drill hole BH-8.

small bodies of granite and pegmatite that were intruded prior to the sulfide mineralization; and it is associated closely with biotite-quartz-plagioclase gneiss. Thin partings and selvages of biotite sköls as much as a foot thick commonly occur in the skarn.

The internal structure of the skarn body at Copper King mine is complex. The skarn is contorted into irregular layers and pods of varying mineral composition that plunge about 45° NE. Some of the layers and pods have been largely replaced by sulfide minerals and magnetite, whereas others are nearly barren.

The skarn in the mapped area can be divided according to mineralogy into three principal types: anthophyllite skarn, cummingtonite skarn, and actinolite skarn. The anthophyllite skarn nearly always contains some cummingtonite and it grades into cummingtonite skarn, a rock that always contains moderate or abundant sulfides. The actinolite skarn is essentially monomineralic; so far as known it does not grade into skarn composed of other amphiboles. The skarns contain variable quantities of sulfides and magnetite and at places these minerals are sufficiently abundant to constitute minable ore.

Anthophyllite skarn and cummingtonite skarn comprise nearly all of the skarn body that has been cut in the workings of the Copper King mine. Actinolite skarn is only locally present. In general the barren skarn consists predominantly of anthophyllite, whereas the mineralized skarn consists principally of cummingtonite.

The anthophyllite skarn is a gray, tan, or pale-green inequigranular massive rock of variable grain size consisting of anthophyllite and minor quantities of cummingtonite, phlogopite, apatite, quartz, calcite, sulfides, and magnetite. The anthophyllite typically occurs as sheaves of curved fibers, oriented at random, as much as an inch long and averaging about half an inch in length. If mica and quartz are present in the rock, the anthophyllite fibers are imbedded in a fine-grained groundmass of these minerals. The cummingtonite, where present, forms straight euhedral blades that distinctly cut the anthophyllite sheaves and appear to be later; less commonly the cummingtonite occurs in parallel growth with anthophyllite. A typical specimen containing both anthophyllite and cummingtonite is shown in figure 44. The index of refraction of the anthophyllite is variable, but nZ averages about $1.652 \pm .003$. The anthophyllite is colorless, $r < v$, and the birefringence is moderate. The mica associated in variable quantities with the anthophyllite is homogeneous phlogopite. In three specimens examined, $nY = 1.595 \pm .003$; $2V = 0°–5°$.

The skarns that contain cummingtonite as their principal silicate mineral always contain appreciable quantities of sulfides or magnetite; in addition they contain mica and sparse or moderate quartz.

FIGURE 44.—Photograph of amphibole skarn, principal host rock for the sulfide-magnetite assemblage. The anthophyllite blades have a random orientation, whereas the cummingtonite blades are elongate and oriented approximately parallel to the lower edge of the photograph.

Because of the abundance of sulfide and magnetite, the original composition of the skarn is not known. The cummingtonite forms straight euhedral to subhedral blades, as much as 6 inches long but more commonly half an inch or less in length. Most, but not all of the blades, have a preferred orientation that imparts a lamellar structure to the rock (fig. 44). Quartz, where present, contains abundant inclusions of euhedral cummingtonite, phlogopite, and magnetite. Some of the quartz fills fractures and vugs in sulfide minerals. The mica varies from colorless phlogopite in the center to green biotite along crystal edges and cleavages, The refractive index changes with the color; for the green biotite nZ is $1.620 \pm .003$, but in one specimen nZ is $1.612 \pm .003$; for the associated phlogopite nZ is $1.605 \pm .003$. The accessory minerals commonly associated with this rock are zircon, calcite, and rare microcline.

The actinolite skarn is a dark-green equigranular massive rock consisting of 95 percent or more of actinolite and traces of quartz and brown mica. At places it contains sparse sulfides and magnetite. So far as known, in the main skarn body at the Copper King mine actinolite occurs only as local small bodies. It is abundant on the dump of shaft 2 (pl. 16).

The actinolite occurs as short, stubby, randomly orientated crystals as much as 4 mm long. The quartz forms small interstitial grains.

The biotite sköls form selvages as much as a foot thick, but generally less than 6 inches thick, around folded podlike bodies of skarn; others occur as wisps and layers up to 6 inches thick, and still others occur along contorted partings within the skarn and sulfide ore; they are dark green. The biotite generally has a strong dimensional orientation parallel to the compositional layering of the skarn and sköls; in one specimen it is dark greenish brown: nY=1.611.

ORIGIN OF METASEDIMENTARY ROCKS

The metamorphic rocks in the mapped area were formed by dynamothermal metamorphism and metasomatism. The biotite-quartz-plagioclase gneiss, biotite schist, quartzite, and amphibolite are interpreted as regionally metamorphosed sedimentary rocks, whereas the skarn and biotite sköls, although possibly of dynamothermal origin, probably formed by metasomatic alteration.

The mineralogic composition of the biotite-quartz-plagioclase gneiss and the biotite schist indicates that these rocks were derived from alumino-siliceous sediments, perhaps without the addition or subtraction of materials. There is no evidence in this area that these rocks were derived originally from amphibolites by granitization processes, which Steven (1957) noted in the Northgate area, Colorado, about 25 miles to the west. The quartzite represents an impure quartz sand. The amphibolite, because it occurs only as local small lenticular bodies, is assumed to be of metasedimentary origin, probably metamorphosed impure carbonate rock. Similar amphibolites have been interpreted as metamorphosed igneous rocks (Adams, 1909; Dodge, 1942, p. 561–83).

The skarn body in the Copper King mine probably consisted originally of anthophyllite and small amounts of phlogopite. Later a new amphibole mineral, cummingtonite, formed at the expense of anthophyllite, and green biotite partly replaced the phlogopite. At this time iron was introduced to form magnetite and slightly later the ore-forming solutions deposited the sulfide minerals and quartz; the quartz continued to crystallize after the cessation of deposition of the sulfides.

The skarn is thought to be metasomatized carbonate rocks because of its mineralogic assemblage, massive to lamellar texture, spatial relation to the granite, and resemblance to known skarn rocks. Nearly all the original carbonate was altered to magnesium-rich skarn minerals; only scattered interstitial carbonate grains remain. Metasomatism probably was effected by solutions from the granite magma.

The alternative hypothesis for the origin of the skarn is that the amphibole rock represents an original magnesia-rich layer that was metamorphosed during regional metamorphism and subsequently modified by hydrothermal solutions that formed the ores. The principal argument against this origin, however, is the absence of marked lineation of the amphiboles, for amphibole rocks of this origin in Fennoscandia typically have a conspicuous lineation, whereas the true skarns, although commonly layered, generally lack lineation.

The amphibole rocks at the Copper King mine are similar to magnesian skarns that have been described from many localities in Fennoscandia. For an excellent summary of these rocks and ideas concerning their origin the reader is referred to Sundius (1935). Anthophyllite skarns have also been described from Jayville, N. Y., in the northwest Adirondacks, but these rocks do not contain cummingtonite.[2]

The biotite sköls, intimately associated with the skarn, could have been deposited directly from hydrothermal solutions; or they may be the result of the alteration of the amphiboles of the skarn by pegmatitic or hydrothermal fluids.

The metamorphic rocks in the mapped area are typical of many Precambrian terranes throughout the world and are characteristic of the amphibolite facies (Eskola, 1939, p. 351–355; Turner, 1948, p. 76).

The dynamothermal metamorphism that resulted in the recrystallization and reconstitution of the original diverse sediments probably occurred during a major period of Precambrian orogeny. With rare exceptions all of the rocks have a texture indicative of a single period of metamorphism; a dominant northeast-trending gneissic structure was developed. (See p. 189.) After this major deformation, local or weak metamorphism, produced by different stresses and probably under more nearly hydrostatic conditions, resulted in the local recrystallization of biotite: large crystals formed at the expense of the smaller (earlier) crystals and were oriented at an angle to the minerals formed earlier.

IGNEOUS ROCKS

Granite and minor amounts of pegmatite constitute 90 percent of the exposed bedrock (pl. 16) and probably underlie most of the covered areas. The granite varies from a leucogranite (Johannsen, 1939, p. 154) to a biotite granite. The inclusions of metasedimentary rocks within the granite are small, probably not more than a few tens of feet in maximum width. The pegmatite and minor amounts of associated aplite form small dikes in the granite and irregular masses in the skarn.

[2] Leonard, op. cit.

BIOTITE GRANITE

The granite is megascopically homogeneous but the proportions of the essential minerals vary considerably, as shown in table 2.

An average of the modes of 7 thin sections indicates that the rock has the composition of a leucocratic biotite granite. Small bodies of streaked granite occur as transitional phases to biotite-quartz-plagioclase gneiss.

Sparse, angular inclusions of metasediments are present in the granite. Generally the inclusions are conformable with the granite, but locally the granite cuts sharply across the foliation of the inclusions.

TABLE 2.—*Modal analyses of granites, Copper King mine*

Mineral	*UG-1*	*A-47*	*C-4-1*	*G-11*	*D-2*	*G-23*	*D-5-2*	*G-8*	*C-1*	*D-17-A*
Quartz	27	44	25	25	34	30	31	31	38	47
Microcline [1]	40	32	40	63	32	40	48	28	46	31
Plagioclase	24	20	30	12	31	26	20	31	9	15
Biotite	8	3	4	tr	2	3	tr	9	6	6
Muscovite	1	1	1	tr	1	1	tr	1	1	1
Opaque iron oxides	-----	tr	tr	tr	tr	tr	1	tr	tr	tr
Apatite	tr	-----	tr	-----	tr	tr	tr	tr	-----	tr
Zircon	tr	tr	tr	-----	-----	tr	tr	tr	tr	tr
Epidote	tr	tr	tr	-----	tr	tr	tr	-----	-----	-------
Anorthite content of plagioclase cores	An_{22}	An_{22}	-----	An_{12}	An_{21}	An_{20}	An_{21}	-----	-----	-------
Anorthite content of rims	An_9	An_4	-----	An_5	An_9	-----	An_6	-----	-----	-------
Anorthite content of plagioclase	-----	-----	-----	-----	-----	-----	-----	An_{24}	-----	An_{24}
Average grain diameter in mm	1.0	.8	2.0	.6	.7	2.0	2.0	.2	.25	.5

UG-1 Biotite granite, 70-foot level, Copper King mine.
A-47 Leucocratic biotite granite, surface.
C-4-1 Leucocratic biotite granite, surface.
G-11 Leucogranite, surface.
D-2 Biotite granite.
G-23 Leucocratic biotite granite, surface.
D-5-2 Leucogranite, surface.
G-8 Streaked granite.
C-1 Streaked granite.
D-17-A Streaked granite.

[1] Mostly perthitic.

The granite has a poor or moderate foliation produced by the subparallel alinement of tabular microcline crystals. The biotite is dispersed uniformly through the rock and has a random orientation. The porphyritic microcline crystals, although tabular, do not show a preferred orientation. The granite throughout the area contains abundant closely spaced incipient fractures almost parallel to the foliation.

The granite is typically a buff or pink medium-grained gneissoid rock consisting essentially of perthitic microline, quartz, and sodic plagioclase. The rock generally is equigranular but locally is porphyritic.

Microcline constitutes 30 to 60 percent of the rock; it typically occurs as interstitial anhedral, but sometimes as subhedral, grains as much as 1 inch long; most of the microcline is perthitic. Albite, occurring as smooth-walled blebs—rods and strings (Alling, 1938, p. 142–147)—or as irregular patches, constitutes from a trace to about 20 percent of the volume of the perthite grains. The (010) plane of the plagioclase in the patch perthite is oriented parallel either to (010) or to (001) of the microcline. The microperthite containing rods and strings is similar to the perthites that Alling interprets as resulting from exsolution.

The plagioclase grains are zoned; cores of oligoclase, generally partly altered to muscovite and epidote, are bordered by rims of clear albite. The contacts between the cores and rims are sharp. The plagioclase in the cores varies from An_{12} to An_{22} and shows a normal continuous zonation. The plagioclase in the rims varies from An_4 to An_9. Rims occur on plagioclase grains at the contacts of the grains with microcline; they rarely are present against quartz. The albite rims in some grains embay the plagioclase of the cores; in others the rims parallel the zonation of the core and the outer margins penetrate the microcline; and in still others the albite rims embay both the plagioclase cores and the microcline.

Quartz constitutes 25 to 47 percent of the rock. It forms anhedral grains that show strain shadows and some mortar structure. For the most part the quartz embays the plagioclase and microcline, but in part it occurs as subrounded grains that show mutual extinction in microcline.

Biotite makes up as much as 9 percent but generally is slightly less than 5 percent of the rock. The biotite is strongly pleochroic, ranges from straw yellow to dark brownish green, and is in part altered to chlorite. (001) forms are well developed, whereas (hk0) forms are either ragged or rounded in abutment with quartz. Zircon inclusions, surrounded by pleochroic halos, are common.

Muscovite is ubiquitous but constitutes only 1 percent or less of the rock. It is mostly fine grained and occurs as ragged crystals in plagioclase cores, along cleavage cracks, fractures, and crystal boundaries, but also occurs as sharply defined crystals in parallel and penetrative growth with biotite.

Epidote, in minor amounts, is present in most of the rocks examined as small grains in fractures, cleavage cracks, and crystal boundaries. Apatite occurs as minute euhedral grains in quartz and microcline or as larger anhedral grains along crystal boundaries. Zircon forms minute grains in biotite and larger crystals in quartz and albite. The opaque iron oxides are dispersed through the rock as minute subhedral grains.

Streaked granite was noted at three places on the surface and locally in the drill cores. It occurs in layers of biotite-quartz-plagioclase gneiss at and near the contact of the gneiss with biotite granite. It always is within 25 feet of a contact with biotite granite, and farther away from the contact it grades into biotite-quartz-plagioclase gneiss. The bodies never exceed a few feet in width and because of their small size they are included with biotite-quartz-plagioclase gneiss on plate 16. Modes of streaked granite are given in table 2.

The streaked granite is a pink fine- to medium-grained generally equigranular rock streaked with gray. The streaked appearance is caused by paper-thin films and wisps of oriented biotite. It differs from the biotite granite principally in having a conspicuous gneisslike structure and somewhat more biotite (table 2).

The plagioclase of the streaked granite is An_{24}, similar to that in biotite granite but more sodic than the plagioclase in the biotite-quartz-feldspar gneiss. Clear albite rims occur on most plagioclase grains but they are smaller than those in the biotite granite. Porphyritic perthitic microcline crystals are euhedral and as much as half an inch long; generally they poikilitically include small grains of plagioclase, subrounded quartz, and biotite. The accessory minerals, opaque iron oxides, apatite, zircon, muscovite, and epidote, are the same suite found in the biotite granite.

GRANITE PEGMATITE

Small bodies of granite pegmatite are present within the granite, at the contacts between the granite and the metasediments, and locally within the skarn. Within the granite, the pegmatite occurs as dikes, generally not more than a foot or two wide, along joints and foliation planes. The contacts are sharp in some places and gradational elsewhere. The pegmatite at the contacts with, and within, the skarn forms small bodies, irregular in shape.

The pegmatites are for the most part homogeneous bodies composed essentially of quartz and feldspar; at places in and adjacent to skarn some pegmatite contains a few percent of biotite. The grain size of the pegmatite minerals is uniform and generally is less than 2 inches in maximum dimension.

The feldspars, microcline perthite and sodic plagioclase, occur in varying proportions, but perthite is dominant. The plagioclase apparently is homogeneous and is oligoclase (An_{17-20}). Most plagioclase shows some alteration to clay minerals. The biotite is dark greenish brown and occurs as books as much as an inch long and one-fourth inch thick. Refractive index measurements indicate that nY ranges from $1.640 \pm .003$ to $1.690 \pm .003$. The biotite and the perthite in the pegmatites are similar to those in the granite. The accessory minerals, muscovite and opaque iron oxides, are sparse.

ORIGIN AND AGE OF GRANITES AND PEGMATITE

The granite of the mapped area, part of the Log Cabin batholith, is considered by Lovering and Goddard (1950, pl. 1) to be Silver Plume granite, which is the youngest Precambrian granite in the Front Range. Alpha/lead determinations upon zircon from the biotite granite in the vicinity of the main shaft indicate a late Precambrian age according to the presently accepted geologic time-scale. Providing this age gives the time of emplacement of the enclosing granite, it is in good agreement with the geologic age as inferred from the field evidence.

The biotite granite, because of its granitic texture and crosscutting relations to metasedimentary inclusions, is thought by the writers to have consolidated from a magma. Regardless of its initial origin, however, the granite was altered after consolidation. Evidence for postconsolidation alteration are: clear albite rims around altered oligoclase cores along the boundaries between plagioclase and microline; clear albite replacing both the plagioclase cores and microcline; quartz truncating rimmed plagioclase; ragged muscovite flakes in plagioclase cores, along cleavages, fractures, and crystal boundaries; and epidote grains along cleavages, fractures, and crystal boundaries.

The streaked granite, on the other hand, is thought to be of replacement origin because of its spatial relations to the biotite granite and biotite-quartz-plagioclase gneiss, its gneisslike structure, and its gradation into biotite-quartz plagioclase gneiss. The wisps and streaks of biotite are interpreted to be inherited from the original gneiss.

The pegmatite is thought to be genetically related to the biotite granite, for so far as known, the granite is the youngest Precambrian intrusive in the area. Age determinations by the Pb^{208}/Th^{232} method on two monazite crystals from a pegmatite quarry about 5 miles east of the Copper King mine by Phair indicate a late Precambrian age for the pegmatite (Phair and Sims, 1954).

STRUCTURE

The Precambrian rocks at the Copper King mine have a definite gneissic structure that trends northeastward and is nearly vertical. The rocks are broken at places by eastward-trending, steeply dipping faults of small displacement and of probable Laramide age.

FOLIATION AND LINEATION

The foliation in the metasedimentary and igneous rocks (pl. 16) trends northeast and generally dips steeply to the northwest or southeast. The metasediments occur as inclusions of various sizes in the granite (pl. 16) and trend northeast parallel to the foliation, but they are crosscut sharply by the granite and for the most part form angular, discordant blocks. To determine the general structural setting, mapping of a larger area would be necessary.

Lineation, produced by elongated plates of biotite and hornblende and by mineral streaking, is conspicuous in the biotite-quartz-plagioclase gneiss, the amphibolite, and the biotite schist; it is poorly developed in the granite, however, except locally where elongated quartz and feldspar grains show a subparallel alinement. The bearing of the lineation in all the rocks is nearly normal to the strike of the foliation; the lineation in the metasediments in the mine workings is parallel to small folds and plunges on the average about N. 45° E.

JOINTS

Joints are conspicuous in both the metasediments and granites, but they are most striking in the biotite granite. The joints are nearly vertical, and can be grouped roughly into two sets, northeastward and northwestward trending. Although most joints are barren, a few contain discontinuous dikes of pegmatite or, less commonly, aplite, generally less than a foot thick, suggesting that the joints formed before the emplacement of these dikes.

Joints that trend about N. 80° W. are present at the surface near the inferred position of the surface trace of *A* fault, which was intersected in the mine workings (pl. 17). Study of drill cores indicates that this joint set is nearly parallel to the fault; joints of this attitude were not observed elsewhere in the mapped area.

FAULTS

Steeply dipping faults of small displacement cut the sulfide-magnetite deposit, skarn, and biotite granite at the Copper King mine (pl. 17). The faults are probably Laramide in age. They are confined to an eastward-trending zone that is a few tens of feet wide and extends the length of the mine; they also were cut in some drill cores. None of the faults has been recognized at the surface. The principal faults, in order of probable age, are herein named: Copper King fault, *B* fault, and *A* fault. Other minor fractures are common, but these are not discussed individually in the pages that follow. The oldest fracture, the Copper King fault, and the complexly branching fractures probably related to it contain pitchblende and were the source of most of the uranium ore mined.

The structural relations of the faults and the mineralogic differences in the fault zones indicate that the faults were open at different times, and there is no evidence that the fractures are contemporaneous. The uranium-bearing Copper King fault and its subsidiary fractures are clearly cut by *B* fault; *B* fault likewise is cut by *A* fault.

COPPER KING FAULT

The Copper King fault is a nearly vertical fracture zone that trends N. 60° W. It has been traced in the mine and in drill cores for a horizontal distance of more than 50 feet; it dies out on the lower level by passing into many thin, branching "horsetail" fractures. The fault has not been recognized at the surface.

Above the 110-foot level the fault is a well-defined, tabular fracture that is filled with angular fragments of the wall rocks and pitchblende and associated ore-forming minerals. At the 110-foot level (pl. 17) the Copper King fault is cut by *B* fault, and this intersection plunges southwestward. Below the intersection, instead of being a well-defined tabular structure, the Copper King fault is characterized by horsetail fractures. The fractures trend eastward, northeastward, and northwestward; fractures of all trends are locally ore-bearing. On the 140-foot level, ore-bearing fractures of one set strike eastward and dip nearly vertically; fractures of another set, apparently subsidiary to the easterly set, strike about N. 65° E. and dip 60°–90° in either direction. Similar fractures were encountered in the stoped ground above the 140-foot level. In the raise from the end of the crosscut on the 140-foot level, however, according to the miners, the principal fracture trended N. 50° W. and dipped about 80° SW.; thin fractures branched eastward from it.

The Copper King fault was reopened several times during mineralization, and grooves and striations on the vein-forming minerals indicate that some movement also took place after deposition of the ores.

B FAULT

B fault is exposed at and below the 110-foot level in the mine. It probably was cut in drill hole BH–8 at a depth of 90 feet (fig. 43), but its identification in the core is not certain.

In the mine, the fault trends N. 80°–85° E. and dips 68°–85° SE. On the 110-foot level (pl. 17) the fault zone is 3 to 9 inches wide and is filled with hematite, goethite, a dark-brown hydrous iron oxide, light-brown hydrous iron oxide, and vuggy quartz. The hydrous iron oxides are colloform; the quartz exhibits comb structure or is platy and commonly fills fractures and vugs in the hydrous iron oxides. The sulfides adjacent to the fault on the 110-foot level are fractured for a distance of about 2 feet from the fracture.

In the stopes between the 110-foot level and the 140-foot sublevel the fault is obscure, but it probably continues through the stopes into the conspicuous breccia and gouge zone on the 140-foot level (pl. 17). The *B* fault zone is abnormally radioactive but nowhere contains sufficient uranium to be ore (pl. 17 and p. 215); no uranium minerals have been identified from the fault zone.

A FAULT

A fault, the most conspicuous and continuous break in the mine, was intersected on all levels and was noted in many of the drill cores. The fault extends nearly the length of the 70-foot level, where it strikes N. 55°–70° W. and dips about 80° SW. It can be traced in the shaft to a depth of about 130 feet (pl. 18). At this depth it passes into the southwest wall, and probably was cut on the 160-foot level (pl. 17). Breccia and gouge zones as much as 5 feet thick, believed to correlate with *A* fault, were intersected in drill holes BH–1, BH–2, BH–11, BH–8 (fig. 43), BH–3, BH–5, BH–6, and BH–7. The fault apparently was not cut, however, in the holes to the west of the mine and may die out in that direction.

The fault consists principally of soft gouge. Commonly the adjacent wall rocks, particularly the granite, are broken and oxidized. On the 70-foot level the fault contains abundant hydrous iron oxides, discontinuous thin pyrite seams, and veinlets of dense white quartz as much as an inch thick; but these minerals are sparse or absent, so far as known, in the lower workings. Throughout its length the fault is abnormally radioactive. (See page 215.)

A fault cuts *B* fault. This relationship was seen most clearly in the stope pillar east of the main shaft about 10 feet below the 110-foot level.

MINERAL DEPOSITS

Mineral deposits of two types differing widely in origin, age, and character are present in the Copper King mine area: massive sulfide-magnetite deposits of Precambrian age, and a pitchblende-bearing vein deposit of early Tertiary age. The sulfides and magnetite replace amphibole skarn and associated rocks and constitute a typical pyrometasomatic deposit. The age of the magnetite in these deposits, as determined by the helium method of Hurley on two samples, is late Precambrian. The pitchblende-bearing vein deposit clearly cuts the sulfide-magnetite ores and surrounding country rocks and was determined, by isotopically corrected lead-uranium ratios, to be of early Tertiary age (Phair and Sims, 1954). Boxwork pyrite, locally containing pitchblende, occurs in the wall rock of the pitchblende-bearing vein.

SULFIDE-MAGNETITE DEPOSITS

Deposits of pyrite, sphalerite, pyrrhotite, chalcopyrite, magnetite, and sparse molybdenite, in order of decreasing abundance, are present in the Copper King mine and at shafts 1 and 2 (pl. 16). The Copper King deposit has a gross layering. The layers range from less than a foot to several feet in thickness and reflect variations in mineralogy, which probably in turn reflect original layering in the skarn host rock.

GENERAL CHARACTER AND STRUCTURE

The sulfide-magnetite deposits are mainly in amphibole skarn; to a lesser extent they occur in the quartzite and related rocks (see page 179) that are closely associated with the skarn. The Copper King deposit is principally in a body of anthophyllite-cummingtonite skarn; the deposits at shafts 1 and 2, to judge from the dumps, are largely in actinolite skarn.

The ore minerals form massive layers, streaks, and knots or are dispersed through the skarn. The massive ore forms lens-shaped layers, some of which have a circular cross section, that conform to the layering in the skarn and are elongated in the direction of the lineation. The sizes and shapes of individual layers and pipes are extremely variable, but commonly they do not exceed two or three feet in thickness.

The deposit at the Copper King mine is an elongate, roughly tabular body that trends east-northeast and dips steeply (pl. 16). It has a maximum stope length of about 40 feet, a width of as much as 14 feet, and a breadth of approximately 25 feet. The pitch length of the body (as defined by Lindgren, 1933, p. 192) is not known. The deposit is smaller than the skarn mass that constitutes the host, for the skarn is in part barren or contains only sparse ore minerals.

The principal shoots of magnetite and massive sulfides within the deposit are distinguished on plates 17 and 18. Pyrite, the most abundant sulfide, forms a steeply dipping layer, 2 to 3 feet thick, on the 70-foot level along the north wall of the drift (pl. 17). Sparse sphalerite, chalcopyrite, and pyrrhotite occur with the pyrite. Magnetite without appreciable sulfides forms a small body on the south wall 10 feet east of the east shaft.

A shoot of high-grade sphalerite ore just below the 70-foot level yielded 55 tons of shipping ore during shaft sinking (pl. 18). The shoot is a lens-shaped layer about 5 feet thick that plunges 45° to the east. Beneath it a 12-foot layer consisting predominantly of pyrite with sparse sphalerite and chalcopyrite is underlain by almost barren skarn.

On the 110-foot level pods of massive pyrite, pyrrhotite, sphalerite, and chalcopyrite occur on the north wall opposite the shaft and plunge about N. 50° to 60° E. Pyrrhotite is more abundant here than elsewhere in the mine, and at places it occurs with other sulfides as lenses as much as 3 feet across.

On the 140-foot level pyrite is the most abundant sulfide, but a few layers of high-grade sphalerite ore, a foot or less thick, that trend across the drift and dip N. 50° to 60° E. were cut about 25 feet northeast of the main shaft.

MINERALOGY

Pyrite is the most abundant and widespread component of the sulfide-magnetite deposits; pyrrhotite, sphalerite, chalcopyrite, and magnetite are locally abundant. Molybdenite is sparsely disseminated at places in the wall rocks at the margins of the deposits but does not occur with the other ore minerals. There is no gold and less than 0.00X percent silver in the ores that have been analyzed. (See table 4.)

At the Copper King mine the sulfide-magnetite body has been brecciated where it is cut by the pitchblende vein, and fragments of the sulfides and magnetite are locally incorporated in the vein.

MAGNETITE

Magnetite is abundant only on the 70-foot level where it forms a massive, irregular layer (pl. 17). Where intergrown with the sulfides, the magnetite occurs sparsely as anhedral or subhedral crystals 1 mm or less in diameter, corroded slightly by the younger sulfides. The magnetite ore on the 70-foot level consists of aggregates of magnetite grains that embay and corrode cummingtonite, green biotite, and quartz. Pyrrhotite, pyrite, chalcopyrite, and sphalerite occur as sparse grains in the interstices of the magnetite grains.

PYRRHOTITE

Pyrrhotite is widespread but not abundant. It occurs as aggregates of anhedral grains, commonly more than 1 mm in diameter, which are intergrown with pyrite and other ore minerals, and also as blebs within sphalerite. The pyrrhotite aggregates embay magnetite and occur between magnetite and silicate grains; in turn, they are apparently embayed by sphalerite. The blebs of pyrrhotite in the sphalerite commonly are associated with blebs of chalcopyrite. The smaller blebs are arranged in straight or curved films. The straight films are along the traces of definite crystallographic planes in the sphalerite. The curved films, however, in part appear to disregard the crystal planes. At places pyrrhotite and chalcopyrite occur together in the same bleb in sphalerite, in which case the pyrrhotite appears to embay the chalcopyrite. Where fractured, the pyrrhotite is veined by pyrite or, less commonly, by marcasite.

PYRITE

The pyrite belonging to this period of ore formation is a distinctive and unusual morphologic type. Most of it is weakly anisotropic. It is characterized by many subrounded to elliptical forms (fig. 45)

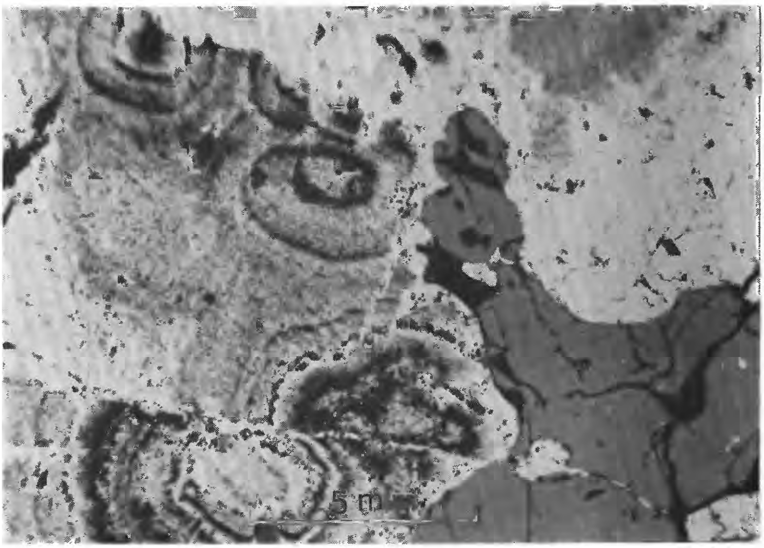

FIGURE 45.—Photomicrograph showing typical elliptical form of early pyrite. Note that the pyrite with elliptical form grades into massive homogeneous pyrite. The pyrite is embayed by sphalerite (dark gray). Both minerals are veined by late pyrite.

that commonly are surrounded by, and gradational into, massive anhedral or subhedral pyrite that appears homogeneous. As shown in figure 45, the massive, homogeneous pyrite at places cuts the elliptical forms. In figure 46 it can be seen that the concentric rings in the

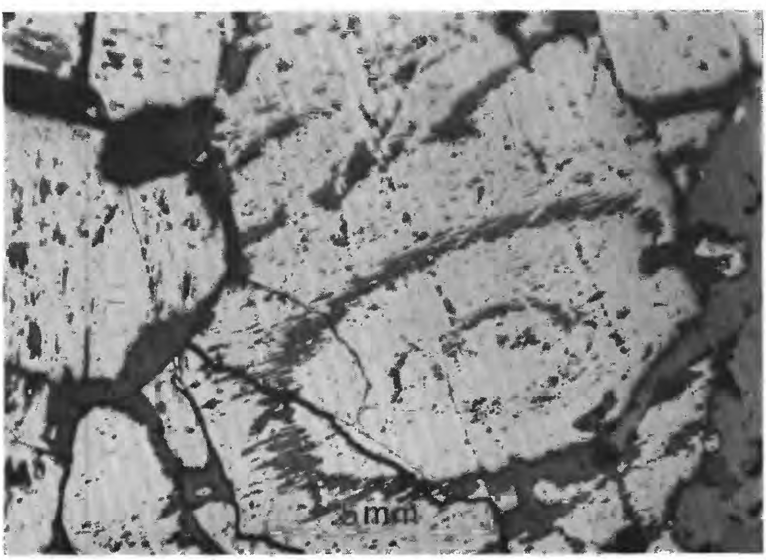

FIGURE 46.—Photomicrograph of early pyrite showing oriented inclusions of amphibole. Sphalerite (dark gray area in right of photomicrograph) embays and veins the pyrite.

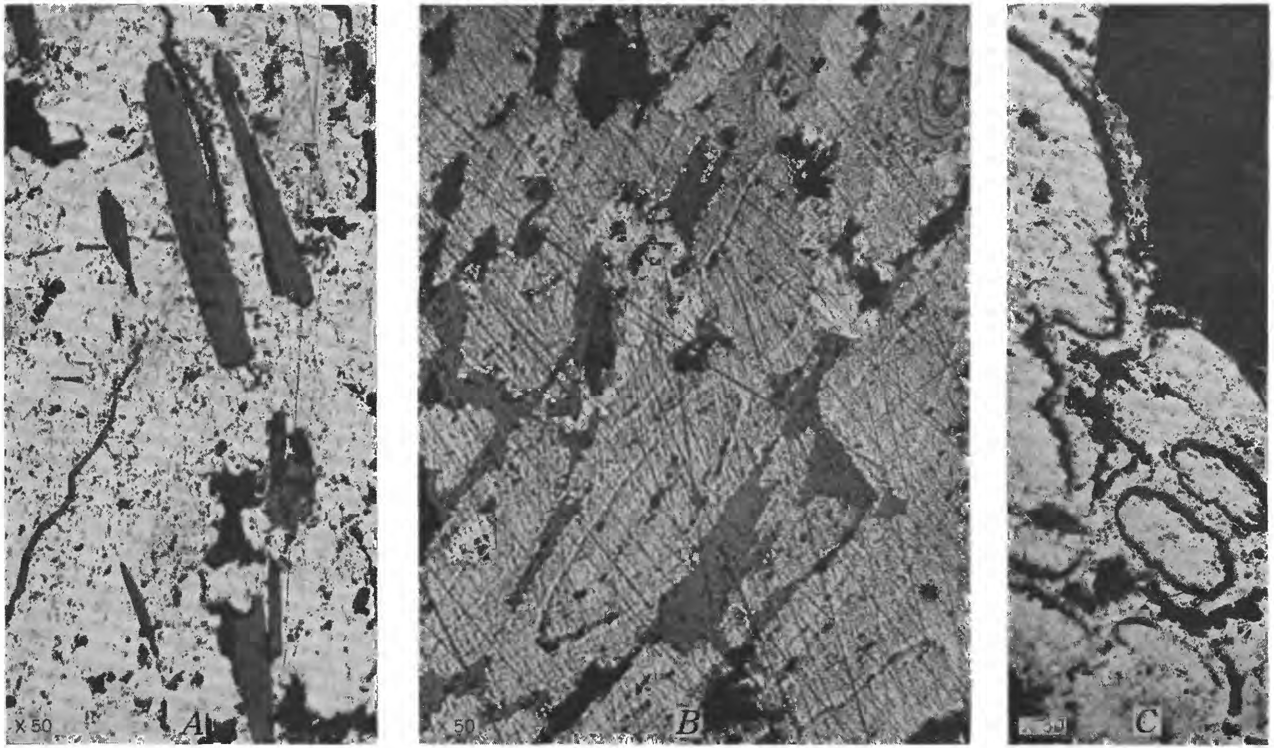

FIGURE 47.—Photomicrographs of early pyrite showing stages in the replacements of cummingtonite. *A*, Pyrite containing oriented inclusions of cummingtonite. The ends of the cummingtonite blades are rounded. *B*, Pyrite with elliptical forms that contain ragged remnants of cummingtonite blades. The elliptical form is interpreted as a relict texture produced by pseudomorphic replacement of elongate oriented slightly warped cummingtonite blades. *C*, Pyrite characterized by well-developed concentric nonopaque layers. Replacement of the host is nearly complete.

pyrite consist of oriented inclusions of the amphibole host. As shown in the large grain in figure 46, the host remnants within an individual concentric ring have a subparallel arrangement. In other pyrite grains the inclusions similarly have a common orientation but do not form a concentric ring.

Because the cummingtonite gangue remnants in the pyrite have a marked preferred orientation, pyritiferous layers have a prominent lamellar structure. Stages in the replacement of the gangue by pyrite are shown in figure 47. Figure 47*A* shows oriented inclusions of cummingtonite in massive pyrite. The cummingtonite is little replaced, and only the ends of the crystals are slightly rounded. In figure 47*B*, ragged remnants of cummingtonite blades occur in pyrite characterized by well-developed elliptical forms. The pyrite with the elliptical forms has concentric layers containing minute inclusions of the host. This structure is inherited by pseudomorphic replacement of the elongate oriented slightly warped cummingtonite blades. In figure 47*C*, where replacement of cummingtonite is nearly complete, the concentric nonopaque layers are clearly defined.

SPHALERITE

Sphalerite is locally abundant in the sulfide-magnetite deposits. It is dark brown and iron rich (marmatite) and contains tiny exsolution blebs, films, and blades of chalcopyrite. At places it also contains exsolution blebs of pyrrhotite. The sphalerite commonly is intergrown with chalcopyrite, pyrite, and pyrrhotite. It embays the early pyrite (figs. 45 and 46) and in turn is embayed and corroded by chalcopyrite. At places it fills interstices between magnetite grains and at other places it corrodes magnetite. The sphalerite commonly forms large anhedral grains 1–3 mm in size. In most specimens the chalcopyrite blebs constitute about 5 percent of the volume; they are oriented principally along the (111) planes of the sphalerite, although some appear to be distributed at random.

CHALCOPYRITE

Chalcopyrite is widespread but it constitutes only a percent or two of the deposits. It occurs (1) as clots and layers of anhedral grains that alternate with layers of sphalerite, pyrite, and pyrrhotite, and (2) as minute blebs in sphalerite. The grains of chalcopyrite embay both pyrrhotite and sphalerite. The textures resulting from minute blebs and films of chalcopyrite in sphalerite are similar to those described by Edwards (1947, p. 79–82).

MOLYBDENITE

Scattered plates of molybdenite are present in the granite wall rocks near the contacts with the skarn ores. So far as known, the

TABLE 3.—*Semiquantitative spectrographic analyses of sulfide-magnetite ores, Copper King mine* [1]

[Analysts: R. G. Havens and S. P. Furman]

Field No.	*Type of Material*	*Location*	*Si*	*Al*	*Fe*	*Ti*	*Mn*	*Ca*	*Mg*	*Na*	*K*	*Ag*	*Ba*	*Cd*	*Co*
UG-23	Massive sphalerite ore	Winze, 70-ft. level.	X.	0.00X+	X.+	-------	0.0X+	0.00X	0.0X−	-------	-----	tr	tr	0.X−	0.00X+
CK-67	Magnetite in amphibole skarn.	Dump	X.	.X+	XX.	0.0X−	.0X+	.00X+	X.	0.0X+	X.−	-------	0.000X+	-------	.00X−
UG-24	Pyrite-sphalerite-chalcopyrite ore.	Winze, 70-ft. level.	.X+	.0X	XX.	.00X−	.0X+	.00X+	.X−	-------	-----	0.00X+	tr	.0X	.00X+
CK-68	Massive pyrite	Dump	.X+	.00X+	XX.	-------	.0X	.0X+	.X−	-------	-----	.00X	tr	.00X+	.00X+
CK-69-1	Massive sulfide ore	Winze, 70-ft. level.	.X+	.0X	XX.	.00X	.0X+	.0X	.X−	-------	-----	.000X	tr	.0X+	.0X−
CK-69-2	Vuggy sulfide ore	do	.X	.00X+	XX.	.00X−	.0X+	.0X−	.0X+	-------	-----	.000X	tr	.0X+	.0X−
PKS-1A-51	Boxwork pyrite	do	.X	.000X	XX.	-------	.0X	tr	.X	-------	-----	.000X	.000X	-------	.0X
PKS-1B-51	Massive pyrite	do	.X	.00X	XX.	-------	-------	tr	.0X	-------	-----	.000X	.000X	-------	.X

Field No.	*Type of Material*	*Location*	*Cu*	*Ga*	*In*	*Mo*	*Ni*	*Sn*	*V*	*U*	*Y*	*Zn*	*Zr*	*eU* [2] *(percent)*
UG-23	Massive sphalerite ore	Winze, 70-ft. level.	0.X+	-------	tr	-------	0.000X	-------	0.00X−	------	-------	XX.	-------	0.009
CK-67	Magnetite in amphibole skarn.	Dump	.0X	-------	------	0.00X	-------	0.00X+	.00X−	------	0.00X	.X	0.00X+	.003
UG-24	Pyrite-sphalerite-chalcopyrite ore.	Winze, 70-ft. level.	XX.−	-------	tr	.00X	.000X+	.00X	.00X−	------	-------	XX.	-------	.002
CK-68	Massive pyrite	Dump	X.+	-------	------	.00X+	.00X−	.00X−	.00X−	------	-------	X.	-------	.005
CK-69-1	Massive sulfide ore	Winze, 70-ft. level.	X.−	-------	tr	-------	.00X−	-------	.00X−	.X−	.00X−	XX.	-------	.27
CK-69-2	Vuggy sulfide ore	do	X.−	-------	tr	-------	.00X−	-------	.00X−	------	.000X+	XX.	-------	.019
PKS-1A-51	Boxwork pyrite	do	.0X	0.000X	------	.00X	.00X	-------	-------	.X	-------	.0X	.00X	-------
PKS-1B-51	Massive pyrite	do	.0X	.000X	------	.00X	.00X	-------	-------	------	-------	.0X	.00X	-------

[1] Looked for but not found: P, As, Au, B, Bi, Ce, Cr, Ge, Hf, Hg, Ir, La, Li, Nb, Nd, Os, Pd, Pt, Re, Rh, Ru, Sb, Sc, Sr, Sm, Ta, Th, Tl, Te, and W. Some elements of this group possibly are present in trace amounts, but because of their low-standard sensitivities were not detected.

[2] Determined by radiometric analysis.

molybdenite is most abundant on the 140-foot level. Spectrographic analyses for molybdenum indicate that it constitutes 0.00X percent or less of the massive ores (table 3). Because molybdenite has not been observed in the ores, little is known concerning its relation to the ore minerals.

TRACE ELEMENTS

Semiquantitative spectrographic analyses that show the minor element content of the ores are given in table 3. It can be seen that the sulfide ores contain sparse quantities of cobalt and nickel, which are characteristic of pyrrhotite-bearing ores. Indium and cadmium are present in some ores, and are particularly abundant in ores rich in sphalerite. The magnetite ore contains as much as 0.0X titanium.

The theoretical ranges for the values reported in tables 3, 4, and 5 are:

Subgroup	*Theoretical range*
0. X+	0. 464–1. 0
. X	. 215– . 464
. X–	. 10 – . 215

PARAGENESIS

The minerals of the sulfide-magnetite deposits are believed to have been formed during a single period of mineralization. The paragenesis of the minerals is shown in figure 48. The order of introduc-

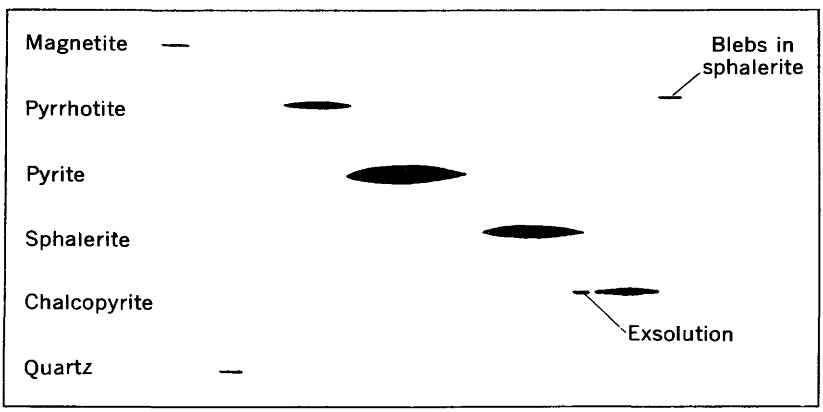

FIGURE 48.—Paragenetic sequence of the massive sulfide-magnetite ore minerals.

tion and replacement of the different minerals follows closely the usual sequence in pyrometasomatic deposits.

Magnetite was the first ore mineral to be deposited. It replaced cummingtonite skarn and quartzite; and oriented, corroded blades of cummingtonite and biotite are widespread in the iron ore. Subsequent to its formation, small quantities of quartz were introduced. The quartz replaced magnetite or filled the interstices between magnetite grains.

Pyrrhotite, the next mineral to be deposited, replaced magnetite and the host minerals. At places it occurs between magnetite and silicate grains. Some of it may have filled cavities in the host and spaces between ore mineral grains.

Pyrite replaced the gangue minerals and also pyrrhotite. It crystallized mostly as spheroidal forms (fig. 45) but in part as massive anhedral or subhedral crystals.

Sphalerite is later than the magnetite, pyrrhotite, and pyrite, for it corrodes and embays these minerals. At places it contains corroded fragments of oriented silicate grains. Some chalcopyrite in solid solution with sphalerite exsolved during cooling as minute blebs and blades; and this generation was closely followed by the deposition of homogeneous chalcopyrite, grains of which replaced the silicate grains of the host and sphalerite along crystal interfaces. Contemporaneously with the chalcopyrite, blebs and films of pyrrhotite exsolved from sphalerite.

AGE AND ORIGIN

The sulfide-magnetite deposits are replacements of amphibole skarn and related biotite sköls and quartzite. The ore minerals were deposited after the skarn had formed and they embay and corrode the host minerals. At the Copper King mine, cummingtonite skarn was a more favorable host than anthophyllite skarn.

Because of the close spatial relationship of the deposits to the biotite granite, it is probable that the ore-forming fluids were derived from the magma that consolidated to form the granite. The correspondence in age of the magnetite of the deposit (see p. 192) and the biotite granite which surrounds the deposit, as reported previously (p. 189), lends strong support to the pyrometasomatic origin of the ore deposit as inferred originally from the field evidence.

The deposits are typical of the class of ore deposits that Lindgren (1933, p. 35–49) has called pyrometasomatic, and they resemble many other deposits of this class in both the western (Knopf, 1933, p. 537–539; Lovering and Goddard, 1950, p. 64–71) and eastern (Leonard [3]; Sims and Leonard, 1952) parts of the United States. The deposits also are strikingly similar to some deposits of sulfides and magnetite in central Sweden (Geijer, 1917; Magnusson, 1940, 1950).

PITCHBLENDE DEPOSIT

Pitchblende and associated minerals occur in the Copper King fault and subsidiary fractures and locally in the interstices of pyrite boxwork in the wall rock adjacent to the fault. Both types of ore provided important quantities of uranium. In order of decreasing

[3] Op. cit.

abundance, siderite, pyrite, marcasite, quartz, sphalerite, and chalcopyrite were deposited with the pitchblende.

COPPER KING VEIN

The pitchblende-bearing vein occurs in the Copper King fault. The vein minerals formed by deposition in open spaces and to a small extent by replacement. In the upper workings the Copper King vein is well-defined, tabular, and nearly vertical and it strikes N. 60° W. (pl. 17), but below the 110-foot level the vein is ill-defined and consists of branching horsetail veinlets of several trends, as described on page 191. The vein dies out laterally and vertically and passes into barren fractures. Above the 110-foot level the wall rock of the vein is mainly ore-bearing amphibole skarn, with subordinate biotite granite, but below this level the wall rock is biotite granite (pl. 18).

Where the vein cuts skarn and massive sulfides, it is hard and compact and consists of angular, brecciated fragments and shreds of the wall rocks that are veined and cemented by pitchblende and associated vein-forming minerals (fig. 49*A*). As seen in the photograph, individual veinlets are extremely variable in trend and in mineralogy; the vein margins are irregular and jagged. Although most veinlets are subparallel to the vein walls many are at a marked angle. As shown in figure 49*B*, most of the radioactivity is limited to the dark veinlets; the variation in pitchblende content of the veinlets is shown by the differences in intensity of radioactivity. The maximum width of the vein in this part of the mine is about 12 inches but the average width is 3 to 6 inches. The walls are frozen; vugs are small and rare.

In the lower workings where the vein cuts biotite granite, it consists of many branching veinlets which are composed largely of pitchblende and siderite. Most veinlets are less than an inch wide, and profitable mining of this part of the deposit is dependent upon a close-spacing of individual veinlets. (See pl. 17.)

PYRITE BOXWORK

Throughout the mine those parts of the sulfide-magnetite deposit that are mostly pyrite have been altered either to boxwork ore or to lacy ore. At places near the Copper King vein the pyrite boxwork contains minable quantities of pitchblende.

The pyrite boxwork is characterized by thin branching and intersecting veinlets of pyrite and marcasite separated by void spaces (fig. 50). At places siderite and pitchblende occur with the pyrite and marcasite in the veinlets, and UO_3-rich pitchblende partly fills the vuggy openings. The half-inch layer parallel to the lower edge of the photo in the middle of figure 50 is sphalerite and pyrite that conforms to the relic layering of the skarn host rock. The remainder

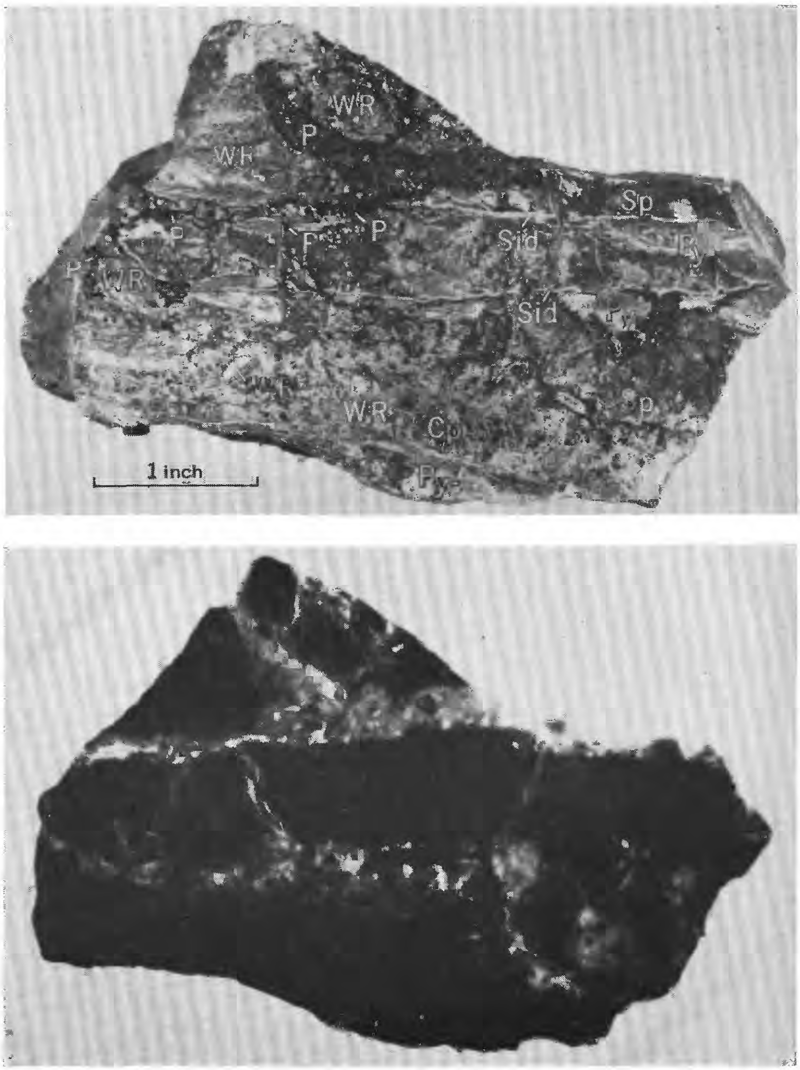

FIGURE 49.—*A* (upper photograph), Specimen showing polished surface of pitchblende-bearing vein from upper part of Copper King mine. *A*, The pitchblende (black) forms irregular veinlets that cut the breccia. (*WR*, wall rock; *Sp*, sphalerite; *Py*, pyrite; *Cp*, chalcopyrite; *Sid*, siderite; *P*, pitchblende.) *B*, Autoradiograph of *A*.

of the specimen, aside from the veinlets, consists of gangue minerals, principally cummingtonite and biotite, that are corroded and veined by pyrite and oriented parallel to the middle sulfide layer. The pyrite veinlets that are oblique to the laminae contain thin films of siderite and at places pitchblende. They are most conspicuous and best developed where they cut the amphibole and associated biotitic layers. Where the veinlets cut the sulfide layer they are weak and composed mostly of siderite.

FIGURE 50.—Photograph of pyrite boxwork. Pitchblende, siderite, pyrite, and local marcasite form intersecting veinlets that cut layered amphibole skarn. Pitchblende rich in UO_3 is present in vugs between the veinlets. The half-inch layer in the middle of the specimen is massive sulfide.

Biotite from replaced sköls is the principal gangue in the vugs between the veinlets. Marcasite rather than pyrite may be the principal iron sulfide in the veinlets.

At places the veinlets do not form a boxwork but are highly irregular and delicate, and form a lacy pattern (fig. 51). Material of this type occurs adjacent to massive sphalerite-pyrite-chalcopyrite ore and is characterized by irregular, small vugs that locally are coated by pitchblende.

PITCHBLENDE SHOOT

The pitchblende-bearing portion of the vein and associated boxwork ore form a nearly vertical shoot extending from 45 to 135 feet below the surface and about 50 feet horizontally (fig. 42). Because the pitchblende is irregularly distributed, not all of the shoot could be mined profitably. The outline of the ore that was extracted from the shoot is shown on figure 42.

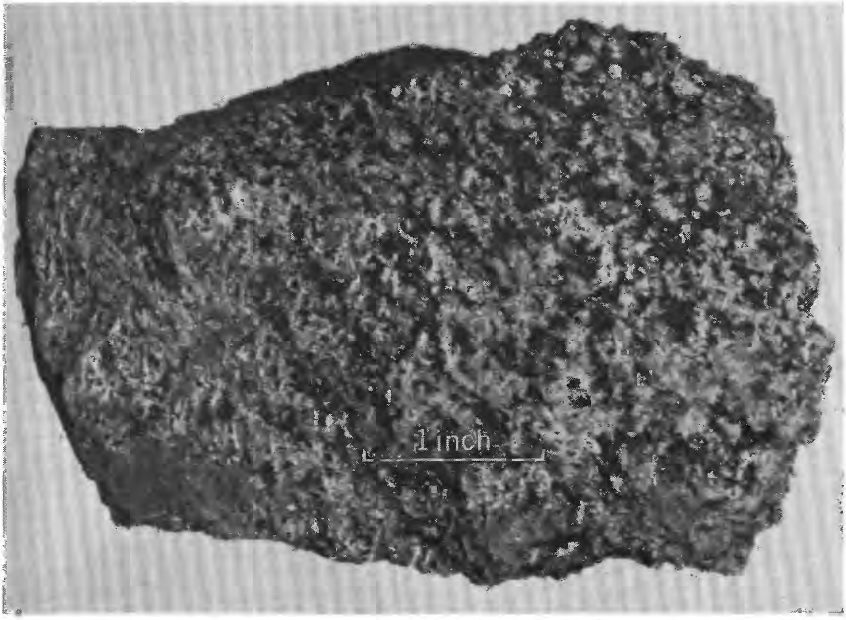

FIGURE 51.—Photograph of lacy ore. Pitchblende (black) is in vugs formed by the leaching of sphalerite from pyrite-sphalerite replacement ore.

The ore within the shoot occurs in three structural envoironments: Above the 110-foot level, the pitchblende primarily is in the tabular Copper King fault; below this level, the uranium occurs in branching fractures related to the Copper King fault, and profitable extraction is dependent upon close spacing and high uranium content of the separate mineralized fractures; and at places adjacent to the Copper King vein high-grade uranium ore occurs in pyrite boxwork.

Mining indicated that the shoot generally is sharply delineated. The western edge of the shoot occurs in the shaft. Except at the 110-foot and 140-foot levels the east wall of the shaft was in ore (pl. 18), but the west wall was barren. Above the 110-foot level, the change from ore to barren vein is abrupt, for at places the ore was as much as a foot thick on the east wall. The eastern limit of the shoot is less well-defined. On the 70-foot level, 35 feet east of the main shaft, the vein is an inch thick and high in grade. Apparently this vein extends into the wall, but it is too thin to be worked profitably. On the 110-foot level the vein is exposed throughout the length of the drift, but beyond a distance of 24 feet east of the shaft it is thin and nearly barren (pl. 18). Uranium-bearing fractures extend into the east face of the 140-foot level and were cut in drill holes BH-3 and BH-8 (fig. 43), but these fractures are too small and too widely-spaced to constitute ore. Similarly, on the 140-foot level, the veinlets that continue into the floor of the drift are not sufficiently abundant or rich to be ore.

Within the shoot the pitchblende occurs in lenses and pods separated by slightly mineralized vein matter. The grade of the ore within the lenses is variable, but ranges from about .2 percent uranium to as much as 20 percent uranium. The largest known lenses are above the 110-foot level. On this level west of the shaft a pod of ore about 12 feet long, 10 feet high, and as much as 12 inches thick was mined (fig. 42). Part of a somewhat larger lens, a maximum of 12 inches thick but averaging 2 to 3 inches thick, was mined east of the shaft. Several tons of ore from this lens was left in the pillar on the east side of the shaft.

The horsetail fractures that comprise most of the ore shoot below the 110-foot level contain veinlets of high-grade uranium generally one-eighth to one-half inch thick. Mining of this part of the vein was largely dependent upon the relative abundance of the veinlets over a mining width. At places along the east side of the shaft (fig. 42) the fractures were sufficiently closely spaced to be mined across a width of as much as 4 feet.

At two places within the deposit uranium-bearing pyrite boxwork ore was extracted (fig. 42). This type of ore occurs only within 5 feet of the Copper King vein or a uranium-bearing horsetail fracture. The pyrite boxwork more distant from a uranium-bearing vein, so far as known, is barren or only slightly uraniferous.

Several tons of high-grade boxwork pyrite ore and lacy ore was mined from the shaft 5 to 10 feet below the 70-foot level (pl. 18 and fig. 42). Plates 50 and 51 show typical ore from this place. The ore occurred in the lower part of the sphalerite-rich pod and in the upper part of the pyrite-rich pod shown on plate 18. The ore was high in grade and much of it contained more than 2 percent uranium. Another body of pyrite boxwork ore, comparable in size and grade, was mined from the 140-foot level, about 35 feet east of the main shaft (pl. 17). This ore occurred in a pyrite boxwork layer, 1 to 2 feet thick, that trended northwestward across the strike of the northeastward-trending veinlets; it decreased in tenor away from uranium-bearing veinlets. Boxwork pyrite containing low-grade uranium is exposed on the 110-foot level opposite the shaft (pl. 17); no attempt was made to mine it. An analysis of this rock (CK–83) gave 0.21 percent equivalent uranium and 0.08 percent uranium.

MINERALOGY

In addition to pitchblende, the deposit consists, in order of decreasing abundance, of siderite, pyrite, marcasite, quartz, sphalerite, and chalcopyrite. Perhaps some of the minerals that coat older minerals and fill vugs and probably all of the sphalerite are of supergene origin.

PITCHBLENDE

Pitchblende is used in this report as a mining term, analogous to limonite or wad, to include 3 distinct uranium-rich phases, which are black and commonly indistinguishable in the field. Only where X-ray diffraction results have confirmed the identification are the specific names uraninite, coffinite, and UO_3-rich pitchblende used. The uraninite is a primary mineral presumably deposited from hydrothermal solutions. The UO_3-rich pitchblende is a secondary mineral attributed to supergene solutions. The origin of the coffinite is not definitely known, but as the coffinite-rich mixtures from the mine gave early Tertiary lead/uranium ages similar to that of the uraninite, it is also probably hydrothermal. It occurs intergrown minutely with uraninite. Coffinite is a newly identified uranium mineral, a hydrous silicate having the zircon structure; hydroxyl groups substitute for a part of the silica (Stieff, Stern, and Sherwood, 1955).

Except in high-grade veinlets, the pitchblende is difficult to distinguish megascopically from nearly barren siderite-rich vein material without radioactivity measurements or chemical analyses. It is also difficult to distinguish under the microscope because of its varied morphologic forms and its generally fine texture and intimate intergrowth with siderite.

The pitchblende has four principal modes of occurrence, in part apparently related to differences in morphologic types. Most commonly, the pitchblende is minutely intergrown with dark-brown siderite. Individual grains are tiny; the exact form cannot be determined even with magnifications greater than 200 times. Possibly this pitchblende is microgranular and constitutes extremely fine-grained aggregates.

Pitchblende also is present as tiny veinlets as much as a few millimeters wide and several millimeters long. A typical occurrence of this type of pitchblende can be seen in figure 52, which shows irregular, anastomosing pitchblende veinlets in granite host rock. As can be seen in the photomicrograph, the pitchblende veinlets appear mottled; tiny subrounded to irregular forms with a bluish tinge are surrounded by irregular areas of less reflective pitchblende.

Colloform grains with prominent concentric cracks commonly filled with siderite are sometimes found in the vein (fig. 53); the largest of these grains measure about 3 mm across. Radial cracks, typical of many pitchblendes with spheroidal outlines, are not common; they are best developed in small rounded forms (fig. 54).

As a fourth mode of occurrence, particularly in the boxwork pyrite ores, the UO_3-rich variety of pitchblende is found in vugs as coatings on older minerals, principally sphalerite and chalcopyrite and less commonly pyrite (fig. 55). This pitchblende forms thin layers and has a generally conspicuous concentric layering.

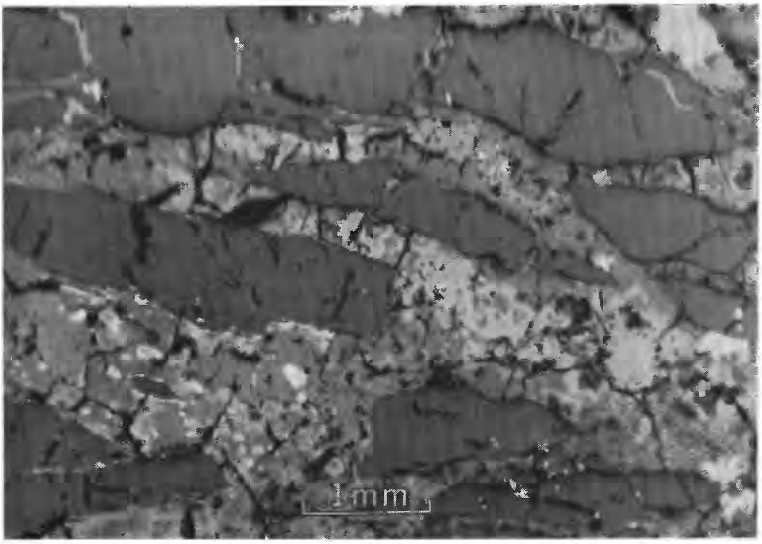

FIGURE 52.—Photomicrograph showing pitchblende veinlets in granite host rock. The veinlets occupy irregular fractures. The white areas within the pitchblende are marcasite.

As the separate phases of the ore cannot be determined in the field, the distribution of each phase in the deposit is not fully known. Uraninite probably is the most abundant and widespread phase, occurring throughout the deposit, but commonly it is minutely intergrown with coffinite. UO_3-rich pitchblende characteristically occurs

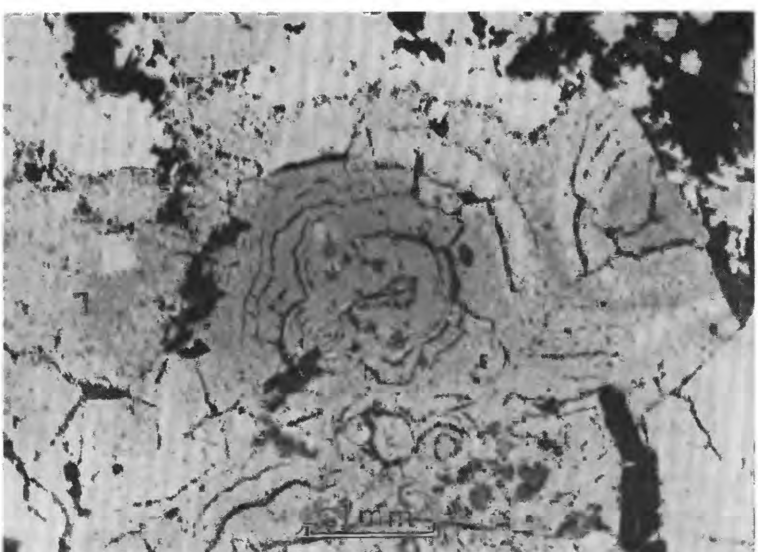

FIGURE 53.—Photomicrograph of pitchblende showing colloform texture and well-developed concentric cracks. Pyrite (white), associated with siderite (dark gray), at places forms a partial rim on pitchblende.

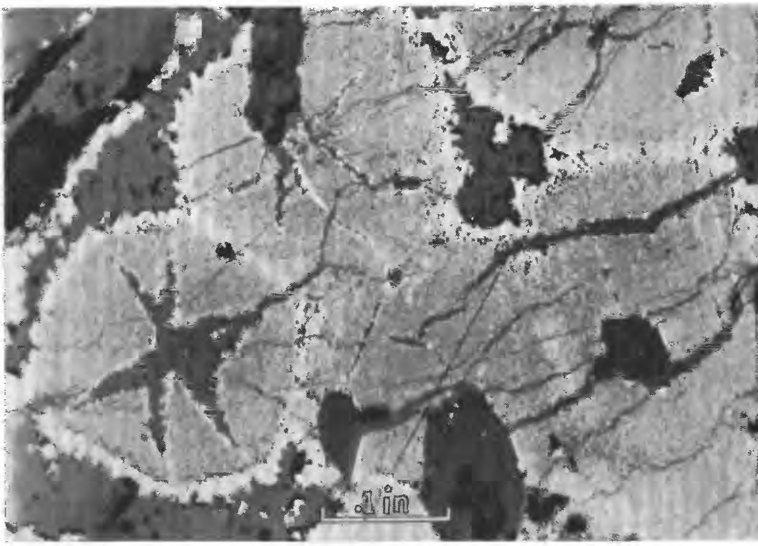

FIGURE 54.—Photomicrograph of colloform pitchblende with radial cracks filled with siderite (dark gray). Siderite also veins the pitchblende. Pyrite (white) forms uniform, complete rims on the pitchblende.

in the boxwork and lacy ores, but it also is present locally within the vein.

Veinlets of high-grade uraninite with a colloform structure occur in fractures within massive sulfide ores. The uraninite has a pitchy

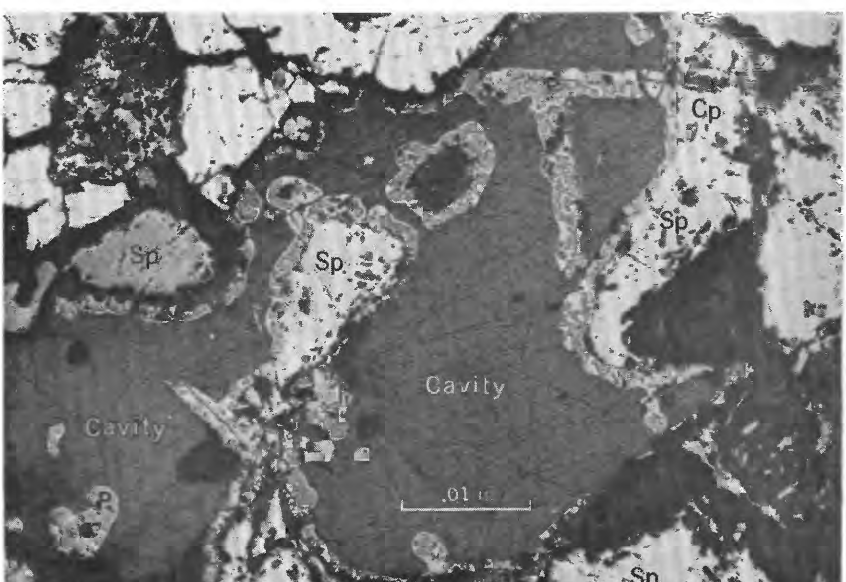

FIGURE 55.—Photomicrograph of pitchblende rich in UO_3. The pitchblende (*P*) forms colloform coatings on fragments of sphalerite (*Sp*) and chalcopyrite (*Cp*). Note that pitchblende is mottled light and dark gray.

or glossy luster and a specific gravity above 6.0. In thin section it is opaque and has a greenish color. It tends to be associated with pyrite and chalcopyrite. Commonly it is intimately intergrown with coffinite and UO_3-rich pitchblende. It also coats wall rock and sulfide fragments in the breccia and forms veins in the crushed matrix.

Pure coffinite has not been obtained. In contrast to uraninite, it has a dark-gray color, a much lower specific gravity, and an earthy appearance. In thin sections it is a translucent brown.

UO_3-rich pitchblende occurs both in the boxwork and lacy ores and in the vein. In the boxwork ores it lines cavities and is dusted on amphibole blades that project into the open spaces; in the lacy ore it fills cavities formed by the selective leaching of sphalerite. The UO_3-rich pitchblende in the veins is intergrown with uraninite and coffinite. The UO_3 pitchblende in part is soft and sooty, but at places it has spheroidal outlines characteristic of colloform structures. It gives no X-ray diffraction pattern and according to the data of Brooker and Nuffield (1952) should contain 80 percent or more of its total uranium as UO_3.

In thin and polished sections, an isotropic mineral with a high index of refraction locally veins the pitchblende or forms rims around it. So far as known, this mineral occurs in the locality studied only in close association with pitchblende; it may be a secondary uranium mineral.

SIDERITE

Siderite, the most abundant and conspicuous gangue mineral in the vein, was deposited at several stages. In general, the earlier siderite is relatively coarse grained and colorless in thin section and forms comb structures in vein fillings, whereas the later siderite is fine grained, tan to dark brown, and forms veinlets that cut the earlier minerals, including pitchblende (fig. 54). Some coarse clear siderite is obviously later than the tan siderite. Regardless of color, all of the siderites have a ω index of 1.86 or greater. Pitchblende apparently occurs generally with the dark-colored siderite.

QUARTZ

Quartz of several varieties was deposited in small lenses and layers a maximum of a few millimeters thick and is generally inconspicuous. Most of the quartz formed early or intermediately in the paragenetic sequence. The earliest quartz typically was clear and formed euhedral crystals. Subsequent to its deposition it generally was brecciated by movements along the vein. Other varieties, in approximate decreasing age, are clear, fine-grained mosaic quartz, euhedral smoky quartz, and yellow botryoidal quartz with concentric layering. In *B* fault clear quartz is concentrically interlayered with goethite in colloform structure.

PYRITE

The pyrite of these ores is characterized by its occurrence in and along fractures and by its generally close spatial association with siderite. It is present in the Copper King vein and subsidiary veinlets and in the pyrite boxwork ores. All of this pyrite is believed to be distinctly later than the pyrite of the sulfide-magnetite ore assemblage, but there is no certainty that all is closely related in time to uranium deposition; possibly some of the pyrite is supergene in origin.

The pyrite is pale brass yellow and has a dull or moderate metallic luster. Typically it occurs in fractures that cut the older minerals (fig. 56). In figure 56, a photomicrograph of pyrite boxwork ore, the

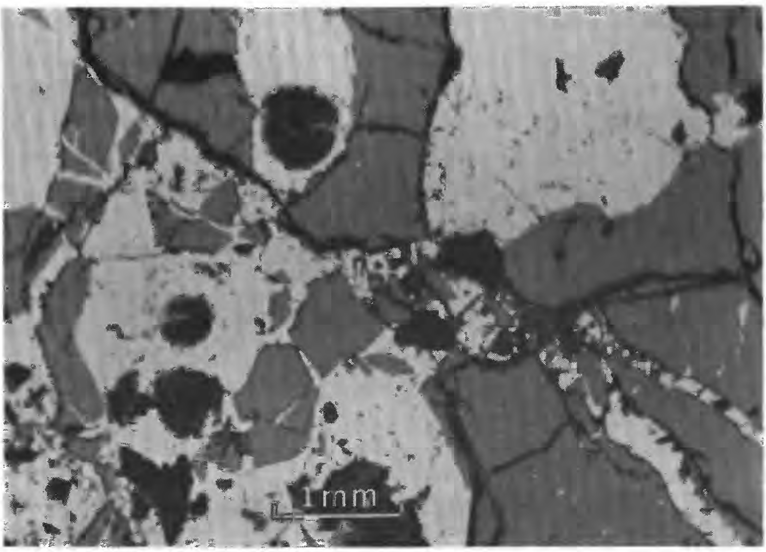

FIGURE 56.—Photomicrograph showing pyrite veinlets that cut sphalerite. The sphalerite formed during the early (Precambrian) period of mineralization. Subsequently it was fractured and veined by the pyrite.

pyrite is seen to fill fractures cutting sphalerite, which formed during the early pyrometasomatic period of mineralization. In figure 45, a thin veinlet of pyrite is seen to cut sphalerite and elliptical pyrite forms. In many specimens pyrite is intergrown with or rimmed by marcasite.

A variety of pyrite common in the vein but sparse in the pyrite boxwork consists of fine-grained aggregates of minute pelletlike grains with spheroidal outlines that are dispersed through tan to brown siderite. Individual pellets are less than 1 mm in diameter. Another variety, less abundant, occurs as tiny wirelike forms.

MARCASITE

Marcasite is a widespread component of the pitchblende-bearing ores. It appears to be more abundant in the lower mine workings where it is associated with siderite and pitchblende. The marcasite occurs as layers, generally less than 2 mm across, that alternate with layers of quartz and siderite in the Copper King vein; as distinct veinlets that occupy fractures, particularly in the boxwork pyrite ores but also in the vein; and as rims on pyrite. The marcasite generally has a well-developed comb structure.

SPHALERITE

Resin sphalerite is common in the pitchblende-bearing ores. It is distinguished from the early generation of sphalerite by the absence of chalcopyrite blebs, strong internal reflections, and low reflectivity. Most commonly it coats vugs, but at places it occurs as anhedral grains and veinlets associated with siderite and pitchblende.

CHALCOPYRITE

A minor amount of chalcopyrite is present in the Copper King vein. It is distinguished from the earlier generation of chalcopyrite by its occurrences in veinlets that were formed later than some of the siderite.

GOETHITE

Goethite is abundant in *B* fault at the 110-foot level, but so far as known is not present in the Copper King vein. It is concentrically interlayered with clear quartz to constitute a colloform structure. Locally it is associated with sparse crystalline hematite and brown hydrous iron oxides.

FLUORITE

A small quantity of purple anhedral fluorite was observed in the altered granite adjacent to a pitchblende-siderite veinlet. The fluorite was dispersed through altered plagioclase and along crystal boundaries. Fluorite was also observed in a prospect pit a quarter of a mile from the Copper King mine.

TRACE ELEMENTS

A spectographic analysis of a uranium ore sample from the stope above the 110-foot level (CK–82) is given in table 4. For comparison, spectrographic analyses, together with the equivalent uranium and chemical uranium analyses, are given for gouge taken from *A* and *B* faults.

Aside from manganese and zinc, which exceed one percent in the vein, the trace element suite of the Copper King vein is similar to that

TABLE 4.—*Semiquantitative spectrographic analyses of material in Copper King vein and A and B faults, Copper King mine* [1]

[Analyst: A. T. Myers]

Field No.	Material [2] in	Width of sample (feet)	Location	Si	Al	Fe	Ti	Mn	Ca	Mg	Na	K	Ag	Ba	Be	Co	Cu
CK-80	*B* Fault	1.0	110-ft level	XX.	0.X−	XX.	0.00X+	0.0X+	0.0X	0.X−	0.X	------	tr	0.00X−	0.000X+	0.00X	0.X−
CK-81	do	.5	do	XX.	.0X+	XX.	.00X	.0X	.0X−	.X−	.X	------	0.000X−	.000X+	.000X	.00X+	.X+
CK-82	Copper King vein.	.2	do	X.	.00X+	XX.	.0X−	X.−	.0X+	.X+	.X	------	.000X	------	.000X	.00X+	.X+
CK-85	*A* Fault	1.0	Crosscut, 160-ft level.	XX.	X.+	X.−	.X−	.00X+	.X−	.X−	.X+	X.	------	.X−	.000X	tr	.X−
CK-86	do	.4	70-ft level	X.	.X	XX.	.0X−	.0X+	.0X	.X+	------	.X+	.000X	.00X−	.000X	.00X+	.X
CK-87	do	.5	do	XX.	X.−	XX.	.0X−	.0X+	.X−	X.	.0X+	X.−	.000X−	.00X+	.000X+	.00X	.X
CK-88	do	.9	do	XX.	X.	XX.	.0X	.0X+	.0X+	.X−	.X+	X.−	.000X−	.0X	.000X+	.00X	.X−

Field No.	Material [2] in	Width of sample (feet)	Location	Ga	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr	eU [3]	U [4]
CK-80	*B* Fault	1.0	110-ft level	0.000X+	0.X−	------	0.00X−	0.00X−	------	------	0.00X	0.00X−	0.000X	0.X+	0.00X−	0.090	0.064
CK-81	do	.5	do	.000X+	.0X	------	.00X−	.00X−	------	------	.00X	.000X+	.000X−	.X	.00X−	.034	.018
CK-82	Copper King vein.	.2	do	------	.0X−	------	.00X−	.0X−	------	------	------	.00X	.000X	X.+	.00X	3.6	5.030
CK-85	*A* Fault	1.0	Crosscut, 160-ft level.	.000X+	------	0.00X	------	.00X+	0.000X	0.00X+	.00X−	.00X	.000X−	------	.0X−	.016	.008
CK-86	do	.4	70-ft level	.000X+	.00X+	------	.000X−	.00X−	------	------	.0X−	.00X	.000X+	.X+	.00X	.024	.013
CK-87	do	.5	do	.00X−	.00X+	------	.00X−	.0X−	------	.000X−	.00X	.00X+	.000X+	.X	.00X	.046	.026
CK-88	do	.9	do	.00X−	.0X	.00X	------	.0X+	------	.00X	tr	.00X+	.000X+	.X	.0X−	.48	.046

[1] Looked for but not found: P, As, Au, B, Bi, Cd, Ce, Cr, Dy, Er, Gd, Ge, Hf, Hg, In, Ir, La, Li, Nd, Os, Pd, Pt, Re, Rh, Ru, Sb, Sm, Sn, Ta, Th, Tl, Te, and W. Some elements of this group possibly are present in trace amounts, but because of their low-standard sensitivities were not detected.

[2] All are chip samples.

[3] Determined by radiometric analysis (S. P. Furman and R. F. Dufour).

[4] Determined by chemical analysis (James Wahlberg).

of the gouge in *A* and *B* faults. The zinc in the vein is contained in sphalerite. The source of the manganese, however, is not known; possibly it is contained in a manganiferous siderite.

The gouge in both *A* and *B* faults contains elements common to the granite and skarn ore wall rocks and elements probably introduced by the Tertiary ore-forming solutions. The elements found in the gouge (table 4) are similar in abundance to those occurring in the fresh granite. (See table 5.) The gouge, however, contains more iron, and less aluminum, calcium, sodium, and barium than fresh granite. In addition the gouge, like the vein material, contains the elements cobalt, silver, copper, niobium, nickel, and zinc which are not present in measurable quantities in the granite.

PARAGENESIS

The paragenesis of the vein-forming minerals is complex. During mineral deposition the vein was repeatedly reopened, as shown by several stages of fracturing and recementation by the vein-forming minerals. Subsequently, supergene solutions altered parts of the deposit.

During initial fracturing, fragments of the wall rocks were incorporated in the vein, particularly in the upper mine workings, and skarn ore minerals, mainly pyrite, sphalerite, and chalcopyrite, were broken into tiny fragments to form a microbreccia texture (Schwartz, 1951, p. 589).

Later the vein was invaded by barren siderite and by pyrite, marcasite, and minor quartz. Some sphalerite and chalcopyrite may also have formed at this time. The main period of pitchblende deposition followed a period of fracturing. The pitchblende, together with fine-grained tan to brown siderite, veined the earlier minerals and filled openings between them. The siderite began to form before the pitchblende and continued to crystallize after the cessation of deposition of the uranium. In part it is in concentric cracks in the pitchblende; much of it also veins pitchblende. A small amount of pyrite was deposited after the pitchblende, largely as rims on pitchblende (fig. 54). Much later, resinous sphalerite, some siderite, and fine-grained quartz were formed, probably by supergene solutions. Also late in the sequence, UO_3-rich pitchblende was deposited as thin coatings and colloform layers in vugs in the vein (fig. 55) and in the boxwork pyrite ore.

AGE AND ORIGIN

Determinations by the methods Pb^{206}/U^{238} and Pb^{207}/U^{235} on two samples of hard pitchblende from the Copper King vein, not from the boxwork pyrite ore, gave ages ranging from 55 to 76 million years after suitable common lead corrections. This range is similar to that obtained for four samples from the Central City, Colo., district when similarly corrected and shows that the uranium deposition in both areas was contemporaneous within those limits.

The hard pitchblende and associated vein minerals in the Copper King vein are thought to have been deposited by hypogene solutions, although subsequently they were somewhat modified by supergene solutions. The primary ore minerals were deposited in the relatively open parts of the Copper King fault. The amphibole skarn and associated sulfide-magnetite deposits, because they were more competent than the biotite granite, remained relatively open when fractured, and hence more permeable to the ore-forming solutions than adjacent broken rocks.

Deposition of the uranium was possibly related to some extent to a chemical reaction between the ore-forming solutions and the wall rocks. It is known from field occurrences that some important deposits of pitchblende are localized in mafic wall rocks (Robinson, 1951; Murphy, 1946, p. 433; Adams, Gude, and Beroni, 1953, p. 2; Adams and Stugard, 1956, p. 202–204). At the Copper King mine, the sulfide-magnetite ores and skarn, a mafic iron- and magnesium-rich host, are the principal wall rocks for the vein, but important quantities of uranium also occur at places in the adjacent granite. Consequently, if the mafic wall rocks did exert a chemical control on ore deposition, the ore was not deposited entirely within the limits of these rocks.

The hard pitchblende-siderite-pyrite-marcasite veinlets within the pyrite boxwork are thought to be related to, and almost contemporaneous with, ore deposition in the Copper King vein. The development of these boxwork ores was complex. The sulfide-magnetite ore assemblage formed during the Precambrian period of pyrometasomatic mineralization. (See page 200.) During Laramide(?) time these ores were fractured contemporaneously with the development of the Copper King fault and subsequently were leached. Pitchblende, pyrite, and marcasite were deposited in the fractures (fig. 50). Subsequently, through the action of circulating supergene solutions, vugs were formed between the veinlets by the leaching of materials, chiefly sphalerite and silicate minerals; and pitchblende in the veinlets was partly oxidized and hydrated(?) and redeposited in the vugs. The lacy ores (fig. 51) formed essentially contemporaneously with the pyrite boxwork, largely by the leaching of sphalerite from sphalerite-pyrite-chalcopyrite ores of Precambrian age.

Supergene alteration extended to the lowest workings in the mine; pyrite boxwork and lacy ores containing UO_3-rich pitchblende are found on the 140-foot level. Because the supergene mine waters were highly acid, colored secondary uranium minerals were not formed. (Phair and Levine, 1953, p. 367).

The hypogene uranium-bearing solutions probably were derived from a magmatic source. The source is not known, however, as the nearest known exposures of igneous rocks of Tertiary age are 10 miles to the southwest in the Manhattan mining district.

RADIOACTIVITY OF A AND B FAULT ZONES

The gouge in *A* and *B* faults is abnormally radioactive throughout the Copper King mine, but no uranium minerals have been identified from them. Analyses giving the equivalent uranium and chemical uranium content of the gouge are presented in table 4.

The anomalous radioactivity of the fault gouge is low, except for sample CK–88 from *A* fault, near the west shaft on the 70-foot level (pl. 17). Without exception, the analyses indicate disequilibrium: There is insufficient uranium to account for the radioactivity. Analysis of a 4-foot chip sample collected from *A* fault in the southwest corner of the main shaft at the sill of the 110-foot level (pl. 17) indicates that the excess radioactivity can be accounted for largely by radium and other disintegration products of uranium, as shown in the following table:

[Analysts: S. P. Furman, J. N. Rosholt, and James Wahlberg]

Field No.	*Percent of*		*10^{-9} curies per gram of*		
	eU	*U*	*Ra*	*Rn*	*Pb^{210}*
CK–92	0.050	0.007	0.32	0.28	0.28

The interpretation is that uranium has been leached recently from the fault zone, leaving the radium content fixed almost in place (Phair and Levine, 1953).

ALTERATION OF WALL ROCK

Aside from the pyrite boxwork and lacy ores formed from the sulfide-magnetite deposit, the wall rocks adjacent to the Copper King vein were little altered.

The amphibole skarn, biotite sköls, and sulfide-magnetite ores, where cut by the vein, are at places strongly sheared for as much as a foot from the vein but little changed mineralogically. Fragments of skarn and mica sköls within and adjacent to the vein were locally chloritized. The chlorite probably was derived from the alteration of biotite.

The granite wall rocks were somewhat more altered than the amphibole skarn and associated ores. Alteration was most intense where many closely-spaced mineralized fractures cut the granite. In the stope east of the shaft, between the 110- and 140-foot levels (fig. 42) where the granite is cut by abundant pitchblende-bearing fractures, the rock is altered to a soft, crumbly rock. Possibly the breakdown largely resulted from saussuritic alteration. The cores of the plagioclase feldspar grains were changed to a fine-grained aggregate of a greenish mineral and clear crystalline albite. Accompanying this change, a new mica formed along fractures, cleavages, and interfaces in quartz and microcline. The mica is slightly pleochroic, varying from colorless to pale olive green. It is biaxial with a 2V of approximately 15°; R>V, strong; *n*Y is 1.59±.01; birefringence is strong. The mica may be vermiculite. The biotite, except where it occurs as inclusions in quartz, was altered to a pale-green mica with a high birefringence. Small quantities of purple fluorite and calcite were formed locally in the saussuritized plagioclase feldspars. In the most intensely altered granite, which is mottled red and green, red flakes of an unidentified mineral occur in the saussuritized feldspar and in fractures. The quartz and microcline in the granite remained unchanged.

Semiquantitative spectrographic analyses of the altered and fresh granite indicate that the principal change accompanying the alteration was the addition of uranium, cobalt, neodymium, samarium, ytterbium, molybdenum, and locally zinc to the rock (table 5). The other elements common to both altered and fresh granite quantitatively show little variation.

RESULTS OF EXPLORATION

To explore for an extension of the Copper King ore body, the Atomic Energy Commission conducted a diamond core drilling project in 1952 (Derzay and Baker, 1953), after the approximate outline of the ore body had been determined underground. Fourteen surface holes totalling 3001 feet were cored. The holes were drilled on a grid system designed to penetrate the ore-bearing zone at a 50-foot vertical and 75-foot horizontal spacing. The drilling explored the zone to a distance of 225 feet west of the main shaft, 350 feet east of the shaft, and to a maximum vertical depth of 350 feet. Although no uranium ore of commercial importance was found, pitchblende-carbonate veinlets were intersected in hole BH–8 (fig. 43), and traces of uranium were found in hole BH–3 at drill depths of 130 and 145 feet and in hole BH–11 at a depth of 189 feet. The uranium in hole BH–8 assayed less than 0.05 percent U_3O_8 for a 2-foot width; the veinlets represent an extension of the uranium mineralization encountered near the face of the 140-foot level.

RECONNAISSANCE FOR RADIOACTIVITY

Radioactivity surveys in the mine area and the surrounding region have failed to locate radioactive anomalies other than pegmatites. In 1952 the Atomic Energy Commission surveyed an area of 700 feet by 1,200 feet in the vicinity of the Copper King mine, using a portable scintillation counter. The data were recorded on an isorad map (Derzay and Baker, 1953); no anomalies other than the

TABLE 5.—*Semiquantitative spectrographic analyses of granite wall rocks, Copper King mine*[1]

[Analysts: P. J. Dunton and R. G. Havens]

Field No.	Type of Material	Location	Si	Al	Fe	Ti	Mn	Ca	Mg	Na	K	Ba	Be
D-2	Fresh granite	Surface	XX.	X +	X. −	0.0X+	0.0X−	X. −	0.X−	X. −	X. −	0.0X+	0.00X−
UG-40	do	70-ft level	XX.	X.+	X. −	.0X+	.0X−	X. −	.X−	X. −	.X+	.0X−	.00X−
UG-66	Altered granite	110-ft level	XX.	X.+	X. −	.X−	.0X−	.X	.X−	X. −	X. −	.X−	.000X
UG-67	Fresh(?) granite	do	XX.	X.+	X. −	.X−	.0X−	.X+	.X−	X. −	X. −	.0X	.000X
CK-50	Altered green granite containing pitchblende seams.	Stope below 110-ft level.	XX.	X.+	X.+	.X−	.0X−	.X	.X−	.X+	X.	.0X	.000X+
CK-51	Altered gray granite containing pitchblende seams.	do	XX.	X.+	X.	.X−	.X−	.X	.X−	X. −	X.	.0X	.000X
CK-52	Altered greenish-gray granite containing pitchblende seams.	do	XX.	X.+	X.+	.X−	.0X+	.X	.0X+	.X+	X.	.0X	.000X

Field No.	Type of Material	Location	Ce	Cr	Cu	Ga	La	Mo	Pb	Sc	Sn	Sr	V
D-2	Fresh granite	Surface	0.00X	0.000X	0.000X−	0.00X−	0.00X	----	0.00X	0.000X	----	0.0X−	0.00X−
UG-40	do	70-ft level	----	.000X−	.000X+	.00X−	----	----	.00X−	.000X	----	.00X+	.00X−
UG-66	Altered granite	110-ft level	.0X−	.000X	.000X	.00X−	.0X−	0.00X−	.0X−	.000X	0.00X−	.0X−	.00X−
UG-67	Fresh(?) granite	do	.00X	.000X	.00X−	.00X−	.00X	----	.0X−	.000X	.00X−	.0X−	.00X−
CK-50	Altered green granite containing pitchblende seams.	Stope below 110-ft level.	.0X+	.000X	.00X−	.000X	.0X	.0X	.0X−	.000X	.000X	.00X+	.000X+
CK-51	Altered gray granite containing pitchblende seams.	do	----	.000X	.00X−	.000X	.00X−	.X−	.00X+	.000X	.000X	.00X+	.000X+
CK-52	Altered greenish-gray granite containing pitchblende seams.	do	----	.000X	.00X−	.000X	.00X	.0X+	.00X+	.000X	.000X	.00X+	.000X+

Field No.	Type of Material	Location	Y	Zn	Zr	U	eU[2]	U[3]	Co	Nd	Sm	Yb
D-2	Fresh granite	Surface	0.00X+	----	0.0X−	----	----	----	----	----	----	----
UG-40	do	70-ft level	.00X−	----	.0X−	----	----	----	----	----	----	----
UG-66	Altered granite	110-ft level	.00X	0.0X	.0X−	----	----	----	----	----	----	----
UG-67	Fresh(?) granite	do	.00X	----	.0X−	----	----	----	----	----	----	----
CK-50	Altered green granite containing pitchblende seams.	Stope below 110-ft level.	.0X−	----	.0X−	X. −	2.3	3.86	0.00X	0.0X	0.0X	0.00X−
CK-51	Altered gray granite containing pitchblende seams.	do	.00X	----	.0X−	.X	.30	.43	.000X+	----	----	.000X+
CK-52	Altered greenish-gray granite containing pitchblende seams.	do	.00X	----	.0X−	.X	.36	.48	.00X−	----	----	.000X+

[1] Looked for but not found: P, Ag, As, Au, B, Bi, Cd, Ge, In, Ir, Hf, Hg, Li, Nb, Ni, Os, Pd, Pt, Re, Rh, Ru, Sb, Ta, Te, Th, Tl, W. Some elements of this group possibly are present in trace amounts, but because of their low standard sensitivities were not detected.

[2] Determined by radiometric analysis (S. P. Furman.)

[3] Determined by chemical analysis (Wayne Mountjoy.)

radioactive mine dump were disclosed. Subsequently a radioactivity reconnaissance was carried out in the immediate region and to the southwest in the Manhattan mining district, but the results of these surveys likewise were negative.

SUGGESTIONS FOR PROSPECTING

It seems unlikely that the Copper King deposit is the only uranium-bearing vein in the region. Accordingly the writers believe that further search for uranium is justified in this area.

The uranium-bearing vein at the Copper King mine is the only vein-type deposit known in the Prairie Divide region. Many small copper-bearing sulfide deposits of Precambrian age have, however, been prospected. The nearest known vein deposits are the gold-bearing pyritic deposits in the Manhattan district, 10 miles to the southwest (Lovering and Goddard, 1950, p. 285–287). These deposits, together with those at the nearby Mayesville and Home districts, are related spatially to a northeast-trending belt of Tertiary(?) intrusive porphyries, ranging in composition from granodiorite to rhyolite, that extends from Radial Mountain, on the divide between Middle Park and North Park, through Cameron Pass to the town of Manhattan, Colo. Exposures of porphyritic intrusive rocks are not known northeast of Manhattan.

The radioactive Copper King vein did not crop out at the surface, nor could it be detected by portable ground scintillation instruments. Other veins in the Prairie Divide area, if present, in all probability likewise would not be observable at the surface, for Prairie Divide is largely mantled by a veneer of glacial deposits of unknown thickness.

It is thought that the search for new radioactive deposits could most effectively be carried on by the use of airborne scintillation equipment. Anomalies, if found, could then be checked on the ground. As radioactive pegmatites are known in the region, it would be necessary to distinguish the anomalies resulting from these bodies. If anomalies of possible economic significance are found, regional geologic studies should be carried out to relate these anomalies to the geologic setting.

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