

(200)
T67A
NO. 424

Geology and Mineralogy

This document consists of 60 pages,
plus 2 figures.
Series A

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGY OF THE COPPER KING URANIUM MINE,
LARIMER COUNTY, COLORADO*

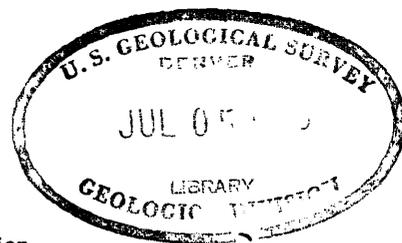
By

Paul K. Sims, George Phair,
and R. H. Moench

June 1955

Trace Elements Investigations Report 424

This preliminary report is distributed
without editorial and technical review
for conformity with official standards
and nomenclature. It is not for public
inspection or quotation.



*This report concerns work done on behalf of the Division
of Raw Materials of the U. S. Atomic Energy Commission.

USGS - TEI-424

GEOLOGY AND MINERALOGY

<u>Distribution (Series A)</u>	<u>No. of copies</u>
Argonne National Laboratory	1
Atomic Energy Commission, Washington	2
Division of Raw Materials, Albuquerque	1
Division of Raw Materials, Butte	1
Division of Raw Materials, Casper	1
Division of Raw Materials, Denver	1
Division of Raw Materials, Hot Springs	1
Division of Raw Materials, Ishpeming	1
Division of Raw Materials, Phoenix	1
Division of Raw Materials, St. George	1
Division of Raw Materials, Salt Lake City	1
Division of Raw Materials, Washington	3
Exploration Division, Grand Junction Operations Office	1
Grand Junction Operations Office,	1
Technical Information Service, Oak Ridge	6
U. S. Geological Survey:	
Fuels Branch, Washington	1
Geochemistry and Petrology Branch, Washington	1
Geophysics Branch, Washington	1
Mineral Deposits Branch, Washington	2
E. H. Bailey, Menlo Park	1
A. L. Brokaw, Grand Junction	1
N. M. Denson, Denver	1
R. L. Griggs, Albuquerque	1
M. R. Klepper, Spokane	1
A. H. Koschmann, Denver	4
J. D. Love, Laramie	1
L. R. Page, Washington	1
Q. D. Singewald, Beltsville	1
A. E. Weissenborn, Spokane	1
TEPCO, Denver	2
TEPCO, RPS, Washington (including master)	<u>2</u>

CONTENTS

	Page
Abstract	6
Introduction	7
Purpose and scope of the report	7
Acknowledgments	8
Geography	8
History and production	10
Mine workings	12
Rock units	12
Metasedimentary rocks	14
Biotite-quartz-plagioclase gneiss	14
Biotite schist	16
Amphibolite	18
Quartzite and related rocks	18
Amphibole skarn	19
Origin of the metasedimentary rocks	23
Igneous rocks	25
Biotite granite	25
Granite pegmatite	28
Origin and age of the granites and pegmatites	29
Structure	30
Foliation and lineation	30
Joints	32
Faults	32
Copper King fault	33
"B" fault	33
"A" fault	34
Mineral deposits	34
Sulfide-magnetite deposits	36
General character and structure	36
Mineralogy	37
Magnetite	37
Pyrrhotite	38
Pyrite	38
Sphalerite	38
Chalcopyrite	39
Molybdenite	39
Trace elements	39
Paragenesis	39
Age and origin	41
Pitchblende deposit	42
Copper King vein	43
Pyrite boxwork	43
Pitchblende shoot	44

Mineral deposits: --Continued

	Page
Pitchblende deposit--Continued	
Mineralogy	46
Pitchblende	46
Siderite	48
Quartz	49
Pyrite	49
Marcasite	49
Sphalerite	50
Chalcopyrite	50
Goethite	50
Fluorite	50
Trace elements	50
Paragenesis	52
Age and origin	52
Radioactivity of "A" fault and "B" fault	54
Wall rock alteration	55
Results of exploration	57
Reconnaissance for radioactivity	57
Suggestions for prospecting	57
Literature cited	59
Unpublished reports	60

ILLUSTRATIONS

Plate 1. Outcrop map of the Copper King mine area, Prairie Divide, Larimer County, Colorado	In envelope
2. Geologic plan maps of the Copper King mine, Larimer County, Colorado	In envelope
3. Section through east wall of Main shaft, Copper King mine, Larimer County, Colorado	35
Figure 1. Index map showing location of the Copper King mine, Larimer County, Colorado	9
2. Claim map of the Copper King mine area, Larimer County, Colorado	11
3. Vertical longitudinal projection of mine workings, Copper King mine, showing approximate outline of pitchblende deposit	13
4. Section through drill hole BH-8	17
5. Section through Copper King mine, showing outline of amphibole skarn body	21
6. Section through Copper King mine	31
7. Paragenetic sequence of the massive sulfide-magnetite ore minerals	41

TABLES

	Page
Table 1. Modal analyses of metasedimentary rocks, Copper King mine	15
2. Modal analyses of granites, Copper King mine	26
3. Semiquantitative spectrographic analyses of sulfide-magnetite ores, Copper King mine	40
4. Semiquantitative spectrographic analyses of material in Copper King vein and faults "A" and "B", Copper King mine	51
5. Semiquantitative spectrographic analyses of granite wall rocks, Copper King mine .	56

GEOLOGY OF THE COPPER KING URANIUM MINE, LARIMER COUNTY, COLORADO

By Paul K. Sims, George Phair, and R. H. Moench

ABSTRACT

The Copper King mine in Larimer County, Colo., in the northern part of the Front Range of Colorado, was opened in 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, and 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.

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 schists. The metasedimentary rocks occur as inclusions that trend north-east, essentially 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 easterly-trending zone through the mine, cut all the Precambrian rocks.

Mineral deposits of two types are present at the mine: 1) sulfide-magnetite ore and 2) a uranium deposit in a filled fissure 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 by Hurley indicate that the mineral assemblage is late Precambrian in age. The deposits are pyrometamorphic in origin and possibly related to the granite.

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 phases of black pitchblende have been identified--uraninite, "coffinite", and UO_3 -rich pitchblende. Colored secondary minerals are absent. The pitchblende occurs in a steeply plunging, tabular shoot between 45 and 135 feet below the surface that has a horizontal length of about 50 feet. Within the shoot the pitchblende occurs in pods or layers generally only a few feet in height and length and as much as a foot thick 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 by the two methods, after suitable common lead corrections, 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 the 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 by the U. S. Geological Survey and examined by R. U. King, H. C. Granger (Granger and King, 1951), and Phair. The ore was found to have come 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 a loan from the Defense Minerals Exploration Administration to further explore the vein. 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 the 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 one inch by plane table and telescopic alidade (plate 1); the mine was mapped on a scale of 5 feet to one inch, using a base map made by a transit, tape, and brunton compass survey (plates 2 and 3). Subsequently, as mining progressed, the new development 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 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), 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. The report was written largely by Sims. J. W. Adams of the U. S. Geological Survey assisted in the field work in September 1951, and several other members of the Survey assisted for short periods during the course of the project.

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 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. 1). From Fort Collins it can be reached by following the road log on page 10:

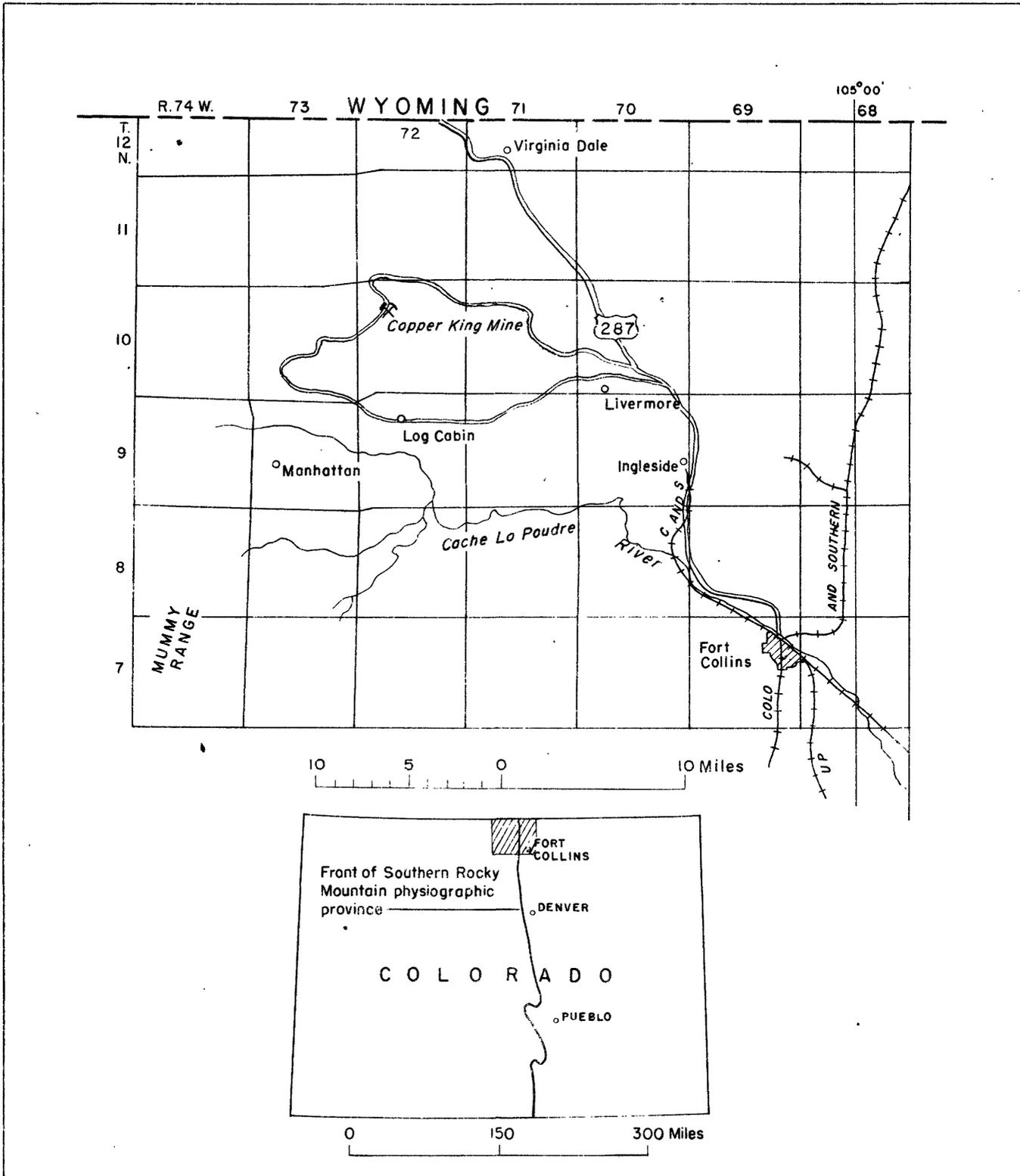


FIGURE 1—INDEX MAP SHOWING LOCATION OF THE COPPER KING MINE, LARIMER COUNTY, COLORADO

Road log from Fort Collins to Copper King mine

	<u>Mileage</u>
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 (pl. 1) were opened during World War I in the search for copper and zinc ore. No ore 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, however, 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 (fig. 2). 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 (fig. 3), were unwatered by the U. S. Geological Survey. 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 were shipped to Salt Lake City in 1951.

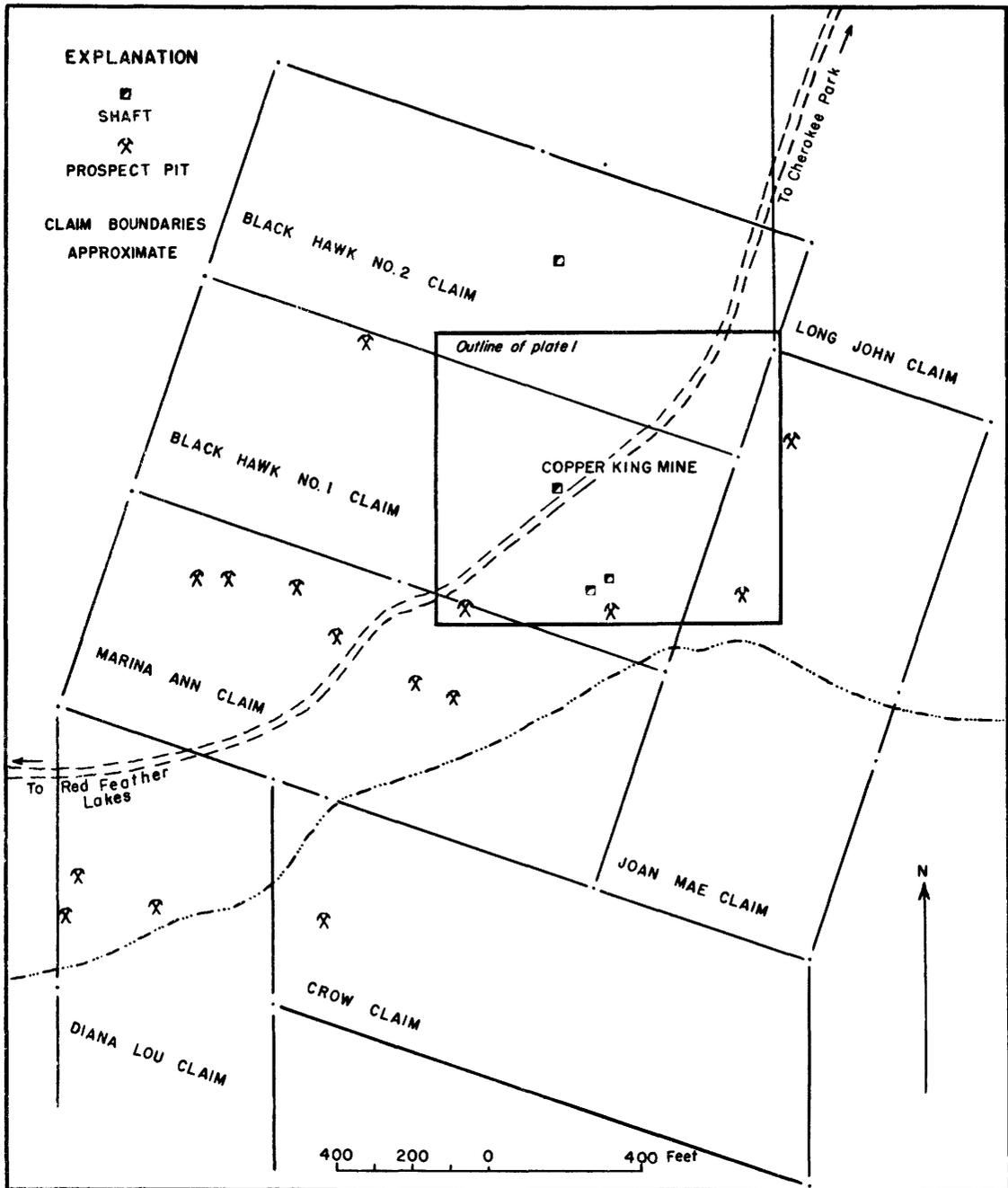


FIGURE 2.-CLAIM MAP OF THE COPPER KING MINE AREA, LARIMER COUNTY, COLORADO.

In 1951, Cherokee Mines, the mine operator, was granted a Defense Minerals Exploration Administration loan to sink a new two-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 (fig. 3). 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 sub-level at a depth of 140 feet was connected to the Main shaft. Subsequently, during mining, a raise was completed connecting the sub-level and the 110-foot level, and another was driven from the 110-foot level to the 70-foot level.

Because of the depletion of the known uranium ore of mining grade and thickness, the mine was closed in August 1953. A total of 652.33 tons of ore at an average grade of 0.28 percent U_3O_8 that contained 3700.06 pounds of U_3O_8 was shipped.

MINE WORKINGS

The mine workings consist of two vertical shafts 52 feet apart totaling 234 feet in length, three short levels about 50 feet vertically apart, a sub-level, and three main raises (fig. 3). The principal manway and hoisting shaft, the main or east shaft, is a two-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 with both 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.

ROCK UNITS

The Copper King mine is near the central part of a Precambrian batholith known as the Log Cabin batholith. Age determinations by the Pb^{208}/U^{232} method on two samples of monazite 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-cla feldspar gneiss and amphibole skarn.

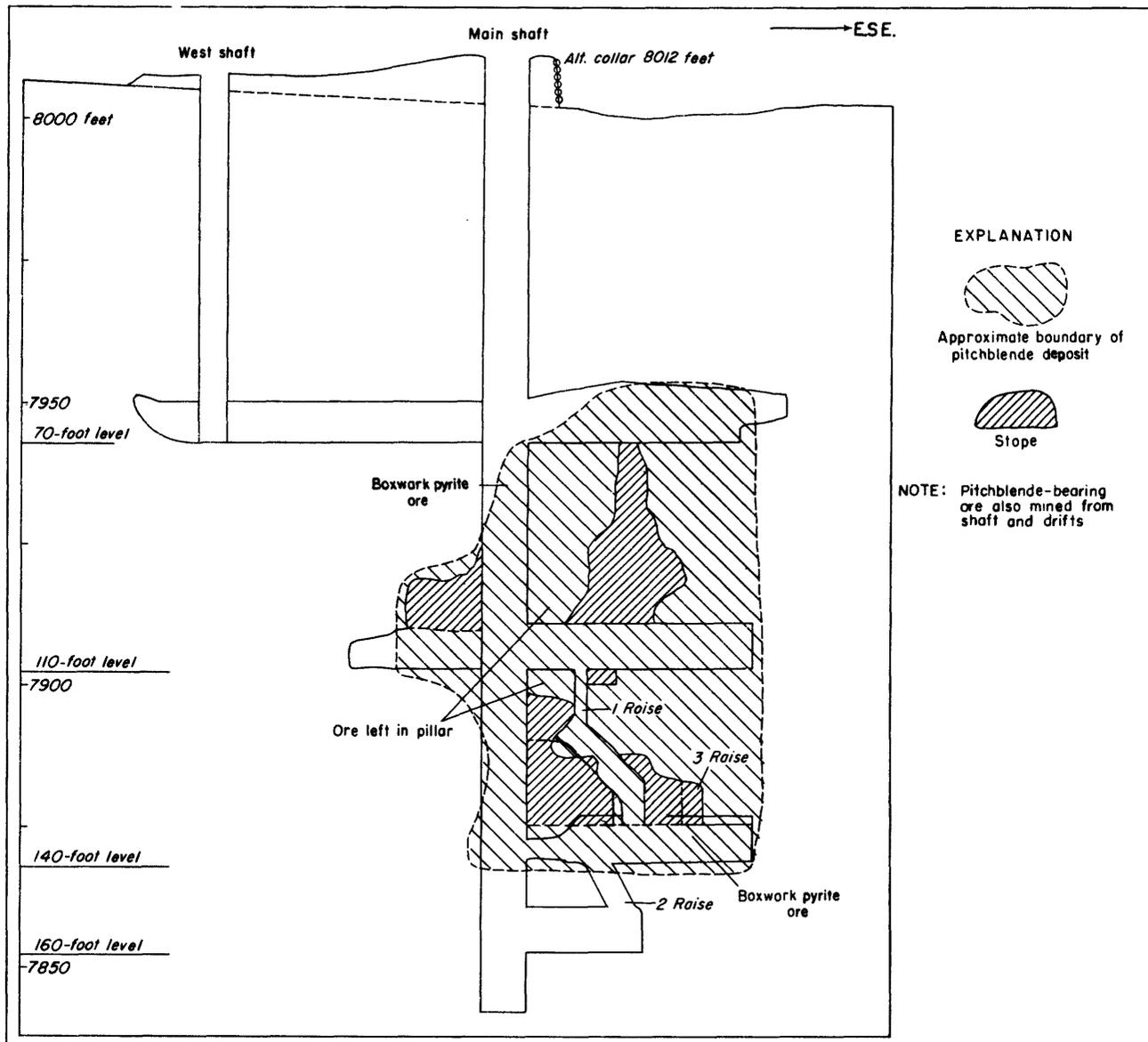


FIGURE 3

Geology and mine workings by P.K. Sims, 1951-53

VERTICAL LONGITUDINAL PROJECTION OF MINE WORKINGS, COPPER KING MINE,
SHOWING APPROXIMATE OUTLINE OF PITCHBLENDE DEPOSIT

30 0 30 Feet
Datum is assumed

Metasedimentary rocks

Metasedimentary rocks constitute about 10 percent of the exposed bedrock in the Copper King mine area (pl. 1). In addition to biotite-quartz-plagioclase gneiss and amphibole skarn, 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 evidence of the original textures have been destroyed. Because they have been folded and 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. 1), 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 northeast-striking foliation, abut against biotite granite; the contact between the two rock types strikes northwest and dips nearly vertical. 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. 27.)

The biotite-quartz-plagioclase gneiss is a dark-gray, fine-grained, equigranular foliated rock that consists essentially 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; $n_Y = 1.685, \pm .003$, 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.

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 An₃₀.

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 An₄₇; hornblende is hastingsite.

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 to 1.25 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, two 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, three feet of schist in biotite-quartz-plagioclase gneiss was intersected at a depth of 67 feet (fig. 4).

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 (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; $n_Y = 1.630$. 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 decussate texture that clearly cut the foliation at all angles. The color and refractive index of both generations of biotite are identical.

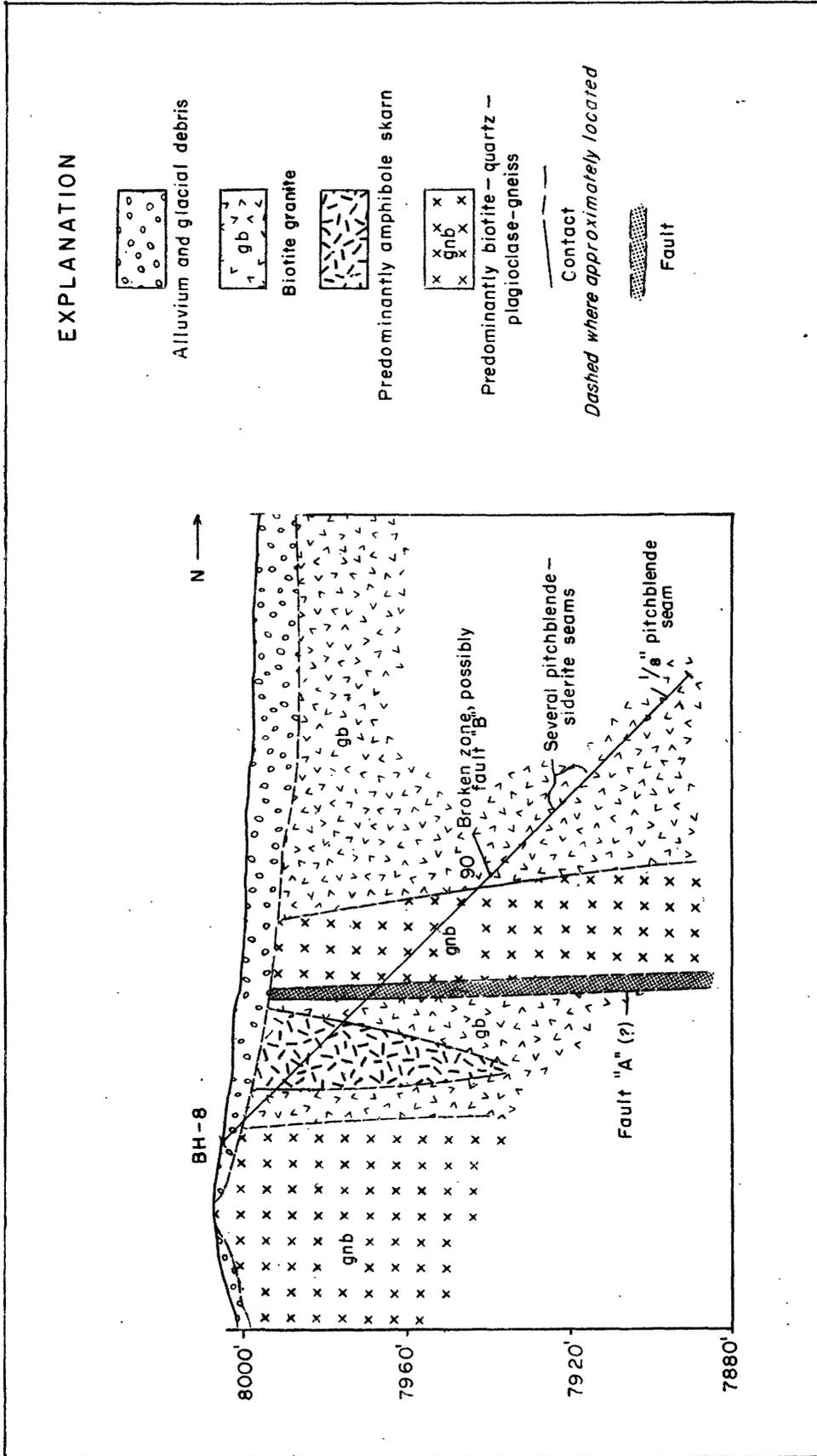


FIGURE 4. — SECTION THROUGH DRILL HOLE BH-8

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 (pl. 1). The foliation is produced by sparse streaks and lenses of plagioclase, generally less than 1/4 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 (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 $n_Y = 1.683 \pm .003$; 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; and two bodies, each less than two 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 10 percent phlogopite and sparse to abundant magnetite (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; $n_Y = 1.610$. 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 essentially 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 essentially of quartz and mica. The hornblende (hastingsite) occurs as euhedral to anhedral blades, some of which are poikilitic with abundant inclusions of sub-rounded quartz. The hornblende is pleochroic: X = very pale yellow-green, Y = green, Z = blue-green; $Z\wedge C = 28^{\circ}$; $n_z = 1.667 \pm .003$. 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. 2). Although lime-rich layers or unaltered carbonate "beds" are not present, the rocks resemble in mineral composition, texture, and structure 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 the 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 (Leonard, 1951; Sims, 1953, p. 271), are referred to as biotite sköls.

Skarn is an old Swedish mining term for aggregates of calcium, magnesium, iron silicates that characteristically are associated with certain deposits of iron ore and sulfides (Holmes, 1920, p. 211). It is generally used geologically for dark, or at least distinctly colored, aggregates of silicate mineral--principally those of the garnet, pyroxene, and amphibole groups--but some writers apply it also to pale or colorless minerals of these groups. Some carbonate usually accompanies skarn, but the quantity varies within wide limits.

Skarn does not crop out at the surface but is present in the Copper King mine and on the dump of shaft No. 1 (pl. 1). The skarn exposed in the mine (pl. 2 and fig. 5) forms a roughly tabular, complexly folded, steeply plunging body, within granite, 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. 4) 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 pinches 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. (See plate 2.) At places the skarn contains small bodies of granite and pegmatite that were intruded prior to the sulfide mineralization, and it is associated closely with biotite-quartz-plagioclase gneiss. Selvages as much as a foot thick but generally only an inch or two wide, and inch-thin partings of biotite ^{skol} 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 transitionally 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 skarns 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.

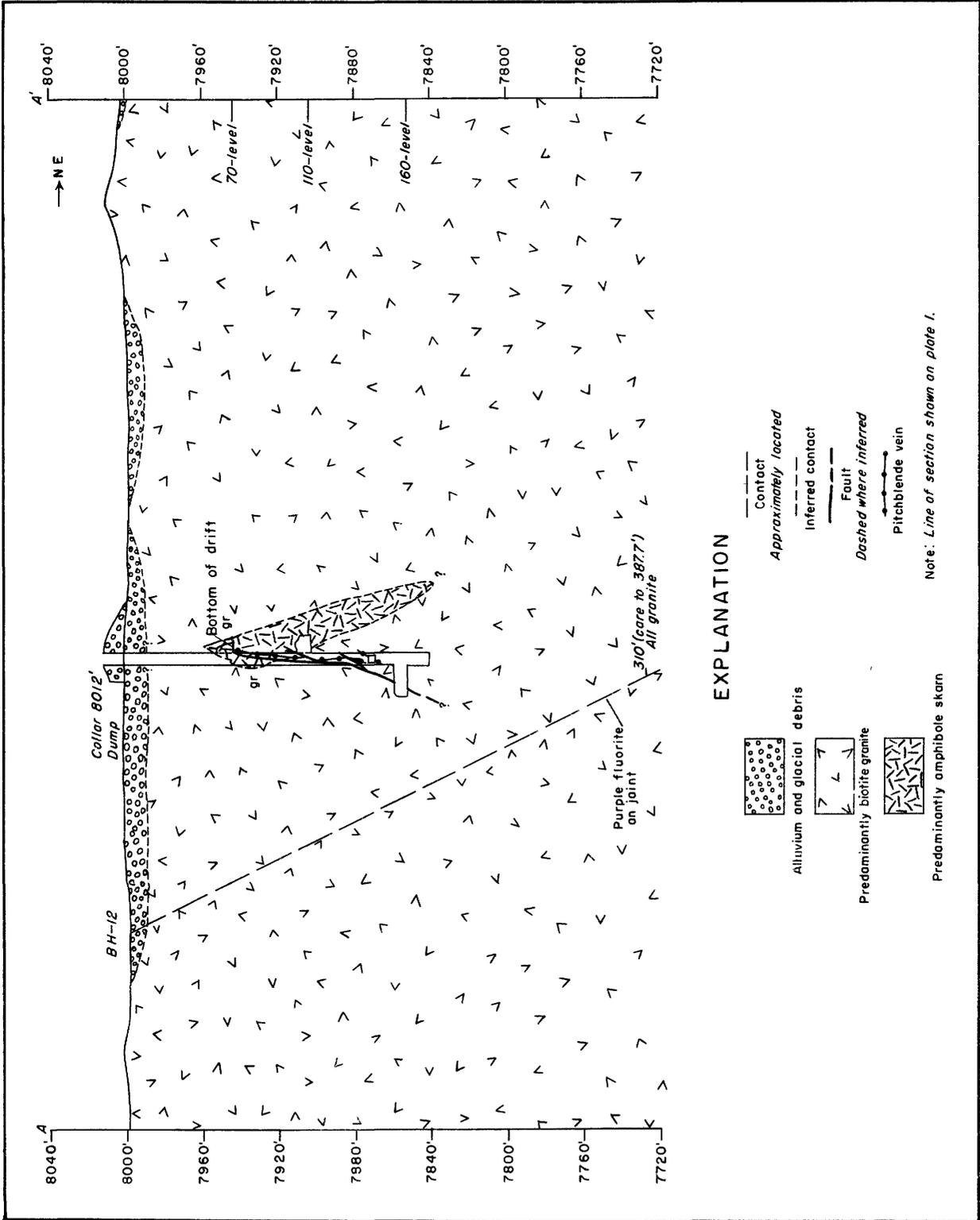


FIGURE 5.—SECTION THROUGH COPPER KING MINE, SHOWING OUTLINE OF AMPHIBOLE SKARN BODY.

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 sheafs of curved fibers, oriented at random, as much as an inch long but 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 sheafs and appear to be later; less commonly the cummingtonite occurs in parallel growth with anthophyllite. The index of refraction of the anthophyllite is variable but averages about $n_Z = 1.652 \pm .003$. 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, $n_Y = 1.595 \pm .003$; $2V = 0^\circ - 5^\circ$.

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. 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 six 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. 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 is inhomogeneous and 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 n_Z is $1.620 \pm .003$, but in one specimen n_Z is $1.612 \pm .003$; for the associated phlogopite n_Z 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, essentially 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, however, on the dump of shaft 2 (pl. 1). So far as known, it is nowhere an important host rock for the sulfide ore minerals.

The actinolite occurs as short stubby crystals, as much as 4 mm long, in random orientation. The quartz forms small interstitial grains.

The biotite sköls form selvages as much as a foot, but generally less than 6 inches thick, around folded, pod-like bodies of skarn; others occur as wisps, thin layers as much as 6 inches thick, and contorted partings within the skarn and sulfide ore. The biotite sköls are dark green; the biotite generally has a strong dimensional orientation parallel to the compositional layering of the skarn and sköls. The biotite in one specimen is dark greenish brown; $n_Y = 1.611$.

Origin of the metasedimentary rocks

The metamorphic rocks in the mapped area were formed by dynamo-thermal 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 probably formed by metasomatic alteration; the skarn, however, could be a dynamo-thermally metamorphosed carbonate rock.

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 (ms. in preparation) noted in the Northgate area, Colo., 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, but this origin cannot be proved in this area. Similar amphibolites have been interpreted as metamorphosed igneous rocks (Adams, 1909; Dodge, 1942, p. 561-583).

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. In this view 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 skarn body in the Copper King mine, to judge from the distribution, paragenesis, and spatial relations of its different constituents, originally consisted of anthophyllite and sparse 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 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. (Leonard, 1951).

The biotite sköls, intimately associated with the skarn, could have been deposited directly from hydrothermal solutions or 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. 55-56.) 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 earlier-formed minerals.

Igneous rocks

Granite and minor pegmatite constitute 90 percent of the exposed bedrock (pl. 1) and probably underlie most of the covered areas. The granite varies from a leucogranite, used in the sense of 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 associated aplite form small dikes in the granite and irregular masses in the skarn.

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.

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, close-spaced incipient fractures that are essentially parallel to the foliation.

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*	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.	Tr.	Tr.
Zircon	Tr.	Tr.	Tr.		Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Hydrous iron oxide										
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	0.8	2.0	0.6	0.7	2.0	2.0	0.2	0.25	0.5

*Most of microcline is perthitic

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

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

Microcline typically constitutes 30 to 60 percent of the rock and occurs as interstitial anhedral grains, but rarely as subhedral grains as much as an inch long; most of the microcline is perthitic. Albite constitutes from a trace to about 20 percent of the volume of the perthite grains and occurs as smooth-walled blebs--rods and string (Alling, 1938, p. 142-147)--or as irregular patches. The (010) plane of the plagioclase in the patch perthite is oriented parallel either to (010) or (001) of the microcline. The microperthite containing rods and strings is similar to the perthites that Alling interprets as the result of 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 45 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 sub-rounded grains that show mutual extinction in microcline.

Biotite makes up as much as 8 percent but generally is slightly less than 5 percent of the rock. The biotite is strongly pleochroic and ranges from straw yellow to dark brownish green in color. (001) forms are well developed, whereas (hk0) forms are either rounded in abutment with quartz, or ragged. Zircon inclusions, surrounded by pleochroic halos, are common. In part the biotite is altered to chlorite.

Muscovite is ubiquitous but constitutes only a 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, and 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 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 1. Modes of streaked granite are given in table 2.

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

The plagioclase 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, sub-rounded 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 in part sharp and in part gradational. 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 pegmatites contain a few percent of biotite. The grain size of the pegmatite minerals is uniform and generally is less than two inches in maximum dimension.

The feldspars--microcline perthite and sodic plagioclase--occur in varying proportions, but the 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 a fourth of an inch thick. Refractive index measurements indicate that n_Y 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 the 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 belong to the Silver Plume type.

The biotite granite, because of its crosscutting relations to metasedimentary inclusions and its granitic texture, 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 post-consolidation alteration are:

- (1) clear albite rims around altered oligoclase cores along the boundaries between plagioclase and microcline;
- (2) clear albite replacing both the plagioclase cores and microcline; (3) quartz truncating rimmed plagioclase;
- (4) ragged muscovite flakes in plagioclase cores, along cleavages, fractures, and crystal boundaries; and
- (5) 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 gneiss-like 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 granite, for so far as known, the granite is the youngest Precambrian intrusive in the area. Age determinations by the Pb^{208}/U^{232} method on two monazite crystals from a pegmatite quarry about five miles east of the Copper King mine by Phair indicate a late Precambrian age for the pegmatite (Phair and Sims, ms. in preparation).

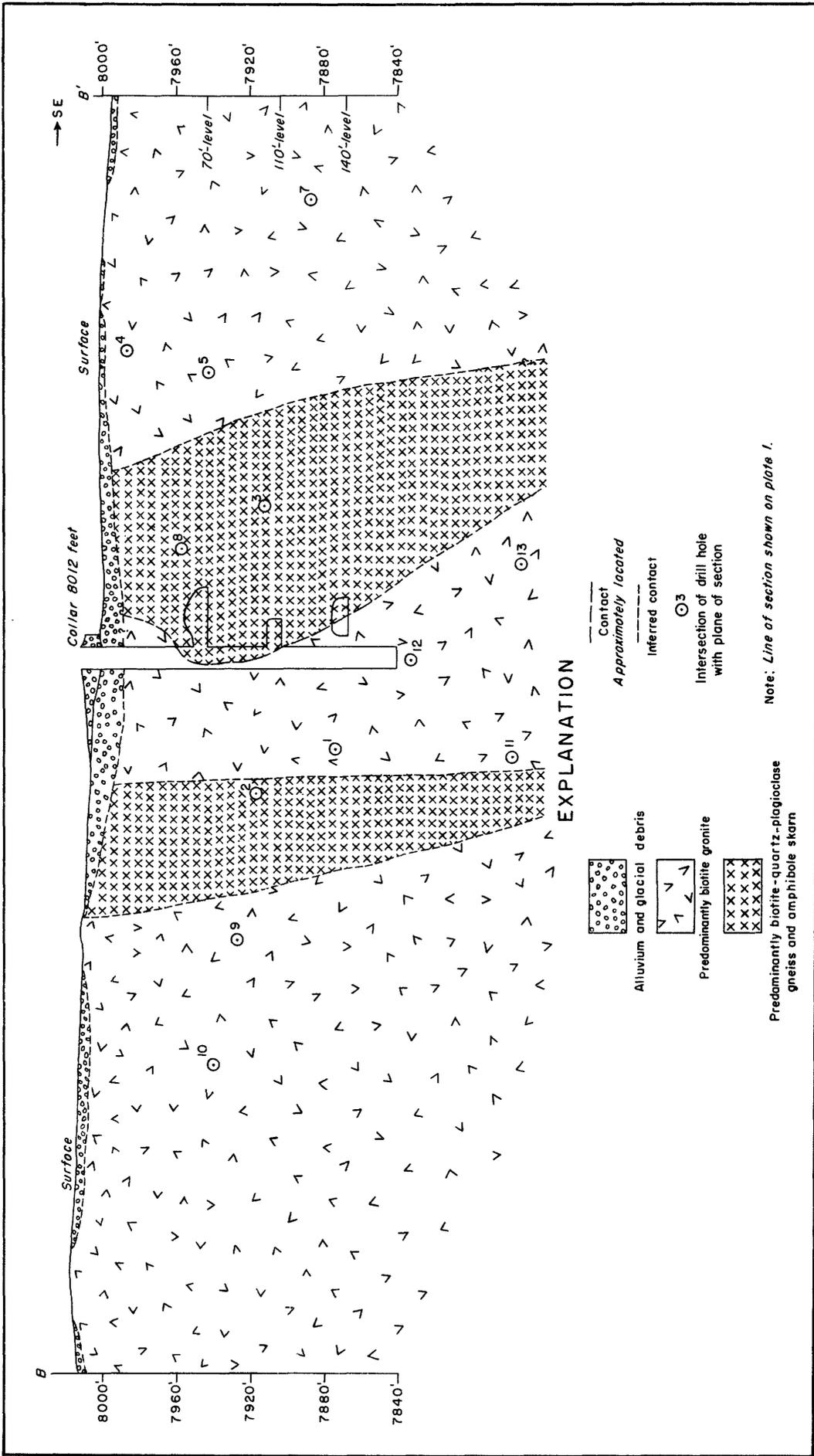
STRUCTURE

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

Foliation and lineation

The foliation in the metasedimentary and igneous rocks (pl. 1) trends northeast and generally dips steeply to the northwest or southeast. The metasediments occur as inclusions of various sizes in the granite (fig. 6) 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 sub-parallel alinement. The lineation in all the rocks exposed at the surface is down dip, nearly normal to the strike of the foliation; the lineation in the metasediments in the mine workings is parallel to the small folds and plunges on the average about 45° NE.



EXPLANATION

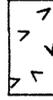
-  Alluvium and glacial debris
 -  Predominantly biotite granite
 -  Predominantly biotite-quartz-plagioclase gneiss and amphibole skarn
 -  Contact
 -  Approximately located
 -  Inferred contact
 -  3
 -  Intersection of drill hole with plane of section
- Note: Line of section shown on plate 1.

FIGURE 6.—SECTION THROUGH COPPER KING MINE.

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 according to their strike roughly into two sets of northeast- and northwest-trending joints. Although most joints are barren, a few contain discontinuous dikes of pegmatite, or less commonly fine-grained aplite, generally less than a foot thick, suggesting that the joints formed before the emplacement of these dikes.

Nearly vertical joints trending about N. 80° W. were found at the surface near the inferred position of the surface trace of "A" fault, which was intersected in the mine workings (pl. 2); study of drill-cores indicates that this joint 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. 2). The faults are probably Laramide in age. They are confined to an easterly-trending zone, a few tens of feet wide, that extends the length of the mine; they also were cut in some drill cores. None of the faults have been recognized at the surface. The principal faults in order of probable formation, are herein named: (1) Copper King fault, (2) "B" fault, and (3) "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, contains pitchblende and was 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; there is no apparent offset. "B" fault likewise is cut by "A" fault.

The type of faulting and stress pattern that formed the faults is not known. As is characteristic of most of the known early Tertiary faulting, displacements are small or nil.

Copper King fault

The Copper King fault is a nearly vertical, heterogeneous 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 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. The 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.

At the 110-level (pl. 2) the Copper King fault is cut by "B" fault, and this intersection plunges southwesterly. Below the intersection the Copper King fault, instead of being a well-defined tabular structure, is characterized by many thin, branching, "horsetail" fractures. The fractures trend east, northeast, and northwest, and fractures of all trends are locally ore-bearing. On the 140-level, ore-bearing fractures of one set strike easterly and dip nearly vertically; fractures of another set, apparently subsidiary to the easterly set, strike about N. 65° E. and dip 60-90 degrees in either direction. Similar fractures were encountered in the stoped ground above the 140-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., and "horsetail" fractures branched eastward from it.

"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. 4), 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. 2) 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 two feet from the fracture.

In the stopes between the 110-foot level and the 140-foot sub-level the fault is obscure; but it probably continues through the stopes into the conspicuous breccia and gouge zone on the 140-foot level. (See plate 2.) The "B" fault zone is abnormally radioactive but nowhere contains sufficient uranium to be ore (see plate 2 and page 54); no uranium minerals have been identified from the fault zone.

"A" fault

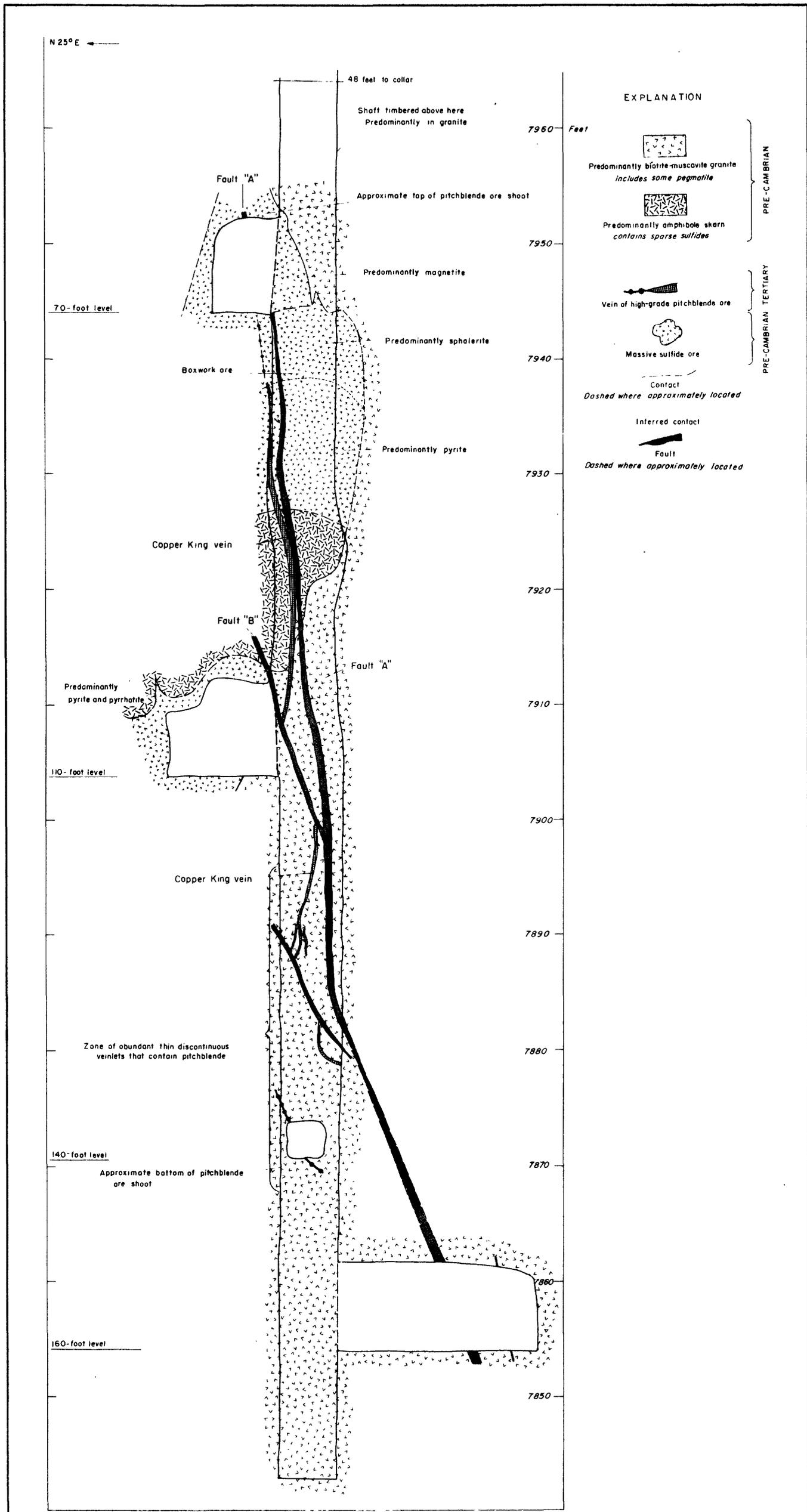
"A" fault, the most conspicuous and continuous break in the mine, was intersected on all levels and was noted in many of the drill cores. The fault extends nearly the length of the 70-foot level, where it strikes N. 55° -70° W. and dips about 80° SW. It can be traced in the shaft to a depth of about 130 feet (pl. 3). At this depth it passes into the southwest wall, and probably was cut on the 160-foot level (pl. 2). 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. 4), 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, crumbly 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 54.)

"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. To the west the faults appear to cross without displacement.

MINERAL DEPOSITS

Mineral deposits of two types differing widely in origin, age, and character are present in the Copper King mine area: (1) massive sulfide-magnetite deposits of Precambrian age, and (2) a pitchblende-bearing vein deposit of early Tertiary age. The sulfides and magnetite replace amphibole skarn and associated rocks and constitute a typical pyrometamorphic deposit. The age of these deposits, as determined by the alpha-helium method on three specimens of magnetite, is late Precambrian. The pitchblende-bearing vein deposit clearly cuts the older sulfide-magnetite ores and surrounding country rocks and was determined by lead-uranium age determinations to be of early Tertiary age. Boxwork pyrite, locally containing pitchblende, occurs in the wall rock of the pitchblende-bearing vein.



Base by P.K. Sims

Geology by P.K. Sims, 1951-1952

PLATE 3. SECTION THROUGH EAST WALL OF MAIN SHAFT, COPPER KING MINE, LARIMER COUNTY, COLORADO.

5 0 10 Feet
Datum is assumed

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. 1). 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, probably in turn reflecting original layering in the replaced skarn.

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 18) 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 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 (figs. 5 and 6). 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 massive sulfides and magnetite within the deposit are distinguished on plates 2 and 3. On the 70-foot level pyrite, the most abundant sulfide, forms a steeply dipping layer, 2 to 3 feet thick, along the north wall of the drift (pl. 3). 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. 3). The shoot is a lens-shaped layer, about 5 feet thick plunging 45° to the east. Beneath it is a 12-foot layer consisting predominantly of pyrite with sparse sphalerite and chalcopyrite, underlain by essentially 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 50° N. 60° E. Pyrrhotite is more abundant here than elsewhere in the mine, and at places it occurs with other sparse 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 50° to 60° NE., 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 .00X percent silver in the ores. (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 can be found locally in the vein.

Magnetite. --Magnetite is abundant only on the 70-foot level where it forms a massive, irregular layer. (See plate 2.) Where intergrown with the sulfides, the magnetite occurs as rare anhedral or subhedral crystals a millimeter 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 one millimeter in diameter, that are intergrown with pyrite and other ore minerals; and as blebs, blades, and films 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 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 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 that commonly are surrounded by, and gradational into, massive anhedral or subhedral pyrite that appears homogeneous. The massive homogeneous pyrite at places cuts the elliptical forms. The concentric rings in the pyrite consist of oriented inclusions of the amphibole host. 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.

Sphalerite. --Sphalerite is the most abundant sulfide mineral in the sulfide-magnetite deposits. Most of it is dark-brown and iron-rich and all the sphalerite examined contains irregular blebs, films, and blades of chalcopyrite. At places it also contains blebs of pyrrhotite. The sphalerite commonly is intergrown with chalcopyrite, pyrite, and pyrrhotite. It embays the early pyrite 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, and 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 molybdenite is most abundant on the 135-foot level. Spectrographic analyses for Mo indicate that it constitutes .00X or less of the massive ores (table 3). Because molybdenite has not been observed in the ores, nothing is known concerning its relation to the ore minerals.

Trace elements. --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 Co and Ni, characteristically present in pyrrhotite-bearing ores, but nowhere are they important constituents. Indium and cadmium are present in some sulfide ores in trace amounts. The magnetite contains as much as .0X Ti.

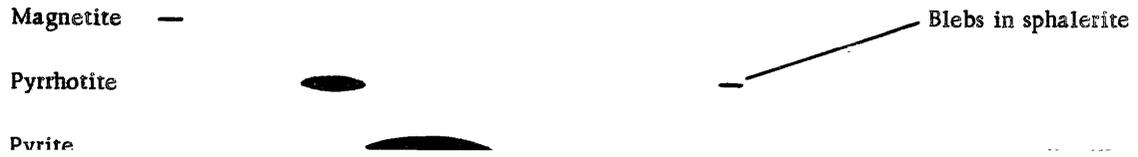
Paragenesis

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 7. The order of introduction and replacement of the different minerals follows closely the usual stages 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 between ore mineral grains.

Figure 7. --Paragenetic sequence of sulfide-magnetite ore minerals.



Field Number	
UG-23	Mass ore.
CK-67	Magn amph
UG-24	Pyri chal
CK-68	Mass
CK-69-1	Mass ore.
CK-69-2	Vugg
PKS-1A-51	Boxw
PKS-1B-51	Mass

1/ Looked for but

2/ Determined by r

Analysts: R. C

Age determinations by the alpha-helium method on two specimens of ore magnetite, the earliest metallic constituent of the deposits, by Patrick Hurley of Massachusetts Institute of Technology, gave ages of 700 and 740 million years respectively. Because there appears to be no important break between the deposition of the magnetite and the later sulfides, these ages probably apply to the sulfide-magnetite deposits as a whole. A discussion of the method and accuracy of the age determinations is given by Phair and Sims (ms. in preparation).

The deposits are typical of the class of ore deposits that Lindgren (1933, p. 35-49) has called pyrometamorphic, and they resemble many other deposits of this class in both the western (Knopf, 1933, p. 537-539) and eastern (Leonard, 1951; 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 abundance, siderite, pyrite, marcasite, quartz, sphalerite, and chalcopyrite were deposited with the pitchblende. Three phases of pitchblende--uraninite, "coffinite", and UO_3 -rich pitchblende--have been identified. 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 known. The pitchblende of primary derivation was deposited late in the sequence of mineral deposition, together with siderite, after most of the pyrite and marcasite had formed.

Copper King vein

The pitchblende-bearing vein fills the Copper King fault. The vein minerals formed by filling openings and to a lesser 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. 2), but below the 110-foot level the vein is ill-defined and consists of several branching, "horsetail" veinlets of several trends, as described on page 33. 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. 3). The vein cuts across the trend of the sulfide-magnetite deposit and the amphibole skarn.

The thickness and mineralogy of the vein to a large extent depends on the type of wall rock. 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.

The veinlets are extremely variable in trend and in mineralogy; the walls are irregular and jagged. Although most veinlets are subparallel to the vein walls, many are at a marked angle to the walls. 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 horsetails, individual veinlets are composed largely of pitchblende and siderite. Most are less than an inch wide, and profitable mining of this part of the deposit is dependent upon a close-spacing of individual veinlets.

Pyrite boxwork

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

The pyrite boxwork is characterized by thin, branching and intersecting veinlets of pyrite and marcasite. At places siderite and pitchblende occur with the pyrite and marcasite in the veinlets, and UO_3 -rich pitchblende partly fills the vuggy openings. In the photograph the half-inch layer in the middle, parallel to the lower edge of the photo, is sphalerite and pyrite and conforms to the relic layering of the skarn host rock. The remainder of the specimen, aside from the veinlets, consists of gangue minerals--principally cummingtonite and biotite--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 and 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.

Locally biotite from replaced skols is the principal gangue in the vugs between the veinlets. Marcasite rather than pyrite may be the principal iron sulfide in the veinlets.

Locally the veinlets, rather than forming a boxwork, are highly irregular, delicate, and form a lacy pattern. Material of this type occurs adjacent to massive sphalerite-pyrite-chalcopyrite ore and is characterized by irregular, small vugs that locally contain coatings of pitchblende.

Pitchblende shoot

The pitchblende-bearing portion of the vein, and associated boxwork ore, forms a nearly vertical shoot extending between 45 and 135 feet below the surface and about 50 feet horizontally (fig. 3). Because the pitchblende is irregularly distributed within the shoot, not all of the shoot could be mined profitably. The outline of the ore that was extracted from the shoot is shown on figure 3.

The ore within the shoot is of three general types: (1) Above the 110-foot level, the pitchblende primarily is in the tabular Copper King vein; (2) below this level, the uranium occurs in horsetail fractures related to the Copper King vein, and profitable extraction is dependent upon close spacing and high uranium content of the separate mineralized fractures; and (3) at places adjacent to the Copper King vein high-grade uranium ore occurs in pyrite boxwork.

Mining indicated that at most places the shoot 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. 3) but the west wall was barren. Above the 110-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 for extraction. 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. (See plate 2.) 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. 5), 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 0.2 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. 3). A somewhat larger lens, a maximum of 12 inches thick but averaging 2 to 3 inches thick, was partly 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 half an 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. 3) the fractures were sufficiently closely spaced to mine over widths of as much as 4 feet.

At two places within the deposit uranium-bearing pyrite boxwork ore was extracted (fig. 3). 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 and lacy ore, were mined from the shaft, 5 to 10 feet below the 70-foot level (pl. 3 and fig. 3). 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 3. 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. 2). This ore occurred in a pyrite boxwork layer, 1 to 2 feet thick, that trended northwesterly, across the strike of the northeast-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. 2); 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. Probably all of the sphalerite, and perhaps also some of the other minerals that coat older minerals and fill vugs, are of supergene origin.

Pitchblende. --Pitchblende is used in this report as a mining term, analagous to limonite or wad, to include intimate mixtures of black uranium minerals that can only be identified in the laboratory. Pitchblende comprises a variety of black uranium oxides that have a wide range of UO_3 / UO_2 ratios, states of hydration, structures, and specific gravities. Only when the UO_3 / UO_2 ratio is known to be low from chemical analysis for UO_2 and UO_3 , and specific gravity determinations, and the mineral can be shown by X-ray diffraction studies to have the face-centered cubic fluorite lattice, is the use of the species term uraninite justified.

The pitchblende is difficult to recognize megascopically and without radioactivity measurements or chemical analyses it generally cannot be distinguished from nearly barren siderite-rich vein material. 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, and even with magnifications greater than 200 times, the exact form cannot be determined. Phair believes that this pitchblende probably is microgranular and constitutes extremely fine-grained aggregates, but this has not been proved.

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 shows irregular, anastomosing pitchblende veinlets in granite host rock. The pitchblende veinlets appear mottled; tiny, sub-rounded to irregular forms with a bluish tinge are surrounded by irregular areas of less reflective pitchblende.

Rarely, colloform grains with prominent concentric cracks, commonly filled with siderite, are found in the vein; the largest of these measure about 3 millimeters across. Radial cracks, typical of many pitchblendes with spheroidal outlines, are not common; they are best developed in small rounded forms.

At many places in the vein and particularly in the boxwork pyrite ores, pitchblende, determined by Phair to be the UO_3 -rich variety, occurs in vugs as coatings on older minerals, principally sphalerite and chalcopyrite, but less commonly pyrite. This pitchblende forms thin layers and has a generally conspicuous concentric layering.

By X-ray diffraction methods Phair has distinguished three black phases of pitchblende. These are (1) uraninite, which has a face-centered cubic lattice and a high specific gravity, (2) UO_3 -rich pitchblende amorphous to X-rays, and (3) a new uranium mineral "coffinite", the precise composition of which is not known, which has a tetragonal lattice similar to zircon. These separate phases and the methods used to determine them are described by Phair and Sims (in preparation).

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 intergrown with "coffinite." UO_3 -rich pitchblende characteristically occurs 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 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 and coats wall rock and sulfide fragments in the breccia and forms veins in the crushed matrix.

"Coffinite" has not been obtained pure. In contrast to uraninite, it has a dark-grey color, much lower specific gravity, and an earthy appearance. In thin sections it is translucent and brown in color.

UO_3 -rich pitchblende occurs both in the boxwork and lacy ores and in the veins. In the boxwork ores it lines cavities and is dusted on amphibole blades that project into the open spaces; in the lacy ores 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 pitchblende or forms rims around it. So far as known this mineral is always closely associated with pitchblende and may be a secondary uranium mineral.

Siderite. --Siderite is the most abundant and conspicuous gangue mineral in the vein and 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. The later siderite is fine-grained and tan to dark brown in color and forms veinlets that cut the earlier minerals, including pitchblende. Some coarse clear siderite clearly is later than the tan siderite. Regardless of color all of the siderites have a w index of 1.86 or greater. So far as known, pitchblende 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 intermediate 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 described with 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 "horse-tail" veinlets and in the boxwork pyrite ores. All of this pyrite is believed to be distinctly later than that of the sulfide-magnetite ore assemblage, but there is no certainty that all is closely related in time to uranium deposition; very probably some of the pyrite is supergene in origin.

The pyrite is pale brass yellow and has a dull or moderate metallic luster. Typically the pyrite occurs of in fractures that cut the older minerals. In some specimens boxwork pyrite ore, the pyrite is seen to fill fractures cutting sphalerite, which formed during the early period of mineralization. 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 grains with spheroidal outlines that are dispersed through tan to brown siderite. Individual "pellets" are less than one millimeter in diameter. Another variety, less abundant, occurs as tiny wire-like 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 (1) as layers, generally less than 2 millimeters across, that alternate with layers of quartz and siderite in the Copper King vein, (2) as distinct veinlets that occupy fractures, particularly in the boxwork pyrite ores but also in the vein, and (3) 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 is noted as coatings in vugs. At places in the ores, however, 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 early generation of chalcopyrite by its occurrences in veinlets that are later than some of the siderite.

Goethite, --Goethite is abundant in "B" fault at the 110-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 very minor 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 by Phair in a prospect pit a quarter of a mile from the Copper King mine.

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

Aside from Mn and Zn, which exceed one percent in the vein, the trace element suite of the Copper King vein is similar to that of the gouge in "A" fault and "B" fault. The Zn in the vein is contained in sphalerite. The source of the Mn, however, is not known; possibly it is contained in the siderite.

The gouge in both "A" fault and "B" fault 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 are similar in abundance to those occurring in the fresh granite (table 7). The gouge, however, contains more Fe, and less Al, Ca, Na, and Ba than fresh granite. In addition the gouge, like the vein material, contains elements Co, Ag, Cu, Nb, Ni, and Zn which are not present in measurable quantities in the granite.

Table 4.--Semi-quantitative spectrographic analyses of material in Copper King vein and faults "A" and "B", Copper King mine.

(All analyses by U. S. Geological Survey Denver laboratory)

Field Number	Type of Material ^{1/}	Width of sample (feet)	Location	Si	Al	Fe	Ti	Mn	Ca	Mg	Na	K	Ag	Ba	Be	Co	Cu	Ga	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr	Equivalent Uranium ^{2/}	U ^{3/}
CK-80	Fault "B"	1.0	110-foot level	xx.	.x-	xx.	.00x+	.0x+	.0x	.x-	.x	-	Tr	.00x-	.000x+	.00x	.x-	.000x+	.x-	-	.00x-	.00x-	-	-	.00x	.00x-	.000x	.x+	.00x-	.090	.064
CK-81	Do.	.5	do.	xx.	.0x+	xx.	.00x	.0x	.0x-	.x-	.x	-	.000x-	.000x+	.000x	.00x+	.x+	.000x+	.0x	-	.00x-	.00x-	-	-	.00x	.000x+	.000x-	.x	.00x-	.034	.018
CK-82	Copper King vein	.2	do.	x.	.00x+	xx.	.0x-	x.-	.0x+	.x+	.x	-	.000x	-	.000x	.00x+	.x+	-	.0x-	-	.00x-	.0x-	-	-	-	.00x	.000x	x.+	.00x	3.6	5.03
CK-85	Fault "A"	1.0	Crosscut, 160-foot level	xx.	x.+	x.-	.x-	.00x+	.x-	.x-	.x+	x.	-	.x-	.000x	Tr.	.x-	.000x+	-	.00x	-	.00x+	.000x	.00x+	.00x-	.00x	.000x-	-	.0x-	.016	.008
CK-86	Do.	.4	70-foot level	x.	.x	xx.	.0x-	.0x+	.0x	.x+	-	.x+	.000x	.00x-	.000x	.00x+	.x	.000x+	.00x+	-	.000x-	.00x-	-	-	.0x-	.00x	.000x+	.x+	.00x	.024	.013
CK-87	Do.	.5	do.	xx.	x.-	xx.	.0x-	.0x+	.x-	x.	.0x+	x.-	.000x-	.00x+	.000x+	.00x	.x	.00x-	.00x+	-	.00x-	.0x-	-	.000x-	.00x	.00x+	.000x+	.x	.00x	.046	.026
CK-88	Do.	.9	do.	xx.	x.	xx.	.0x	.0x+	.0x+	.x-	.x+	x.-	.000x-	.0x	.000x+	.00x	.x-	.00x-	.0x	.00x		.0x+	-	.00x	Tr.	.00x+	.000x+	.x	.0x-	.48	.046

^{1/} All are chip samples.^{2/} Determined by radiometric analysis (S. Furman and R. Dufour).^{3/} Determined by chemical analysis (J. Wahlbert).

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.

Analyst: A. T. Myers

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 ore minerals--mainly pyrite, sphalerite, and chalcopyrite--in the skarn were broken into tiny fragments to form a microbreccia texture. (See 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. 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 and in the boxwork pyrite ore.

Age and origin

Age 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 by the two methods 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 district when similarly corrected and shows that the uranium deposition in both areas was contemporaneous within those limits. The details of these determinations are presented by Phair and Sims (in preparation).

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 modified some 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. Where breccia fragments were incorporated, the fracture zone was particularly open.

Possibly, deposition of the uranium was related in some manner 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). 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 surrounding 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 essentially 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. (See page 41.) During Laramide times 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. 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 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-level. The absence of colored secondary uranium minerals probably is due to acid mine waters (Phair and Levine, 1953, p. 367).

The ore-forming solutions possibly did not exceed a temperature of $135^{\circ}C$ and may have been acid. The pyrite in the Copper King vein is anisotropic. According to Smith (1942, p. 13) anisotropic pyrite, which is sulfur-deficient, forms below a critical temperature between room temperature and $135^{\circ}C$. If these data hold, the pitchblende and associated vein minerals formed at a temperature below $135^{\circ}C$. The presence of marcasite with the pitchblende suggests, if the marcasite is a hypogene mineral, that the pitchblende formed in an acid environment and at low temperatures (Buerger, 1934).

The hypogene uranium-bearing solutions probably were derived from a magmatic source. A source for such solutions 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" fault and "B" fault

The gouge in "A" fault and "B" fault 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 5.

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. Without exception, the analyses indicate disequilibrium--there is insufficient uranium to account for the radioactivity. Analyses of a 4-foot chip sample collected from "A" fault in the southwest corner of the main shaft at the sill of the 110-level indicate that the deficiency in uranium can be largely accounted for by radium and other disintegration products of uranium, as shown in the following table.

Field number	Equivalent uranium		Radium Radon Pb^{210}		
	(percent)	Uranium	(10^{-9} curies/gm)		
CK-92	0.050	0.007	0.32	0.25	0.28

Analysts: S. Furman, J. Rosholt, and J. Wahlberg, U. S. Geological Survey, Denver, Colorado.

Wall rock alteration

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 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-levels (fig. 3), the granite is cut by abundant pitchblende-bearing fractures and is altered to a soft, crumbly rock. 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 $1.59 \pm .01$; 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.

Spectrographic analyses of the altered granite and fresh granite are given in table 5. The analyses indicate that the principal change accompanying the alteration was the addition of U, Co, Nd, Sm, Yb, Mo, and locally Zn to the rock. The other elements common to both altered and fresh granite quantitatively show little variation.

Table 5.--Semi-quantitative spectrographic analyses of granite wall rocks, Copper King mine.

(All analyses by U. S. Geological Survey Denver Laboratory)

Field Number	Type of Material	Location	Si	Al	Fe	Ti	Mn	Ca	Mg	Na	K	Ba	Be	Ce	Cr	Cu	Ga	La	Mo	Pb	Sc	Sn	Sr	V	Y	Zn	Zr	U	Equivalent Uranium ^{1/}	U ^{2/}	Co	Nd	Sm	Yb	
D-2	Fresh granite.	Surface.	xx.	x.+	x.-	.0x+	.0x-	x.-	.x-	x.-	x.-	.0x+	.00x-	.00x	.000x	.000x-	.00x-	.00x	-	.00x	.000x	-	.0x-	.00x-	.00x+	-	.0x-	-	-	-	-	-	-	-	-
UG-40	Do.	70-foot level.	xx.	x.+	x.-	.0x+	.0x-	x.-	.x-	x.-	.x+	.0x-	.00x-	-	.000x-	.000x+	.00x-	-	-	.00x-	.000x	-	.00x+	.00x-	.00x-	-	.0x-	-	-	-	-	-	-	-	-
UG-66	Altered granite.	110-foot level.	xx.	x.+	x.-	.x-	.0x-	.x	.x-	x.-	x.-	.x-	.000x	.0x-	.000x	.000x	.00x-	.0x-	.00x-	.0x-	.000x	.00x-	.0x-	.00x-	.00x	.0x	.0x-	-	-	-	-	-	-	-	-
UG-67	Fresh(?) granite.	do.	xx.	x.+	x.-	.x-	.0x-	.x+	.x-	x.-	x.-	.0x	.000x	.00x	.000x	.00x-	.00x-	.00x	-	.0x-	.000x	.00x-	.0x-	.00x-	.00x	-	.0x-	-	-	-	-	-	-	-	-
CK-50	Altered, green granite containing pitchblende seams.	Slope below 110-level.	xx.	x.+	x.+	.x-	.0x-	.x	.x-	.x+	x.	.0x	.000x+	.0x+	.000x	.00x-	.000x	.0x	.0x	.0x-	.000x	.000x	.00x+	.000x+	.0x-	-	.0x-	x.-	2.3	3.86	.00x	.0x	.0x	.00x-	
CK-51	Altered, gray granite containing pitchblende seams.	do.	xx.	x.+	x.	.x-	.x-	.x	.x-	x.-	x.	.0x	.000x	-	.000x	.00x-	.000x	.00x-	.x-	.00x+	.000x	.000x	.00x+	.000x+	.00x	-	.0x-	.x	.30	.43	.000x+	-	-	.000x+	
CK-52	Altered, greenish-gray granite containing pitchblende seams.	do	xx.	x.+	x.+	.x-	.0x+	.x	.00x+	.x+	x.	.0x	.000x	-	.000x	.00x-	.000x	.00x	.0x+	.00x+	.000x	.000x	.00x+	.000x+	.00x	-	.0x-	.x	.36	.48	.00x-	-	-	.000x+	

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.

(+) near top of bracket; (-) near bottom of bracket.

^{1/} Determined by radiometric analysis (S. Furman).

^{2/} Determined by chemical analysis (Mountjoy).

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

Results of exploration

To explore for an extension of the Copper King ore body, the AEC 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 3,001 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 encountered, pitchblende-carbonate veinlets were intersected in hole BH-8 (fig. 4), 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 two-foot width; the veinlets represent an extension of the uranium mineralization encountered near the face of the 140-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 AEC 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 contoured on an isorad map (Derzay and Baker, 1953); no anomalies other than the 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 Manhattan. Exposures of porphyritic intrusives 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.

LITERATURE CITED

- Adams, F. D., 1909, On the origin of the amphibolites of the Laurentian area of Canada: *Jour. Geology*, v. 17, p. 1-18.
- Adams, J. W., Gude, A. J., 3rd, and Beroni, E. P., 1953, Uranium occurrences in the Golden Gate canyon and Ralston Creek areas, Jefferson County, Colorado: *U. S. Geol. Survey Circ.* 320.
- Alling, H. L., 1938, Plutonic perthites: *Jour. Geology*, v. 46, p. 142-165.
- Brooker, E. J., and Nuffield, E. W., 1952, Studies of radioactive compounds: IV-Pitchblende from Lake Athabaska, Canada: *Am. Mineralogist*, v. 37, p. 363-385.
- Buerger, M. J., 1934, The pyrite-marcasite relation: *Am. Mineralogist*, v. 19, p. 37-62.
- Dodge, T. A., 1942, Amphibolites of the Lead area, northern Black Hills, S. Dak.: *Geol. Soc. America Bull.*, v. 53, p. 561-583.
- Edwards, A. B., 1947, Textures of the ore minerals and their significance: Melbourne, Australasian Inst. Min. and Metallurgy (Inc.).
- Eskola, Pentti, 1914, On the petrology of the Orijärvi region in southwestern Finland: *Comm. geol. Finlande*, Bull. 40.
- Eskola, Pentti, 1939, *in* Barth, T. F. W., Correns, C. W., and Eskola, P., *Die Entstehung der Gesteine*, Springer, Berlin.
- Geijer, Per, 1917, Falutraktens berggrund och malmfyndigheter: *Sveriges geol. undersökning, ser. C.* no. 275 (German summary, p. 296-316.)
- Holmes, Arthur, 1920, *The nomenclature of petrology*; Thomas Murby and Company, London.
- Johannsen, Albert, 1939, *A descriptive petrography of the igneous rocks*, v. 1, Introduction, textures, classification, and glossary, 2d ed.: Univ. Chicago Press.
- Knopf, Adolph, 1933, Pyrometasomatic deposits, *in* *Ore deposits of the Western States*, (Lindgren volume), *Am. Inst. Min. Met. Eng.*, p. 537-577.
- Lindgren, Waldemar, 1933, *Mineral deposits*, 4th ed.; McGraw-Hill Publishing Co.
- Lovering, T. S., and Goddard, E. N., 1950, *Geology and ore deposits of the Front Range, Colorado*: U. S. Geol. Survey Prof. Paper 223.
- Magnusson, N. H., 1940, Ljusnarsbergs malmtrakt, berggrund och malmfyndigheter: *Sveriges geol. undersökning ser. Ca.* no. 30, Summary: *Geology and ore deposits of Ljusnarsberg*, p. 180-188.
- _____, 1950, Zinc and lead deposits of central Sweden: Part VII, The geology, paragenesis and reserves of the ores of zinc and lead, XVIII Int. Geol. Congress, London, p. 371-379.
- _____, v. 39
- Murphy, Richard, 1946, *Geology and mineralogy at Eldorado mine*: *Can. Inst. Min. Met. Bull.*, p. 426-435., and *Can. Inst. Min. Met. Trans.*, v. 49, p. 426-435.

- Phair, George, and Levine, Harry, 1953, Notes on the differential leaching of uranium, radium, and lead from pitchblende in H_2SO_4 solutions: *Econ. Geology*, v. 48, p. 358-369.
- Phair, George, and Sims, P. K., 1954, The paragenesis and age of the uranium minerals in the Copper King mine, Larimer County, Colorado (abs.): *Geol. Soc. America Bull.*, v. 65, p. 1385.
- Ray, L. L., 1940, Glacial chronology of the Southern Rocky Mountains: *Geol. Soc. America Bull.*, v. 51, p. 1851-1918.
- Robinson, S. C., 1952, The occurrence of uranium in the Lake Athabasca region: *Can. Min. Met. Bull.*, v. 45, no. 480, p. 203-207.
- Schwartz, G. M., 1951, Classification and definitions of textures and mineral structures in ores: *Econ. Geology*, v. 46, p. 578-591.
- Sims, P. K., 1953, Geology of the Dover magnetite district, Morris County, New Jersey: *U. S. Geol. Survey Bull.* 982-G, p. 245-305.
- Sims, P. K., and Leonard, B. F., 1952, Geology of the Andover mining district, Sussex County, New Jersey: *New Jersey Dept. Conservation and Econ. Development, Bull.* 62, Geol. series.
- Sims, P. K., and Phair, George, 1952, Geology of the Copper King mine area, Prairie Divide, Larimer County, Colorado: *U. S. Geol. Survey TEI-311, U. S. Atomic Energy Comm., Tech. Inf. Serv.*, 44 p.
- Smith, F. Gordon, 1942, Variation in the properties of pyrite: *Am. Mineralogist*, v. 27, p. 1-19.
- Steven, T. A., Metamorphism and the origin of the granitic rocks in the Northgate district, Colorado: *U. S. Geol. Survey Prof. Paper* in preparation.
- Sundius, N., 1935, On the origin of late magmatic solutions containing magnesia, iron, and silica: *Sveriges geol. underSökning, Ser. C*, no. 392.
- Turner, F. J., 1948, Mineralogical and structural evolution of the metamorphic rocks: *Geol. Soc. America Mem.* 30.

UNPUBLISHED REPORTS

- Derzay, R. C., and Baker, K. E., 1953, Results of exploration at the Copper King mine, Larimer County, Colorado: *U. S. Atomic Energy Comm., Tech. Inf. Serv., R.M.E.* 4018.
- Granger, H. C., and King, R. U., 1951, Uranium in the Copper King mine, Blackhawk No. 1 claim, Larimer County, Colorado: *U. S. Geol. Survey Trace Elements Memo, Rept.* 128-A.
- Leonard, B. F., III, 1951, Magnetite deposits of the St. Lawrence County district, New York: Ph.D. dissertation, Princeton Univ.