

Geology and Sulfide Mineralogy of the Number One Orebody, Ruby Creek Copper Deposit, Alaska

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Abstract

The Number One orebody is the largest and most sulfide-rich ore zone (at least 200,000 tons containing 8.4 wt % Cu) at the Ruby Creek copper deposit, in the southwestern Brooks Range of Alaska. Pyrite and copper-bearing sulfide minerals are concentrated within the matrix of a dolostone breccia body, which is enclosed by phyllite and calcic marble of Middle to Late Devonian age. The Number One orebody has three mineralogical zones that grade into each other: (1) an outer zone, widest toward the hanging wall, containing mostly pyrite with minor amounts of chalcopyrite and traces of carrollite and sphalerite; (2) an intermediate zone containing major chalcopyrite and pyrite, minor tennantite-tetrahedrite, bornite, carrollite, and sphalerite, and traces of galena; and (3) a core zone containing major bornite, chalcopyrite, pyrite, and chalcocite, minor carrollite, digenite, and sphalerite, and traces of galena, covellite, and the germanium-bearing sulfides renierite and germanite. Small clots of anthracitelike organic material (anthraxolite) are found throughout the ore. Much of the pyrite is fine grained and was deposited before the other sulfides, being increasingly replaced by Cu-bearing sulfides from the outer zone to the core. Some of this pyrite recrystallized into coarser grains having cobaltiferous rims, and these grains were generally not replaced. The sulfide minerals are commonly pseudomorphous after lath-shaped crystals within the dolomite clasts; no unreplaced examples were found, though the crystals closely resemble those of marcasite. The abundant fine-grained, porous pyrite also may represent replacement of marcasite. The origin and timing of brecciation and ore deposition remain unknown, though dolomitization and ore deposition appear to have occurred in preexisting carbonate breccia. Close mineralogical and geologic similarities are noted with the Kipushi Cu-Zn-Pb deposit in Zaire and with several other carbonate-hosted copper-rich organic-bearing deposits. The common concentration of the rare metals Co, Ge, and Ga in these structurally and mineralogically complex ores should increase their economic attractiveness.

Introduction

THE Ruby Creek copper deposit, in the southwestern Brooks Range of Alaska, consists of sulfide-rich dolostone breccia zones within Middle Devonian back-reef facies carbonate rocks. The ore consists predominantly of copper-rich sulfide minerals partly replacing earlier fine-grained pyrite. Sulfides containing Zn, Co, Pb, As, Sb, or Ge are present in minor to trace quantities. Anthracitelike organic material (anthraxolite) is found sporadically distributed throughout the ore. Brecciation, apparently of more than one generation and at scales ranging from millimeters to meters, greatly complicates zonal relations of the minerals.

The deposit was investigated by Runnells (1963, 1969), who reported the results of geologic, mineralogical, and sulfur isotope studies. More recently, Hitzman et al. (1982) and Hitzman (1983, 1986) described the geology of the deposit and surrounding areas in considerable detail; this material will not be

repeated here. Hitzman (1983, 1986) also provided a reinterpretation of Runnells' sulfur isotope data, detailed analyses of anthraxolite and other organic matter, an hypothesis concerning the genesis of the deposit, and analogies to other deposits.

This report describes the geometry, internal structure, and sulfide mineralogy of the largest and most sulfide-rich orebody at Ruby Creek, the Number One orebody. The surface exposure at the Berg Camp area, in the western part of the Ruby Creek deposit, is also described. The sequence of crystallization and implications to the genesis of the ore are then discussed.

Location and Description of Workings

The Ruby Creek deposit is located about 24 km north of Kobuk village in the Cosmos Hills, Alaska (67°05'00" N, 156°56'40" W), about 350 km northwest of Fairbanks. Copper-bearing sulfide mineralization crops out at the original discovery site at Berg Camp and is also encountered in numerous drill holes within an area of about 1.5 km² (Fig. 1). In these sites, grades of 1 to 3 wt percent Cu are common, with chalcopyrite generally being the predominant copper mineral. In a few drill holes, mainly within

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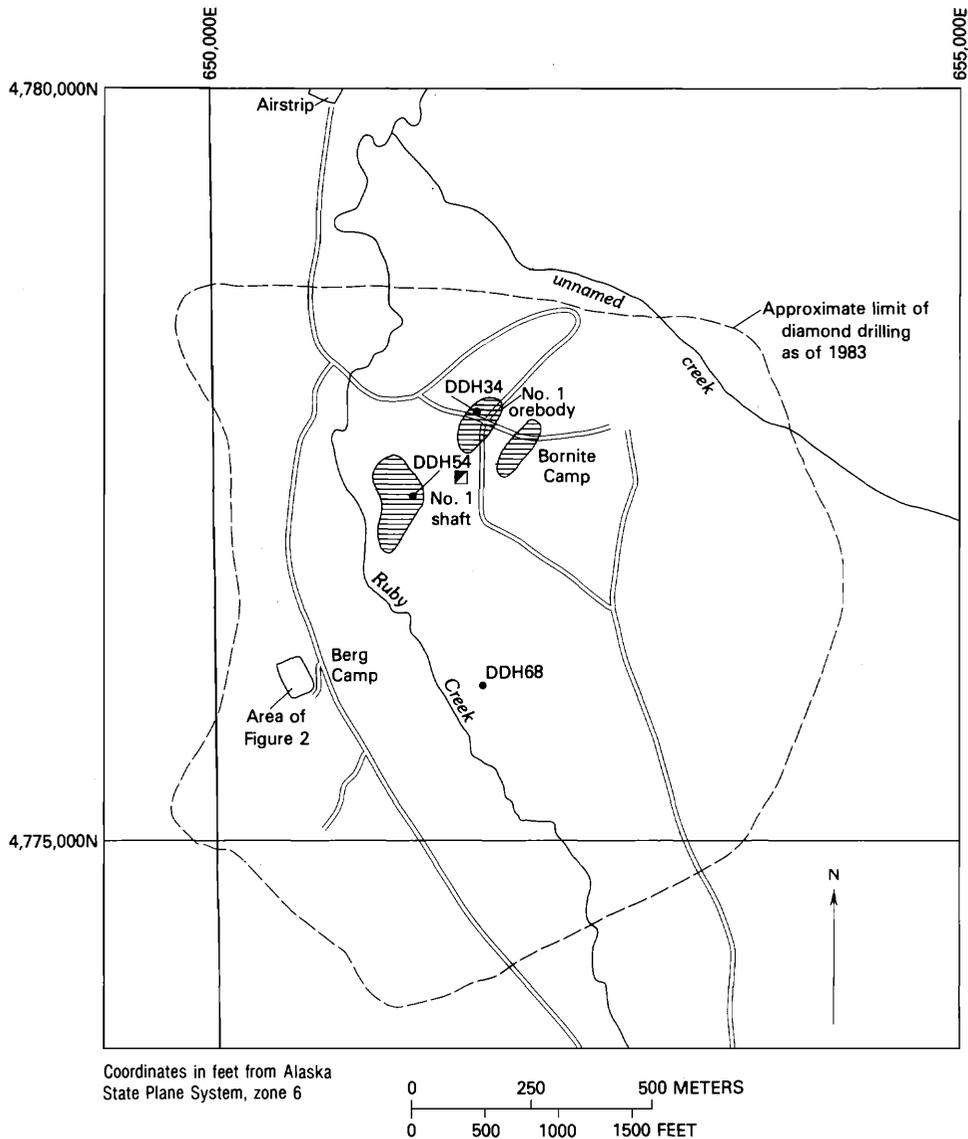


FIG. 1. Location map of the Ruby Creek area. Shaded areas show the approximate subsurface limits of bornite-chalcocite mineralization as indicated by diamond drilling.

the shaded areas shown in Figure 1, bornite-chalcocite ore occurs that has higher Cu grades.

In 1965 the Kennecott Corporation sank a shaft to investigate a large high-grade ore zone encountered in the drill holes, which became known as the Number One orebody. (In this report, we refer to this high-grade zone as the "orebody" for simplicity. We do not imply that this zone everywhere necessarily meets any particular economic definition of ore.) A north-trending crosscut at the 975-ft (300 m) level, as well as underground drilling, served to outline the dimensions of the orebody. The orebody contains a minimum of 200,000 short tons of chalcopyrite, bornite, and chalcocite ore with an average grade of about 8.4

wt percent Cu (C. T. Penney, unpub. Kennecott Corp. report, 1968).

Methods

Surface exposures at Ruby Creek, including Berg Camp, were examined in 1979, 1980, and 1981. Underground areas could not be examined due to flooding that occurred in 1967. Approximately 12,000 ft (3,700 m) of Ax diamond drill core that penetrated the Number One orebody and adjacent areas was logged and sampled. From these data, cross sections were constructed that were subsequently used to produce geologic plans at levels 980, 1000, and 1020.

From the drill cores, 177 polished sections were

prepared. These sections were observed microscopically in reflected and transmitted light; minerals and textures were identified and recorded and the proportions of the sulfide minerals were estimated. Approximately 20 polished sections were examined on a Cambridge Stereoscan scanning electron microscope (SEM) equipped with an energy dispersive X-ray elemental analyzer at the U. S. Geological Survey in Menlo Park, California. The latter work assisted in mineral identification and in determining the distribution of elements within mineral grains. Approximately 15 polished sections were analyzed on an ARL-SEMQ electron microprobe at the U. S. Geological Survey in Menlo Park; the operating conditions and standards are given in Tables 2 and 3, below. Powder X-ray diffraction was used to identify several minerals. Semiquantitative emission spectroscopy was performed by Chris Heropoulos of the U. S. Geological Survey in Menlo Park on several hand-picked sulfide, carbonate, and anthraxolite samples of about 50 mg each. Additional types of data were collected on renierite from this deposit; these are presented by Bernstein (1986b).

Geology

Copper deposits at Ruby Creek lie within the Bornite Carbonate sequence of Hitzman (1983), a 1,000-m-thick unit of Middle Devonian age composed of marble, dolostone, and minor graphitic to calcareous phyllites. These rocks were metamorphosed to greenschist facies during the Cretaceous, with the marble and phyllite being penetratively deformed. The dolostone acted competently during deformation and blocks of dolostone up to several hundreds of meters in size are now enclosed in marble and phyllite. The origin of breccia in the ore-bearing zones is not clear; brecciation is, however, clearly older than most sulfide mineralization and appears younger than some dolomitization and the formation of some sparry dolomite.

Berg Camp area

The Berg Camp area provides a surficial exposure of mineralized dolostone breccia very similar to that found underground in the Number One orebody. At Berg Camp, a body of dolostone breccia 46 m wide has been scraped clean of vegetation and soil and has been cut by trenches. The breccia is bounded on the southeast by foliated marble and on the northwest by a thin phyllite layer and dark carbonaceous marble. Drilling (holes RC20, RC28, and RC157) indicates that the breccia body is a thin wedge whose lower contact lies 5 to 21 m below the surface, dipping gently to the southeast. A geologic map of part of this exposure (Fig. 2) shows the locations of the larger breccia clasts, which range in size from 50 cm to greater than 4 m. The clasts consist of light gray, tan-

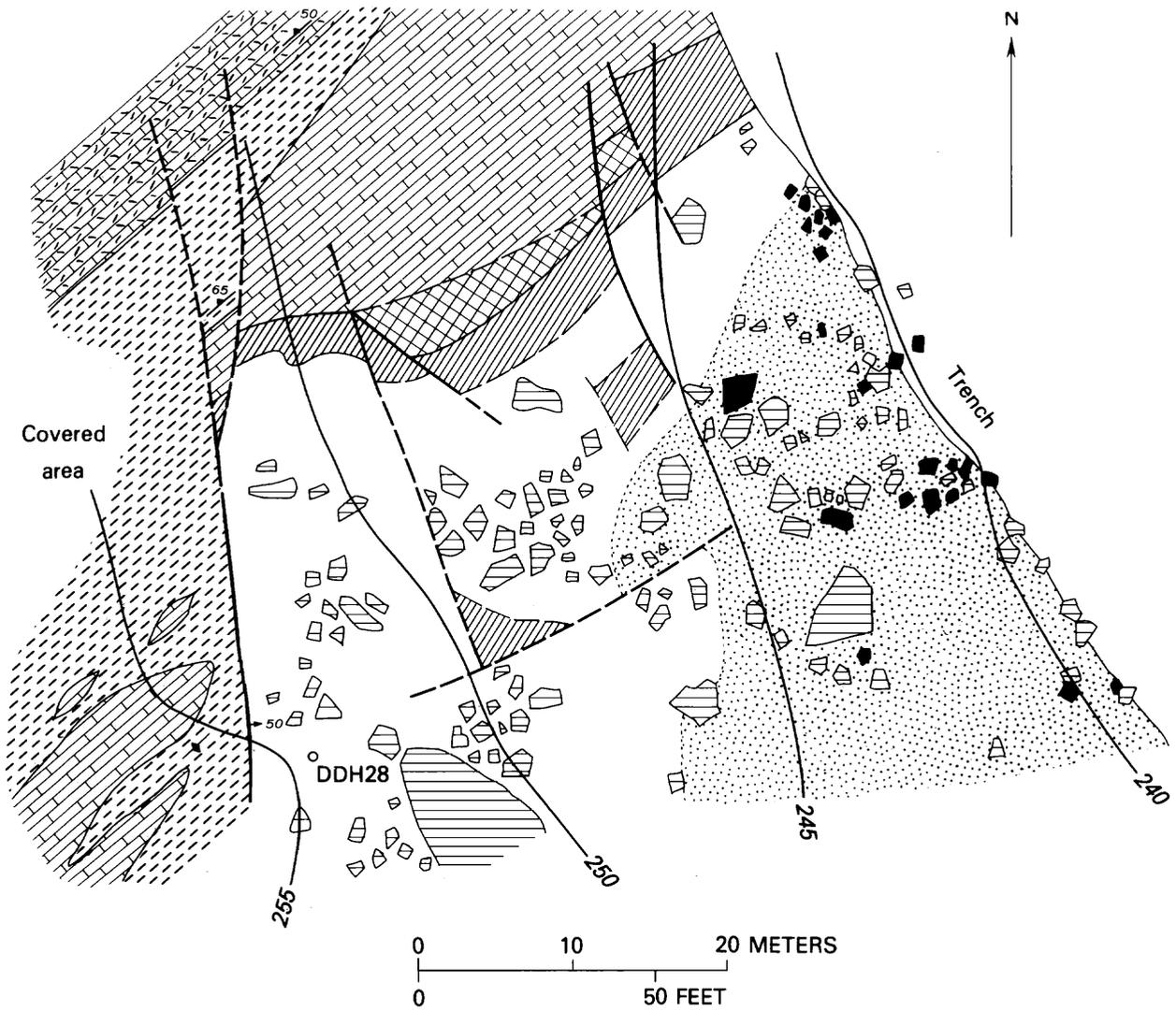
weathering dolostone and less abundant dark gray, fenestral, fossiliferous dolostone. These resemble Hitzman's (1983, 1986) hydrothermal and diagenetic dolostones (A and B), respectively. The light gray dolostone is cut by numerous sparry dolomite veins that terminate at the edges of clasts (Fig. 3). Most clasts range from 3 to 10 cm across, with clasts larger than 50 cm across constituting 18 percent of the mapped area. Calculations show that in any linear measure through the breccia, such as a diamond drill core, over 50 percent of the sample would likely be in clasts 1 to 3.3 m across.

The matrix of the breccia at Berg Camp is partly weathered, making its detailed composition difficult to determine. In the northwest part of the exposure, the matrix is composed of fine-grained to sparry dolomite that shows little contrast with the dolostone clasts. Within this area, breccia clasts are locally surrounded by areas of red-brown soil that is probably derived from the weathering of pyritic, iron-rich dolomitic matrix material. A continuous band of this soil lies between the breccia and the adjacent phyllite. To the southeast and south, pyrite is increasingly abundant in the matrix, giving the breccia a darker color (Fig. 4). Chalcopyrite and bornite are also increasingly abundant in the matrix to the southeast. Some white sparry dolomite veins cut the matrix in places.

A gamma-ray scintillometer was used to measure radioactivity in the area of Figure 2, to search for the presence of pitchblende or other uranium minerals noted by Runnells (1969). Radiation levels of three to ten times the background level were found to correspond to the areas of red-brown soil noted above. No correlation was found between radioactivity and copper-bearing sulfide mineralization.

Number One orebody

The Number One orebody lies in the lower 11 to 17 m of a mass of dolostone breccia that reaches a maximum thickness of about 75 m. The breccia clasts consist mainly of dark gray fenestral and locally fossiliferous dolostone and light gray featureless dolostone. The dark and light gray clasts correspond to the diagenetic dolostone and hydrothermal dolostone of Hitzman (1983, 1986). Clasts of marble and marble interlayered with dark gray phyllite are locally present, mainly in drill holes U38, U45, and U55. The breccia is matrix supported with subangular to subrounded clasts ranging widely in size. Drill cores record many intercepts of monolithologic dolostone 1 to 3 m long that are interpreted as large breccia clasts, indicating that the breccia hosting the Number One orebody has a clast size distribution similar to that of breccia mapped at the Berg Camp area. The breccia matrix is composed of fine-grained dolomite and abundant fine-grained, commonly colloform pyrite.



EXPLANATION

Bornite Carbonate Sequence (Middle Devonian)

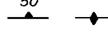
Lithologies:

-  Black phyllite
-  Dark gray marble
-  Tan phyllite
-  Light gray foliated marble
-  Red-brown limonitic soil

Breccia

-  Dolomite matrix (white)
-  Sulfide matrix (stippled)
-  Light gray dolomite clasts (lined)
-  Dark gray dolomite clasts (black)

Structures:

-  Contact, dashed where inferred
-  Fault, with dip, dashed where inferred
-  Strike and dip of inclined and vertical foliation

Drill hole:

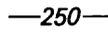
-  DDH28
-  —250— Contour line, elevation in meters

FIG. 2. Geologic map of cleared area near Berg Camp, showing breccia clasts greater than 50 cm across.



FIG. 3. Large dolomite clast in breccia showing sparry dolomite veins, Berg Camp area. White square is 5 cm on edge.

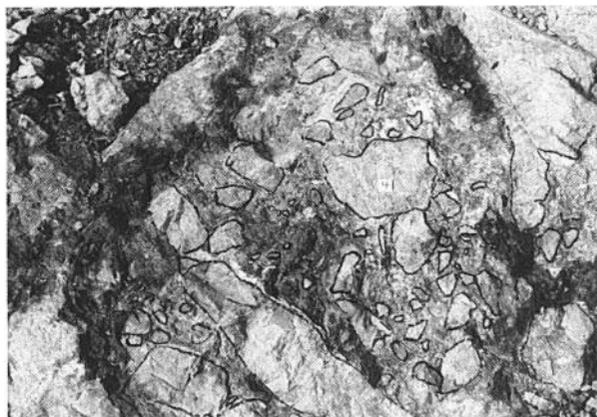


FIG. 4. Breccia with pyrite-chalcopyrite matrix, Berg Camp area. Note sparry dolomite veins within clasts, and later dolomite-calcite veins within the matrix. Clasts are outlined in ink. White square is 5 cm on edge.

The matrix is cut by one or more stages of white dolomite veins and scarce quartz veins. Copper-bearing sulfide minerals occur in the matrix, partly replacing pyrite and locally the dolostone clasts.

The orebody is underlain by dark gray to black phyllite, here referred to as the footwall phyllite, that contains disseminated pyrite and pyrrhotite and scarce clasts of marble and dolostone. As far as can be discerned from drill core examination, the contact between the mineralized breccia and phyllite is sheared and abrupt in most places, but in a few areas on the northwest side of the orebody (drill holes U41, U46, and U48) and on the south side (drill hole U35) the contact is gradational over a few tens of centimeters. The matrix of the dolostone breccia typically grades into black unfoliated argillite near the contact. Beyond the contact, there are few dolostone clasts and the argillite grades into phyllite. The phyllite cleavage locally wraps around dolostone clasts near the contact. Subangular fragments of fine-grained pyrite resembling the pyritic breccia matrix are found along with clasts of dolostone and calcitic marble in the argillite-phyllite matrix. These observations suggest that soft sediment mixing preceded metamorphic deformation and that soft sediment slumping occurred at some time after the breccia matrix was filled by pyrite. The available drill hole data were insufficient to work out the relation between copper mineralization and this early deformation.

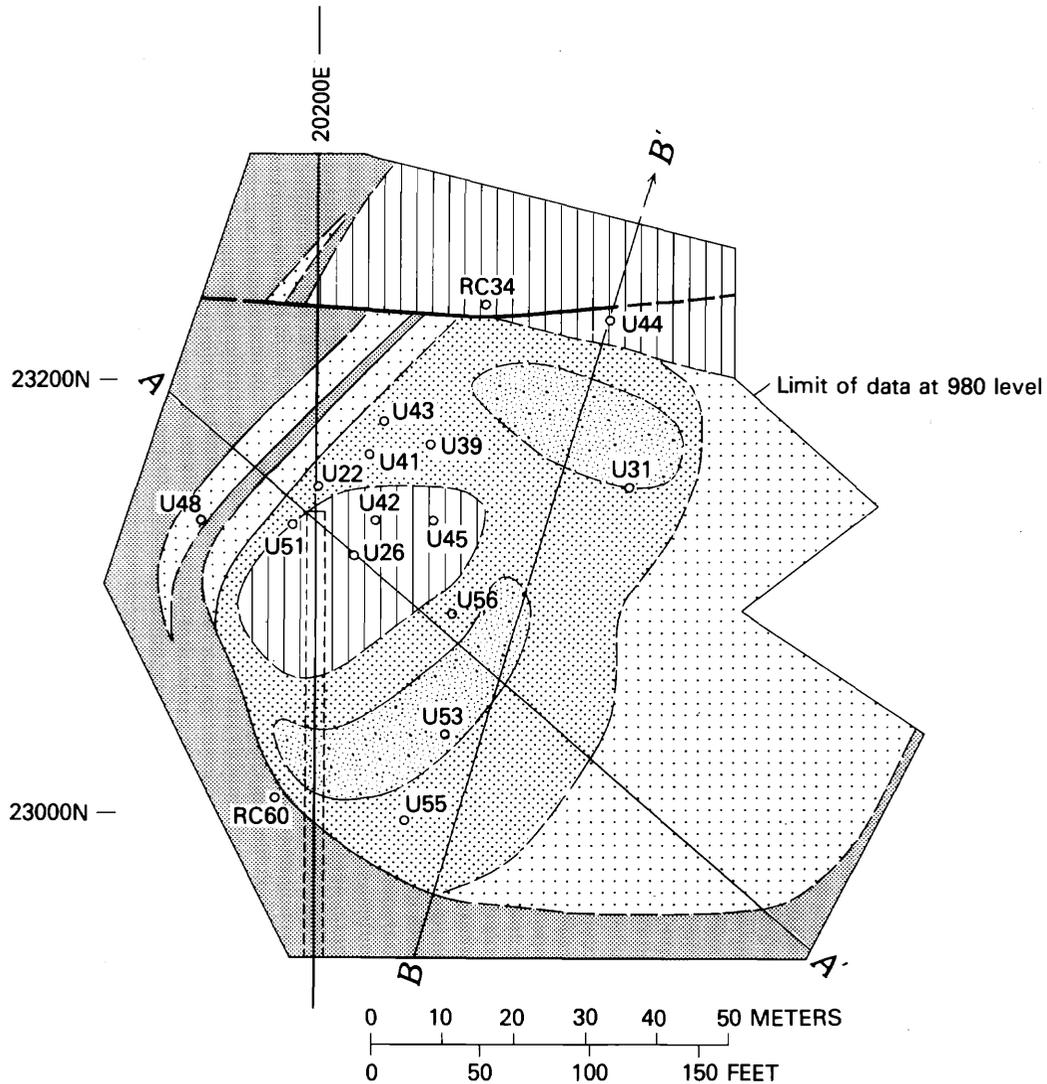
The footwall phyllite extends about 75 m vertically below the orebody, where it is in sharp contact with another body of pyritic dolostone breccia. The upper contact of the footwall phyllite with dolostone breccia is the best stratigraphic marker in the Number One area. The only recognizable horizon within the dolostone breccia is the top of the basal sulfide-rich zone. As a result, correlation of observations among drill holes suffers from a high degree of subjectivity; the

maps and sections presented here should be considered as partly speculative.

The footwall phyllite contact shown in Figure 5B has an asymmetrical spoon shape with a steep dip on the west side and a gentle plunge to the northeast. The north end of the orebody and the underlying phyllite are displaced downward 15 m along an inferred vertical east-west-striking fault (Fig. 5B). The Number One orebody appears to lie wholly within this spoon-shaped depression, although drilling has not defined its extreme east side. The orebody has a length of 137 m in a N 30° E direction, a width of 45 to 58 m, and a thickness ranging from about 11 m at the south end to 17 m at the north end. Boundaries of the orebody appear to be abrupt on the west side and gradational to the east. Near the crosscut (Fig. 5B), the orebody thins abruptly, with chalcopyrite ore grading into dolomite matrix breccia over a few meters. To the east and north chalcopyrite replacement of pyrite matrix diminishes and the Cu-rich ore becomes a breccia with pyrite matrix. The outermost extent of the pyritic breccia was not intercepted by drilling. The upper contact grades over a few meters from chalcopyrite-rich matrix to dolomite matrix breccia.

Distribution of Sulfide Minerals within the Number One Orebody

Sulfide minerals in the Number One orebody are concentrated in the matrix of gray dolostone breccia. They are commonly accompanied by white dolomite or calcite, particularly toward the core of the orebody, together with minor amounts of anthraxolite, quartz, and locally fluorite. Some sulfides (pyrite, chalcopyrite, bornite, chalcocite, and carrollite) are also found in smaller amounts disseminated as fine anhedral grains (generally 10–200 μm) in the dolostone clasts,



EXPLANATION

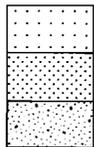
Bomite Carbonate Sequence (Middle Devonian)

Lithologies:



Dolomite matrix breccia

Sulfide matrix breccia (orebody):



Outer zone (>85%* pyrite)

Intermediate zone (>15% chalcopyrite, <15% bornite)

Core zone (>15% bornite)



Phyllite

Structures:

— Contact, dashed where inferred

— Fault, dashed where inferred

Mine workings:

— o Drill holes

□ — Crosscut, dashed where projected from 975 level

* Relative to total sulfides

FIG. 5A. Geologic plan of the 980 level, Number One orebody showing distribution of ore zones and overlying dolomite matrix breccia. Coordinates from the Kennecott Corporation.

apparently filling preexisting pores. Pyrite, chalcopyrite, bornite, and chalcocite also are commonly found in dolomite clasts as pseudomorphs after lath-shaped crystals, commonly with chisellike terminations, of an unknown mineral about 20 to 150 μm long and 3 to 20 μm wide (Fig. 6). These typically occur concentrated within layers a few millimeters wide. Runnells (1969) suggested that the replaced mineral was cymrite (micaceous $\text{BaAl}_2\text{Si}_2(\text{O},\text{OH})_8 \cdot 2\text{H}_2\text{O}$), whereas Hitzman (1986) suggests it was cymrite replacing barite. We note that this habit is similar to that commonly displayed by marcasite (Murowchick and Barnes, 1984; Bernstein, 1986a).

Zoning

The Number One orebody does not display sharp mineralogical or textural zonation but rather varies gradationally in sulfide mineralogy from margin to core; pyrite is predominant at the lateral margins, with increasingly copper-rich phases becoming abundant inward. The order of first appearance of the sulfides from margin to core is: pyrite, chalcopyrite-carrollite-sphalerite-tennantite, bornite-galena-renierite-germanite, and chalcocite-digenite. The general distribution of sulfide minerals in the orebody is shown in Figure 5A and B and Table 1. It is noted that the zonation is only an average feature, with many disruptions to the general pattern occurring on a scale

of a few centimeters. Observations of sulfide distribution patterns are complicated by the presence throughout the ore of irregular dolostone blocks up to several meters across.

For descriptive purposes in this report, the orebody is divided into three broad zones: (1) an outer pyrite-rich zone containing 85 to 100 percent pyrite (relative to total sulfides), 0 to 15 percent chalcopyrite, and minor carrollite and sphalerite; (2) an intermediate zone containing 15 to 100 percent chalcopyrite, 1 to 85 percent pyrite, 0 to 15 percent bornite, with minor tennantite-tetrahedrite, sphalerite, carrollite, and chalcocite; and (3) a core zone containing 15 to 90 percent bornite, 0 to 40 percent chalcocite and digenite, 1 to 60 percent chalcopyrite, 2 to 50 percent pyrite, with minor to trace carrollite, sphalerite, galena, renierite, germanite, and covellite.

Descriptive Mineralogy

Pyrite

Pyrite is ubiquitous in the orebody, commonly being the predominant mineral. Only in small regions of the most copper-rich sections is it scarce. It is most abundant as fine-grained massive material forming the matrix of dolostone breccia, particularly in the outer zone (Fig. 7). In this environment it occurs primarily as anhedral grains a few micrometers across showing

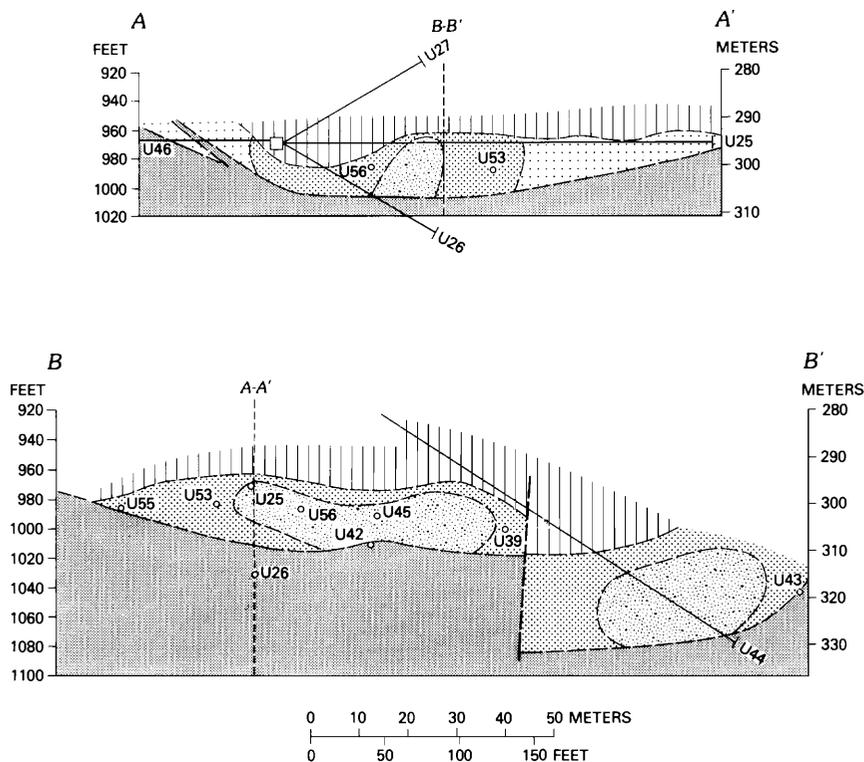


FIG. 5B. Geologic sections through the Number One orebody. Symbols are the same as in Figure 5A.

TABLE 1. Distribution of Sulfide Minerals within the Three Zones at the Number One Orebody, Ruby Creek

Mineral	Abundance of mineral as a percentage of total sulfides		
	Outer zone	Intermediate zone	Core zone
Pyrite	85-100	1- 85	1-50
Carrollite	<1	<1- 5	<1-15
Sphalerite	<1	<1- 3	<1- 3
Chalcopyrite	<1- 15	15-100	1-50
Tennantite		<1- 20	<1
Bornite		<1- 15	15-85
Galena		<1	<1
Renierite			<1
Germanite			<1
Digenite			<1- 5
Chalcocite			1-40
Covellite			<1

all degrees of coalescence with each other. Much of this pyrite has a spongy texture with considerable fine porosity (Fig. 8a). In places, colloform (Fig. 8b) or framboidal textures are present. The anhedral grains locally range up to subhedral or euhedral crystals 0.1 to 2 mm across, the variation in size commonly occurring within a millimeter (Fig. 8c). Many of the coarser grains appear to result from the thorough coalescence of fine grains due to recrystallization. In the intermediate and core zones much of the pyrite is coarser grained (0.01-5 mm), rounded to sharply euhedral, surrounded by Cu-bearing sulfides. Most of the euhedral grains are pyritohedral, with cubes being somewhat more scarce. Commonly, irregular corroded-looking grains (both fine and coarse) occur that appear to be partly replaced by chalcopyrite or bornite. In places, the core of a grain is preferentially replaced, producing an "atoll" structure (Fig. 8d). Pseudomorphs of pyrite after the lath-shaped mineral are locally common throughout the ore, particularly in the intermediate and core zones.

The lath-shaped pseudomorphs (Fig. 6), the spongy, porous habit (Fig. 8a), and colloform textures (Fig. 8b) are all suggestive of preexisting marcasite. Lath-shaped, lozenge-shaped, and cockscomb habits are commonly observed for marcasite. Fine-grained marcasite crystals nearly identical in appearance to those at Ruby Creek were observed (Bernstein, 1986a) at the Apex mine in southwest Utah. Murowchick and Barnes (1984) and J. B. Murowchick (pers. commun., 1985) report that finely porous pyrite is characteristic of replaced marcasite, the porosity resulting from a 2.2 percent volume decrease for the inversion. These authors also report that collomorphic textures are commonly observed in replaced marcasite.

Much of the pyrite is cobaltiferous, generally containing 0.1 to 0.5 wt percent Co (from electron mi-

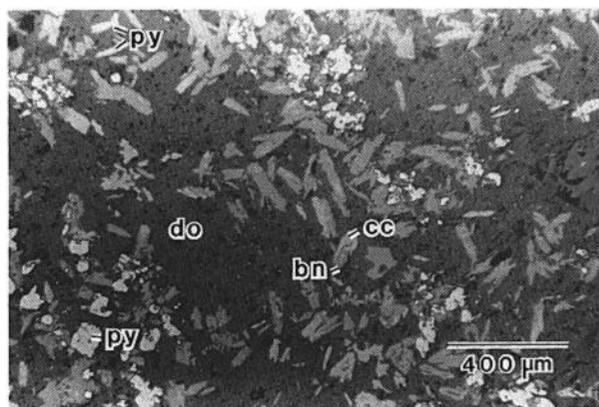


FIG. 6. Pseudomorphs after the lath-shaped mineral. Laths are mostly bornite (bn), intergrown with a little chalcocite (cc), in dolomite (do). Several laths replaced by pyrite (py) are also shown in the upper left. Drill hole RCU53, 31'. Plane polarized reflected light.

croprobe analyses). Emission spectroscopy detected roughly 200 ppm Ni in one sample of coarse pyrite (Table 2), though Ni was not detected in measurable quantities with the electron microprobe (<500 ppm). Traces of Cu (<0.1 wt %) were noted in cobaltian pyrite with the microprobe. Most coarse crystals are zoned, containing more Co toward the rims. Euhedral crystals surrounded by bornite tend to have the most Co (up to 4.3 wt % Co in the rims, 0.2 wt % Co in the center), whereas fine-grained and acicular pyrite crystals generally have less than 0.5 wt percent Co. Pyrite grains near large carrollite grains generally do not have Co-rich rims. The atoll structure mentioned above may result from the preferred replacement of Co-poor core zones in crystals by chalcopyrite and bornite, as suggested by Hitzman (1986). Alternatively, it could have resulted from the accretion of pyrite around a nucleus of another mineral or of organic material, which was later replaced.

Carrollite

Carrollite, Co_2CuS_4 , occurs as silvery anhedral to subhedral grains 0.05 to 1 mm across. It is locally concentrated (up to at least 5 vol % of the rock) in the intermediate and core zones. It occurs both as discrete grains and as overgrowths on subhedral pyrite crystals. In places it appears to be intergrown with chalcopyrite, though it generally appears older than chalcopyrite and bornite based on vein relations. Electron microprobe analysis (Table 3) and powder X-ray diffraction show it to be near end-member carrollite; nickel was not detected with the electron microprobe.

Chalcopyrite

Chalcopyrite is the most abundant copper-bearing sulfide, occurring in all parts of the orebody except

TABLE 2. Semiquantitative Emission Spectrographic Analyses of Some Samples from the Number One Orebody, Ruby Creek

	Bornite	Chalcopyrite	Pyrite	Anthraxolite		Calcite	
	RC34-30	RCU60-3	RCU60-3	RCU23-1	RCU37-28	RCU39-39	RCU39-43
Weight percent							
Al	0.07°	0.005°	—	—	0.005	0.005°	0.02°
Ca	1.0	0.007°	0.1°	0.07	0.01	major	major
Fe	major	major	major	0.01	0.015	0.15	0.15
Mg	1.0°	0.0015°	0.003°	0.005	0.01	0.7	0.7
Na	<0.01	<0.01	0.015°	0.03	<0.01	0.07	0.1
Si	0.1°	0.002°	—	—	0.005	0.005°	0.01°
Parts per million							
Ag	150	3	1	2	<0.2	<0.2	<0.2
Ba	150°	70°	70°	20	30	200	200
Bi	50	<7	<7	<7	<7	<7	<7
Co	15	<1	300	<1	<1	<1	<1
Cu	major	major	1,000°	300	500	30	30
Ge	30°	<7	<7	<7	<7	<7	<7
La	30°	30°	30°	<10	<10	50	50
Mn	300°	<1	15°	3	1	1,500	1,500
Ni	<0.7	<0.7	200	20	20	2	<0.7
Pb	70°	<7	<7	<7	<7	<7	<7
Sn	<2	30	<2	<2	<2	20	20
Sr	15°	<1	7°	<1	<1	700	700
Ti	10	7	15	15	10	10	3
Yb	<0.7	<0.7	<0.7	<0.7	<0.7	5	2
Zn	30°	700°	3°	70	70	<15	<15

* These values are due primarily to admixed minerals; — indicates that the element was not looked for

Elements looked for but not found at the indicated detection limit (ppm): As(150), Au(10), B(2), Be(0.7), Cd(20), Ce(50), Cr(1), Eu(1), Ga(1), Hf(50), In(1.5), K(300), Li(100), Mo(2), Nb(10), Nd(20), P(1,500), Pd(1), Pr(20), Pt(10), Re(7), Sb(20), Sc(0.7), Sm(50), Ta(50), Te(300), Th(150), Tl(3), U(150), V(1), W(10), Y(7), Zr(3)

for some of the marginal areas that contain only pyrite. In the intermediate zone it is commonly the predominant sulfide. It is most common as massive material

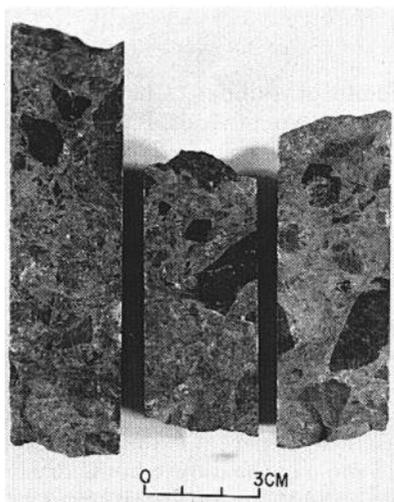


FIG. 7. Drill cores from holes U40 (left and center), and U45 (right) showing dark gray dolostone breccia clasts in a matrix of fine-grained pyrite.

having a grain size of 10 to 300 μm . Pseudomorphs after the lath-shaped mineral are observed in places, as are disseminated anhedral grains 10 to 200 μm across in dolomite. Electron microprobe analysis showed the chalcopyrite to be stoichiometric CuFeS_2 , with no detectable Zn, Ga, In, As, Sb, or Ge.

Tennantite-tetrahedrite

Although absent through most of the Number One orebody, this mineral is locally abundant (up to 15 vol % of the rock) in some chalcopyrite-rich areas. It is rarely found in the bornite-rich core of the orebody. Tennantite-tetrahedrite occurs mainly in veinlets up to several millimeters wide intergrown with chalcopyrite; discrete anhedral grains are also present. Semiquantitative energy-dispersive X-ray analysis in the SEM showed roughly equal amounts of As and Sb, with no Ag, Hg, or Au detected; similar compositions were reported by Runnells (1969) using X-ray fluorescence and emission spectroscopy.

Bornite

Bornite is abundant in the core zone where it forms massive, slightly anisotropic material with a grain size of 10 to 300 μm . It is also found in smaller quantities

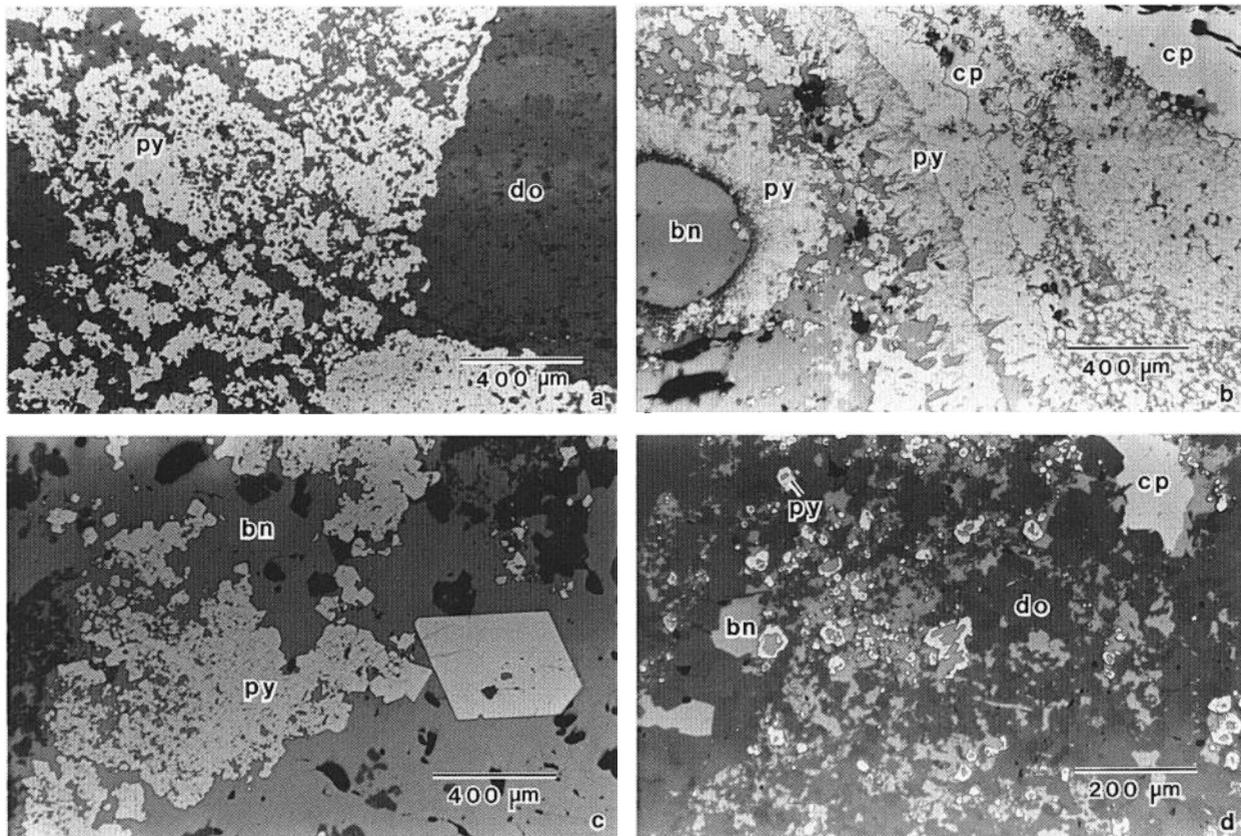


FIG. 8. Some typical habits of pyrite in the Number One orebody. (a). Spongy, fine-grained pyrite (py) with dolomite (do), forming matrix between dolostone breccia clasts (such as that shown in the right of the photo). Drill hole RCU25, 266'. (b). Colloform fine-grained pyrite (py), associated with, and partly replaced by, bornite (bn) and chalcopyrite (cp). Drill hole RCU44, 648'. (c). Pyrite (py) in bornite (bn), showing gradation from anhedral fine-grained to euhedral coarse-grained crystals. Drill hole RC34, 988'. (d). Pyrite (py) showing atoll structures with cores of bornite (bn). Note that the grain in the center shows pseudomorphs after the lath-shaped mineral. A large grain of chalcopyrite (cp) is present in the upper right. Drill hole RC34, 988'. All photographs taken in plane polarized reflected light.

in the intermediate zone as discrete grains and masses 10 to 1,000 μm across. Pseudomorphs after the lath-shaped mineral are common in both zones (Fig. 6), as are disseminated anhedral grains in dolomite 10 to 200 μm across. Electron microprobe analysis shows the bornite to be nearly stoichiometric Cu_5FeS_4 , with a trace of Zn (≈ 0.02 wt %) and no detectable Ga, In, As, Sb, or Ge. Semiquantitative emission spectroscopy (Table 2) found 150 ppm Ag, 50 ppm Bi, 70 ppm Pb, 30 ppm Ge, and other trace elements; many of these are due to inclusions of renierite, galena, and other minerals.

Chalcocite and digenite

These minerals are found only in the Cu-rich core zone, always associated with bornite. Although they are generally subordinate to bornite, they are locally

the predominant sulfides. Chalcocite is the more common of the two minerals. It is distinguished from digenite by its lighter shade of gray. It occurs in several distinct habits: (1) patches in bornite up to several millimeters across; (2) veinlets cutting bornite; (3) reticulated intergrowths in bornite; and (4) pseudomorphs after the lath-shaped mineral. The patches in bornite commonly have a diffuse boundary. In places, chalcocite texturally appears to have replaced bornite, though in other places the reverse relationship apparently occurs. Digenite most commonly occurs as lamellar intergrowths several micrometers wide in chalcocite, in an apparent exsolution texture. It also constitutes some of the diffuse boundary material between bornite and some chalcocite grains. Chalcocite is found to be nearly stoichiometric Cu_2S by electron microprobe analysis, with less than 0.4 wt percent

TABLE 3. Electron Microprobe Analyses of Chalcocite, Digenite, and Carrollite from the Number One Orebody, Ruby Creek

	Chalcocite RCU44-5		Digenite RCU44-5		Carrollite RCU25- 12
	Weight percent				
Cu	80.87	80.88	76.10	76.12	20.37
Fe	0.03	0.00	3.15	2.50	1.72
Co	—	—	—	—	35.80
S	20.54	20.38	21.98	21.76	41.59
Total	101.44	101.26	101.23	100.38	99.48
	Atomic proportions				
	Sum = 3 atoms		Sum = 14 atoms		Sum = 7 atoms
Cu	2.00	2.00	8.64	8.73	1.00
Fe	0.00	0.00	0.41	0.33	0.10
Co	—	—	—	—	1.88
S	1.00	1.00	4.95	4.95	4.02

— indicates that the element was not looked for

Analyses performed on ARL-SEMQ electron microprobe, U.S. Geological Survey, Menlo Park, California

Operating conditions: 15 kV, sample current on brass 15 nA, beam size approximately 1 μ m

Standards: synthetic CuFeS_2 (for Cu, Fe, S); synthetic FeS containing 4.09 weight percent Co (for Co)

Fe. Digenite grains, due to their small size, were difficult to analyze in the microprobe but were found to have a variable iron content up to 3.15 wt percent, and are close to $(\text{Cu, Fe})_9\text{S}_5$ in composition. Representative chemical analyses of chalcocite and digenite are presented in Table 3.

Sphalerite

Sphalerite is irregularly distributed in small amounts in the intermediate and core zones. It occurs as anhedral to subhedral grains, commonly rounded, together with chalcopyrite, pyrite, and bornite. It is locally intergrown with the Cu-bearing sulfides, but generally appears older, in places being rounded and corroded by them. In thin section, sphalerite in the Number One orebody is reddish-brown to red in transmitted light, though color banding within grains is absent. Tiny (<1 μ m) disseminated blebs of chalcopyrite are common in sphalerite grains, probably the result of exsolution. Runnells (1963) reported that emission spectroscopy of sphalerite from drill hole 25, 199 ft (60.7 m), found (in wt %) 4.0 Fe, 0.59 Cd, 0.15 Cu, 0.02 Mn, and 0.008 Co.

Galena

Galena occurs sporadically in small amounts through the intermediate and core zones. It is most

common as small anhedral grains (usually 10–100 μ m), commonly rounded, embedded in bornite. Less commonly it is found as somewhat larger anhedral grains intergrown with chalcopyrite and bornite. Concentrations of galena are commonly associated with anthraxolite.

Renierite and germanite

These germanium-bearing sulfides occur in the core zone as anhedral grains 1 to 75 μ m across, commonly rounded, embedded in bornite or more rarely in chalcocite. Chemical analyses of these minerals are given in Table 4. Zincian renierite, $\text{Cu}_{10}\text{ZnGe}_2\text{Fe}_4\text{S}_{16}$, is the more common. It superficially resembles bornite in relief and color, though it is more orange, does not tarnish in air, is slightly anisotropic, and is somewhat harder. Compositionally, renierite from Ruby Creek is unusual in containing up to 1.1 wt percent Sb, not previously reported in this mineral. Arsenian renierite, $\text{Cu}_{11}\text{GeAsFe}_4\text{S}_{16}$, is less common than zincian renierite, occurring as discrete grains not associated with zincian renierite. It closely resembles zincian renierite though it has a slightly redder color, is slightly harder, and is less anisotropic. Ruby Creek is one of two type localities for arsenian renierite, the other being Jamestown, Colorado. Germanite, $\text{Cu}_{11}\text{Ge}(\text{Cu, Ge, Fe, Zn, W, Mo, As, V})_{4-6}\text{S}_{16}$, is very scarce, being observed in only a few polished sections. It occurs as rounded grains 5 to 20 μ m across rimmed by renierite. In appearance it is similar to renierite but has a duller gray-orange color and is isotropic. The germanite is vanadian, containing up to 3 wt percent V.

Covellite

A few grains of covellite as much as 200 μ m across were observed in several polished sections from the core zone. The mineral is found intergrown with bornite, appearing to be a primary phase.

Isotope Studies

Light stable isotope studies carried out by J. F. Whelan (U. S. Geological Survey) in conjunction with core logging at Ruby Creek were inconclusive and are only briefly described in this report. Whelan (writ. commun., 1981) found $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in calcite and dolomite ranging from 18 to 26 and –1.65 to 1.24 per mil, respectively. In the two vertical drill holes sampled (34 and 38) there is a decrease in $\delta^{18}\text{O}$ from top to bottom, consistent with Hitzman's (1986) model of hydrothermal dolomitization proceeding upward from depth. The light gray dolostone (Hitzman's type A) is isotopically heavier in both carbon and oxygen than the other carbonate phases, and the

TABLE 4. Electron Microprobe Analyses of Germanium-Bearing Sulfides from the Number One Orebody, Ruby Creek

	Zincian renierite RC34-19		Arsenian renierite RCU44-5		Germanite RC34-19	
	Wt percent	Sum = 33 atoms	Wt percent	Sum = 33 atoms	Wt percent	Sum = 33 atoms
Cu	41.12	10.30	43.37	10.81	44.88	11.41
Zn	2.50	0.61	1.25	0.30	5.95	1.47
Ge	7.34	1.61	5.79	1.27	10.86	2.42
W	0.15	0.01	0.24	0.02	0.18	0.02
As	1.09	0.24	3.08	0.65	0.87	0.19
Sb	0.67	0.08	0.18	0.03	0.25	0.03
V	0.07	0.02	0.03	0.02	3.00	0.95
Fe	14.17	4.04	14.17	4.02	1.28	0.37
Ga	0.04	0.02	0.00	0.00	0.09	0.01
S	32.42	16.09	32.20	15.89	31.99	16.13
Total	99.57		100.31		99.25	

Analyses performed on ARL-SEM-Q electron microprobe, U.S. Geological Survey, Menlo Park, California

Operating conditions: 15 kV, sample current on brass 15 nA, beam size approximately 1 μ m

Standards: synthetic crystals as follows: CuFeS₂ (chalcopyrite) for Cu, Fe, S; Zn_{0.6}Fe_{0.4}S (sphalerite) for Zn; GaAs for Ga; Cu₃AsS₄ (enargite) for As; Cu₃SbS₄ (famatinitite) for Sb; and Ge, V, and W metals

Wavelength scans were run and additional elements were not detected

late carbonate veins are the lightest. This suggests that the fluid responsible for dolomitization was a brine and that isotopically light material was leached from the rocks and deposited in the veinlets. Sulfur isotope values for sulfides in dolostone breccia ranged from near zero to -11 per mil $\delta^{34}\text{S}$. Pyrite in associated phyllite layers gave $\delta^{34}\text{S}$ values between 5 and 16 per mil.

Lead isotope compositions (Table 5) were determined by Holly Stein (U. S. Geological Survey) on three galena samples from Ruby Creek. Samples 1 and 2 (Table 5) lie close to the Stacey and Kramers (1975) two-stage model lead evolution curves, having model ages of roughly 280 to 300 m.y. Sample 3, from the ore dump at Ruby Creek, appears high in

^{206}Pb relative to the other samples and to the Stacey-Kramers model curves.

Data for the Arctic Camp, Rammelsberg, and Meggan ore deposits, all of which are in Devonian host rocks, are included for comparison. The Arctic Camp deposit, located 27 km northeast of Ruby Creek, consists of semimassive zones and lenses up to several hundred meters across containing fine-grained sphalerite, chalcopyrite, galena, and pyrite within a Late Devonian volcanoclastic sequence. The Rammelsberg and Meggan deposits, in northeastern West Germany, consist of conformable lenses several hundred meters across containing fine-grained pyrite, chalcopyrite, galena, sphalerite, and barite within Middle Devonian marine shales and sandstones (Wedepohl et al., 1978).

TABLE 5. Lead Isotope Ratios from Galena at Ruby Creek and from Some Other Ore Deposits in Devonian Host Rocks

Sample	Locality	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	Reference
1	Ruby Creek, AK	18.233	15.589	38.084	1
2	Ruby Creek, AK	18.191	15.583	38.065	1
3	Ruby Creek, AK	18.612	15.600	38.106	1
4	Arctic Camp, AK	18.308	15.569	38.061	1
5	Rammelsberg, FRG	18.242	15.611	38.195	2
6	Rammelsberg, FRG	18.257	15.629	38.215	2
7	Rammelsberg, FRG	18.233	15.609	38.171	2
8	Meggan mine, FRG	18.197	15.606	38.123	2

Samples 1-4 analyzed by Holly Stein (U.S. Geological Survey) in 1983 using the surface emission (silica gel) ionization method of solid source mass spectrometry

Detailed sample locations: 1, DDH34, 268.5'; 2, DDH54, 1,676'; 3, ore dump containing material extracted from the 975 level crosscut; 5, 6, 10th layer, "New Deposit"; 7, 11th layer, "New Deposit"; 8, 2nd layer, "New Deposit"

References: 1, B. R. Doe, writ. commun., 1983; 2, Wedepohl et al., 1978

Discussion and Conclusions

Sequence of sulfide crystallization

The texture of the ore provides only a few clear clues to the order of sulfide crystallization: (1) pyrite, both fine- and coarse-grained, is commonly veined by chalcopyrite and bornite, in places appearing to be partly replaced by them—the coarse pyrite grains appear to be the result of hydrothermal recrystallization; (2) carrollite commonly forms overgrowths on pyrite and is itself commonly veined by chalcopyrite and bornite; (3) chalcocite in places veins bornite, in places forms exsolved reticulated crystals in bornite, and in other places appears partly replaced by bornite; (4) germanite is always rimmed by renierite; (5) renierite always occurs as inclusions within bornite or chalcocite, appearing slightly older than both. Chalcopyrite and bornite generally appear mutually intergrown and embayed with each other (Fig. 9); clear veins of one in the other were never observed. In some places, bornite appears to have replaced chalcopyrite, as evidenced by a motheaten texture; in other places, the reverse relationship is observed. The Cu-bearing sulfides are restricted in their distribution to areas of abundant preexisting fine-grained pyrite.

These observations indicate that fine-grained pyrite crystallized early throughout the orebody. The fine porosity and common lath-shaped habit of the pyrite suggest replacement of some earlier marcasite. Subsequently, the early pyrite recrystallized to coarser grains having cobalt-rich rims; locally, carrollite crystallized at this time or slightly later. Copper-rich mineralization followed, with chalcopyrite-bornite-chalcocite crystallizing near the core, and chalcopyrite or chalcopyrite-tennantite crystallizing toward the margins. Some replacement as well as local recrystallization of pyrite took place during this stage.

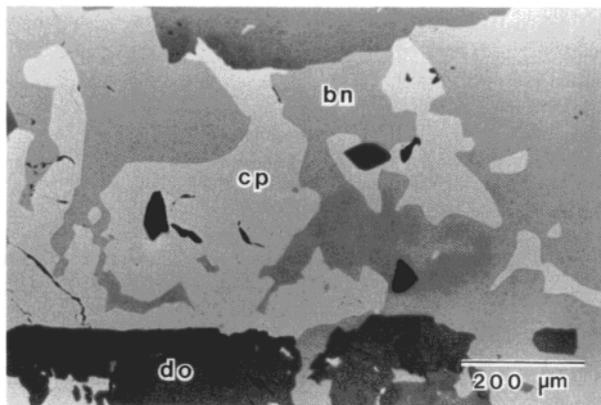


FIG. 9. Typical mutually intergrown and interembayed texture of bornite and chalcopyrite in Number One orebody. Note that small islands of each mineral are present within grains of the other. Drill hole RC34, 978'. Plane polarized reflected light.

tallization of pyrite took place during this stage. The order of crystallization among chalcopyrite, bornite, and chalcocite apparently varied from place to place, depending on variations in temperature and chemical potentials. These variations probably resulted from the irregular porosity of the dolostone breccia, which created numerous microenvironments for crystallization. The germanium minerals germanite and renierite apparently crystallized only from the copper-rich fluids that formed bornite and chalcocite, with germanite crystallizing first.

Ore-forming processes

The distribution of sulfides in the Number One orebody can be explained most simply as the result of two major periods of mineralization. Available data from the Number One orebody do not indicate the interval of time that separated the two events. In the first period of mineralization, solutions presumably rich in iron entered the breccia, depositing abundant fine-grained slightly cobaltiferous pyrite and marcasite. Marcasite was replaced by finely porous pyrite, due to increasing temperature or pH ($T > 160^{\circ}\text{C}$, $\text{pH} > 5$; Murowchick and Barnes, 1984). Some pyrite recrystallization took place during the late part of this stage, producing coarser grains that have Co-rich rims; some carrollite and traces of sphalerite were also deposited. The region of abundant pyrite deposition is apparently in a structural depression. This depression, lying at the base of permeable breccia on much less permeable shale or mudstone, now metamorphosed to phyllite (Fig. 5B), may have been the principal control on pyrite deposition.

Subsequently, perhaps immediately following pyrite crystallization or possibly much later, copper-rich solutions were introduced into what became the core of the orebody. These may have entered through faults, such as the one shown in Figure 5A and B. The fine porosity of the matrix-forming pyrite (Fig. 8a) helped permit entrance of these solutions into the rock. Most of the pyrite in the core zone was replaced by bornite, chalcocite, digenite, and chalcopyrite. As the ore-forming fluids migrated outward into the breccia, they decreased in copper content as copper-rich sulfides were deposited. As a result, increasingly copper-poor phases (tennantite-tetrahedrite, chalcopyrite) were deposited outward from the core. In the outer zone, only small amounts of chalcopyrite were deposited and some of the pyrite was recrystallized.

Though the ore clearly appears epigenetic, the origin of the mineralizing fluids is unknown. Runnells (1969) suggests that the metalliferous solutions were derived from an igneous or metamorphic source. Hitzman (1986) suggests that they resulted from Devonian basinal brines heated by volcanic activity. Ex-

isting O, S, C, and Pb isotope data (Runnells, 1969; Hitzman, 1986; H. Ohmoto, writ. commun., 1978; and this study) are ambiguous and somewhat contradictory concerning the age of mineralization, origin of sulfur, and temperatures of deposition. It is possible that the ore-forming solutions (including the metals and sulfur) were derived from both sedimentary and igneous sources, as suggested above.

The origin of the breccia hosting the ore is not clear and remains a key problem. No evidence of collapse or explosion structures was observed. The polymictic clasts indicate transport, suggesting the brecciation may have been depositional. The texture of the breccia strongly suggests that sulfide mineralization occurred after brecciation; undeformed sulfides occur interstitially to a jumbled mass of angular to subrounded, poorly size-sorted clasts of dolostone, and rarely of marble and phyllite (limestone and shale when the breccia formed). If in the future the deposit is mined, detailed structural and textural observations could be made that may help to resolve the nature and timing of brecciation and mineralization.

Similarities to the Kipushi deposit, Zaire, and implications from other ore deposits

Hitzman (1983, 1986) has made detailed comparisons of the Ruby Creek deposit with some other carbonate-hosted, commonly organic-bearing, copper-rich hydrothermal deposits, including McArthur River (Cooley and Ridge) and Mt. Isa, Australia, and Tynagh, Ireland. We here note close similarities with the Kipushi Cu-Zn-Pb deposit in the Zaire-Zambia copper belt, as described by DeVos et al. (1974), Dimanche (1974), and Intiomale and Oosterbosch (1974).

The orebody at Kipushi forms a highly irregular subvertical pipe at the faulted boundary of dolomitic shale and marine dolostone, commonly within breccia zones. Sulfide replacement extends along bedding planes and fracture zones. Early formed fine- to coarse-grained pyrite occurs mostly toward the margins of the ore, together with sphalerite and chalcopryrite; elsewhere in the ore, pyrite is corroded and replaced by other sulfides. Carrollite is present through much of the ore, commonly replaced by bornite and chalcocite. The bulk of the ore consists of the assemblages chalcopryrite-pyrite, chalcopryrite-bornite-tennantite, bornite-chalcocite, and sphalerite-pyrite-galena. Some of the bornite is argentiferous. Anthracitelike organic material (shungite) is found dispersed through the ore. Germanium-bearing sulfides, mainly renierite with lesser germanite, vanadian germanite, and briartite ($\text{Cu}_2(\text{Fe}, \text{Zn})\text{GeS}_4$), are locally common in copper-rich ore, often near zinc-rich ore. Gallite, CuGaS_2 , is present in small quantities as inclusions in renierite, germanite, and sphalerite. The

origin of the ore-forming solutions at Kipushi remains unclear.

The type of ore deposit represented by Ruby Creek, Kipushi, McArthur River, Mt. Isa, and others is chemically and structurally complex. These deposits do, however, have the following features in common: (1) they are carbonate hosted, the orebodies being surrounded by dolomite that is at least partly of hydrothermal origin; (2) they contain hard, carbonaceous organic matter; (3) they are very copper rich, at least in certain zones; (4) their ore is commonly in the matrix of breccia; (5) they appear to be near the margins of sedimentary basins; (6) Co, Ge, As, Sb, Ag, V, and Ga are common, probably characteristic, minor metals; and (7) a connection with igneous activity is either not clear or appears absent. The genetic relation, if any, of the organic material within the ores to the metallic mineralization is not known. Some of the metals present, in particular Ge, V, and As, are known to have high affinities to some types of organic material; hydrothermal solutions possibly could have leached the metals out and redeposited them as sulfides. The rare metals Co, Ge, and Ga that are commonly concentrated in these ores could ultimately make such deposits more economically attractive than some less complex Cu-Zn-Pb ore deposits.

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