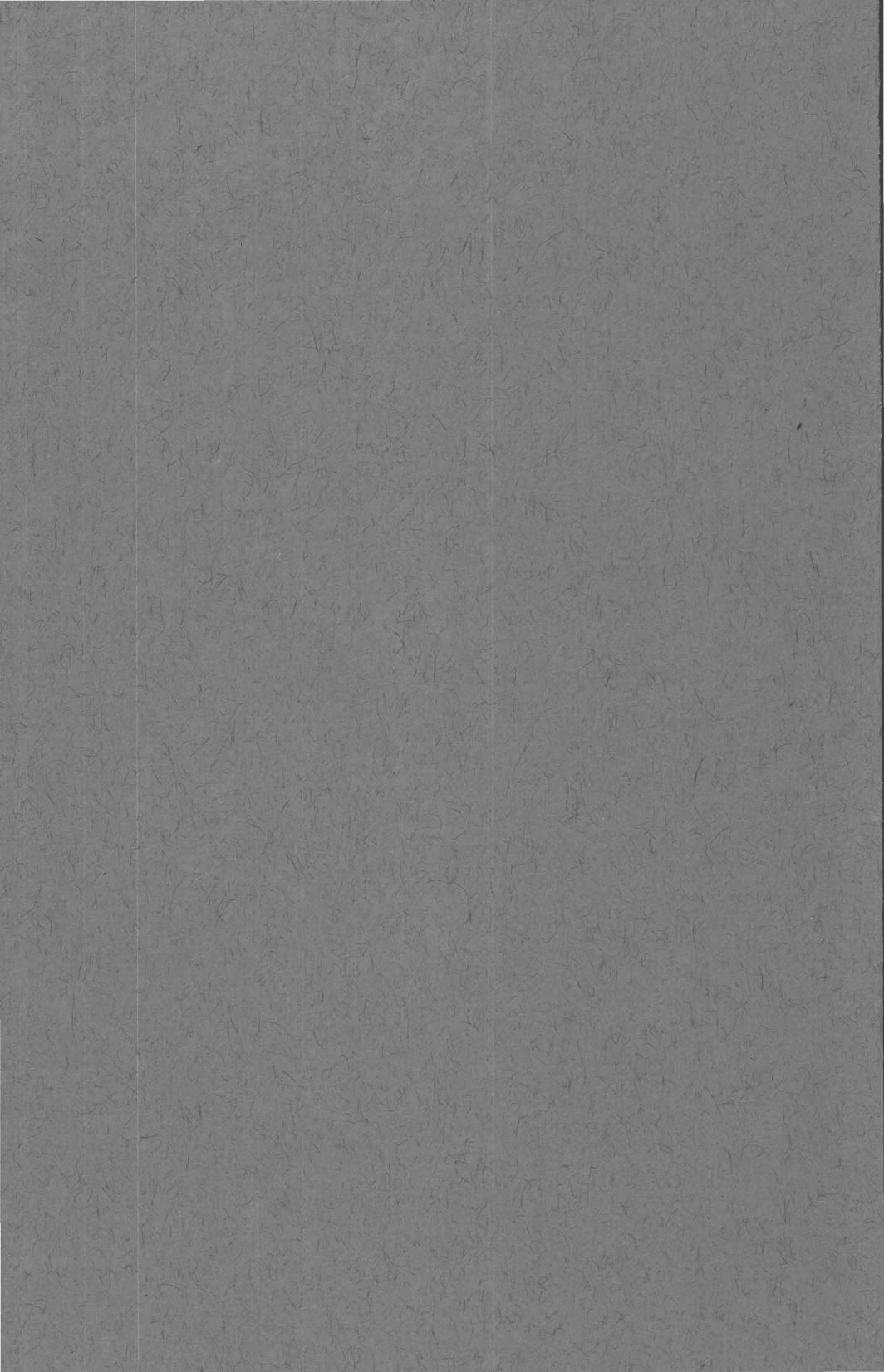


Geology and Ore Deposits of the Philipsburg District Granite County, Montana

GEOLOGICAL SURVEY BULLETIN 1237





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By WILLIAM C. PRINZ

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*A study of the silver-zinc and
manganese deposits of the
Nation's only battery-grade
manganese dioxide district*



UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

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GEOLOGY AND ORE DEPOSITS OF THE PHILIPSBURG DISTRICT, GRANITE COUNTY, MONTANA

By WILLIAM C. PRINZ

ABSTRACT

The Philipsburg district is an economically important zinc- and silver-producing area and virtually the only domestic source of natural battery-grade manganese dioxide. It is in an area of folded and faulted Precambrian, Paleozoic, and Mesozoic sedimentary rocks that have been intruded by early Tertiary batholiths. Straddling part of the western border of one of the batholiths, the district is underlain partly by granodiorite of the batholith and partly by Precambrian and Paleozoic sedimentary rocks that have been folded into a north-plunging anticline. The sedimentary rocks consist mainly of limestone, dolomite, shale, and quartzite which near the batholith have been metamorphosed to marble, tactite, and hornfels.

The ore deposits near Philipsburg are divided into four groups: (1) steeply dipping quartz veins, (2) quartz veins along bedding, (3) manganese-rich replacement deposits, and (4) contact metasomatic magnetite deposits. Quartz veins that have been mined primarily for silver, zinc, and lead cut both the batholith and the sedimentary rocks; they strike west or northwest and dip vertically or steeply south. The steeply dipping veins originated from hydrothermal solutions flowing through fissures along which movement was small but generally continuous throughout mineralization. The veins were formed in part by cavity filling and in part by replacement of wallrock.

Quartz veins that follow bedding planes in sedimentary rocks are common in the northern part of the district. Such veins on Hope Hill yielded much high-grade silver ore early in the history of the district, and their distribution suggests that they may pass downward into steeply dipping veins.

Replacement deposits rich in manganese are irregularly distributed in favorable host beds along many steeply dipping quartz veins and the border of the batholith. The shape of these deposits is controlled by the character of the host rock. In thin-bedded host rocks they are tabular, whereas in massive or thick-bedded rocks they tend to be vertical pipes. The pipes are extremely irregular, swelling out in more favorable beds or below impermeable zones, such as faults or shale beds, and pinching out in less favorable beds or above impermeable zones. Although many of the manganese deposits occur at the intersections of favorable host beds and veins, favorable beds are not everywhere replaced along these intersections, and no relationship exists between the size of the steeply dipping vein and the size of the associated manganese-rich replacement deposit. Lateral spreading of deposits below impervious beds indicates that the movement of the ore-bearing solutions was upward.

The primary ore in these deposits consists mainly of rhodochrosite and manganiferous dolomite, which in places contain recoverable amounts of zinc and silver sulfides. The manganiferous carbonates formed mainly by replacement of original carbonate rocks.

The bulk of the manganese ore produced in the district has come from the oxidized zone near the surface, where downward-percolating water altered the manganoan carbonate deposits to cryptomelane, todorokite, nsutite, pyrolusite, chalcophanite, hetaerolite, and manganite. The depth of oxidation ranges from 100 feet in relatively impervious hosts to at least 850 feet in highly permeable ones. The vuggy nature and relict primary textures of the oxide ore indicate that the alteration to oxide was accomplished by removal of materials from the carbonate masses.

Contact metasomatic irregular magnetite pods occur in marble along the border of the batholith and along a preintrusion high-angle reverse fault. Little magnetite has been mined, and the prospects for its future production appear poor.

Several stages of mineralization are recognized. From oldest to youngest, they are characterized by deposition of iron oxide, iron sulfide, zinc, lead, copper-silver, and manganese. Variations in composition and character of the ore bodies and the rude zoning that has been recognized in the district are explained by progressive changes both in structural conditions and in composition of the ore solutions.

INTRODUCTION

The Philipsburg (or Flint Creek) mining district, once a major silver-producing area and now virtually the only domestic source of natural battery-grade manganese dioxide, is in Granite County, southwestern Montana. It covers an irregular and poorly defined area of about 8 square miles on the west flank of the Flint Creek Range east of the town of Philipsburg (figs. 1, 2). Silver ore valued at \$70 million has been produced from quartz veins throughout the district. Zinc, some lead, and a little gold and copper have also been recovered from some of the silver ore. The bulk of the manganese ore has come from replacement deposits in the central part of the district within $1\frac{1}{2}$ miles of Philipsburg.

Philipsburg is at an altitude of 5,275 feet on the east side of the Philipsburg Valley at the base of the Flint Creek Range, which rises abruptly from the valley. The mines extend from Philipsburg eastward for about 3 miles up the mountains to an altitude of about 7,500 feet. Most recently productive mines are within 1.5 miles of the town and are below 6,200 feet. The topography in the district is moderately steep.

Philipsburg, the county seat of Granite County, is an agricultural, logging, and mining center that had, in 1960, a population of 1,107. It is on U.S. Highway 10A, 78 miles by road southeast of Missoula and 54 miles northwest of Butte. A spur south from the main line of the Northern Pacific Railroad at Drummond, 27 miles to the north, ends at Philipsburg.

Temperatures at Philipsburg generally range from below 0°F in the winter to 90°F in the summer. Spring tends to be wet and the summer dry. Snowfall is moderate, increasing in the higher parts of the district. Mining can be carried on throughout the year; snow removal is not much of a problem except at the higher altitudes.

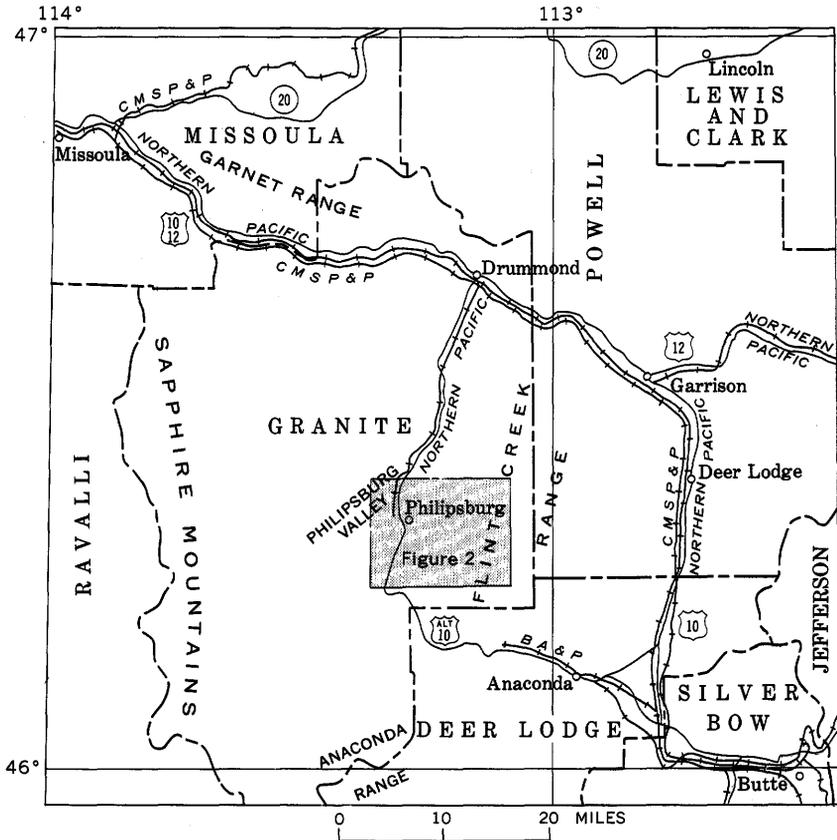


FIGURE 1.—Part of western Montana. Names of railroads are abbreviated as follows: CMSP & P, Chicago, Milwaukee, St. Paul and Pacific; BA & P, Butte, Anaconda & Pacific.

HISTORY AND PRODUCTION

The Philipsburg district started as a silver camp in 1864 with the discovery of the Hope mine on the southwest side of Hope Hill (pl. 1). The town of Philipsburg was founded in 1867, and the Hope mill was built in the same year. Many other mines were located and several mills erected shortly after the Hope discovery, but mining was difficult and expensive because of the remoteness of the area from supply points and from markets for the ore. Several attempts were made to smelt the ore locally, but none was very successful.

The Northern Pacific Railroad completed its transcontinental route in 1883, and the spur from Drummond to Philipsburg was completed in 1887. The transcontinental railroad improved access to supply

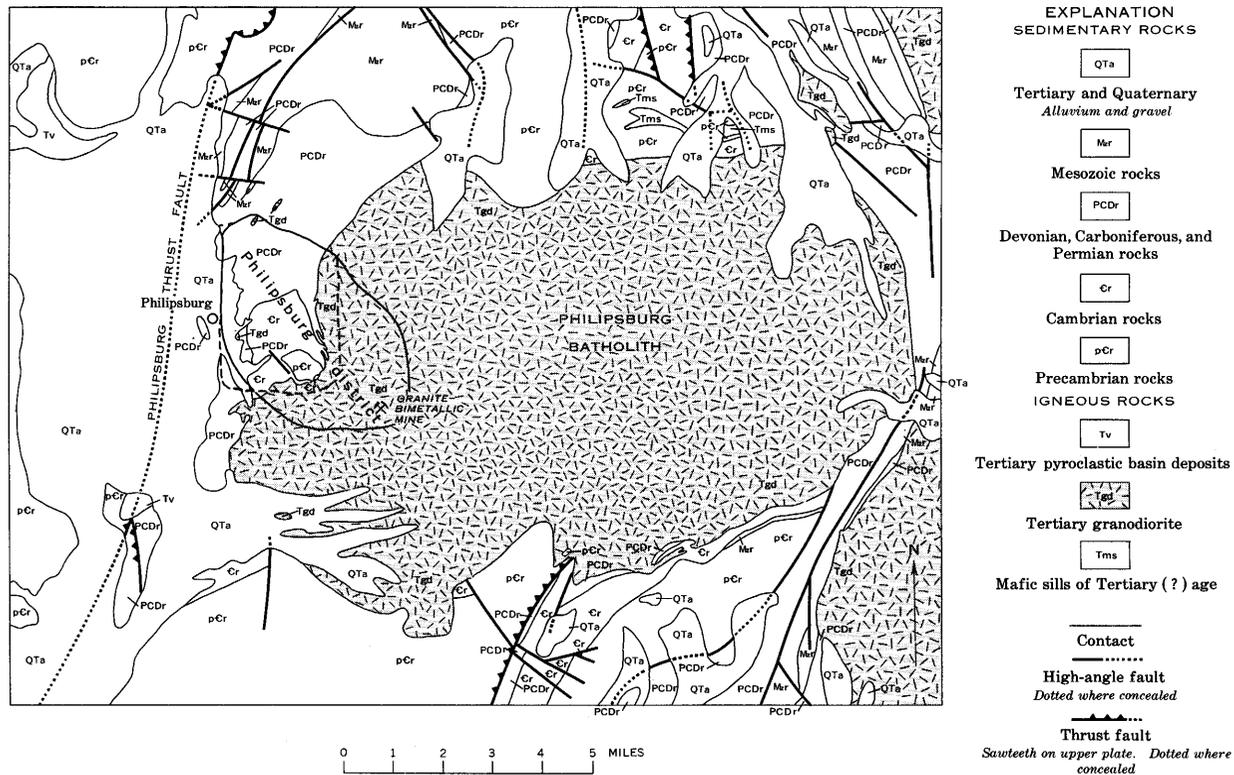


FIGURE 2.—Generalized geology of the Philipsburg batholith and surrounding area showing location of the Philipsburg district (solid outline) and the area shown on plate 1 (dashed outline). Modified from Emmons and Calkins (1913, pl. 1).

points and markets, and the Philipsburg district prospered. Large ore bodies were mined at the Granite Mountain, Bimetallic, and Hope mines, and Philipsburg soon became one of the country's foremost silver-producing districts.

The prosperity was short lived, because after the drop in the price of silver in 1892, most of the mines except the Hope were forced to close. Five years later, the Granite Mountain and Bimetallic mines were consolidated to form the Granite-Bimetallic mine and were reopened, but production never reached pre-1892 levels.

Before World War I, almost all the ore produced in the district was marketed for its silver and low gold content; the zinc, lead, and copper in the ore were discarded. Since then, most of these metals have been recovered from the ores and from many of the old tailings as well.

The first recorded production of manganese ore from the Philipsburg district was in 1900, when 153 short tons was shipped from the Coyle mine. However, the venture was not profitable, and no more manganese was produced until demand for this metal by the steel industry increased at the outbreak of World War I. Production soared from nothing in 1915 to a peak of 142,000 short tons in 1918, which represented almost 40 percent of the total United States production of ore containing 35 percent or more manganese. After the war, Philipsburg producers were unable to compete in the metallurgical market because of their remoteness from steel-producing centers, but manganese dioxide concentrates from the district were found to be particularly well suited for the manufacture of dry-cell batteries. Since then, Philipsburg has been the major domestic source of natural battery-grade manganese dioxide (fig. 3).

Between 1904 (the first year for which detailed records are available) and 1962, the Philipsburg district produced about 24,000,000 ounces of silver, 83,000 ounces of gold, 80,000,000 pounds of zinc, 23,000,000 pounds of lead, and 4,000,000 pounds of copper having a total value of almost \$30,000,000 (McNabb, 1955, table 1; U.S. Bur. Mines, 1951-62). Production prior to this period probably totaled about \$39,000,000, of which more than 90 percent was silver (Emmons and Calkins, 1913, p. 201). More than \$32,000,000 of this early production was from the Granite Mountain and Bimetallic mines.

From 1916 through 1921, the district produced about 260,000 short tons of ore containing 35 percent or more manganese. Most of this ore was used for metallurgical purposes. Since then, most of the manganese production has gone into the manufacture of dry cells, and from 1921 to 1962 the district produced about 450,000 short tons of battery-grade concentrates averaging 65-72 percent MnO_2 (equivalent to 41-45.5 percent manganese).

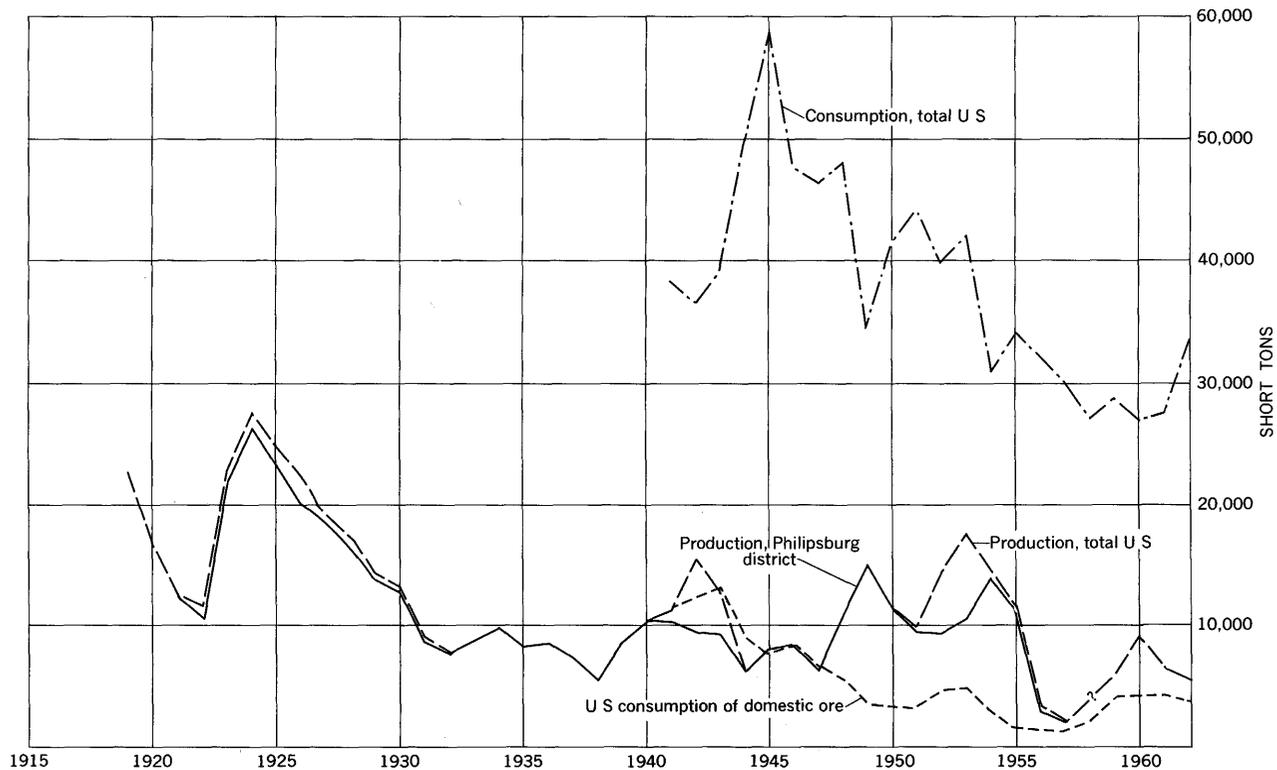


FIGURE 3.—Salient statistics for battery-grade manganese dioxide in the United States. Data compiled from U.S. Geological Survey (1918–23), and U.S. Bureau of Mines (1924–31; 1932–62). The excess of production over consumption of domestic ore represents consumption for uses other than in dry cells and sales to the Government for stockpile.

Besides metallurgical ore and battery-grade concentrates, the district has produced several types of manganese ore for which complete production figures have not been published. Large tonnages of ferruginous manganiferous tailings from the battery-ore mills that averaged between 16 and 25 percent manganese, and of crude manganese oxide ores containing less than 35 percent manganese, have been shipped both to commercial consumers and to Government stockpiles. The Government has also purchased for stockpile rhodochrosite and sintered rhodochrosite, but very little carbonate ore or sinter has been sold to commercial consumers.

PREVIOUS STUDIES

The Philipsburg district was first investigated by the U.S. Geological Survey in 1906-08, when the Philipsburg 30-minute quadrangle was mapped under the supervision of F. C. Calkins and the mines within the quadrangle were studied by W. H. Emmons. A description of the Granite-Bimetallic mine was published in 1907 (Emmons, 1907), and a comprehensive report on the whole quadrangle appeared a few years later (Emmons and Calkins, 1913). A condensed account of the geology of the Philipsburg quadrangle was published by the U.S. Geological Survey in the Geological Atlas (Folio) series (Calkins and Emmons, 1915).

The work by Emmons and Calkins was completed before the manganese boom of World War I. In 1918, the manganese-producing part of the district was studied by J. T. Pardee (1921) as part of a Geological Survey assessment of available domestic supplies of manganese. Further work was done in the district by Pardee in the late 1920's, and a brief discussion of the geology and origin of the ore deposits and up-dated production and reserve figures were released in a "Memorandum for the Press" on October 16, 1929.

After passage of the Strategic Minerals Act (Public Law 117, 76th Cong.) in 1939, the Federal Government took a renewed interest in the manganese deposits of the Philipsburg district. E. N. Goddard made a detailed study of the manganese-rich part of the district in 1939 and prepared detailed geologic maps of the surface and of some mine workings (Goddard, 1940). The U.S. Bureau of Mines diamond drilled several properties in 1940 (Lorain, 1950).

Early in World War II, the rhodochrosite deposits of the Philipsburg district were examined by S. K. Neuschel and M. D. Crittenden, Jr., of the U.S. Geological Survey, but the results of their work were not published. In an effort to enlarge the potential base-metal productive area of the district, the U.S. Bureau of Mines diamond drilled two holes under the old Hope mine in 1946. Although both were bar-

ren, the holes yielded useful data regarding the position of various formations in the northern part of the district (Cole, 1949). W. T. Holser (1950) studied the metamorphic features and magnetite mineralization of the Philipsburg region in 1947 and 1948.

In 1949 the Geological Survey and Bureau of Mines cooperated in a program to explore for manganese by diamond drilling (McNabb, 1955). The results were negative. During the 1950's the U.S. Bureau of Mines studied the manganese and the tungsten resources of an area that includes the Philipsburg district. The manganese studies were under the direction of R. N. Apling. The tungsten study was made by D. D. Walker (1960). Between 1959 and 1961, L. T. Larson (1961, 1962, 1964), studied several manganese oxide ore bodies in the True Fissure and Cliff Millsite mines.

PRESENT INVESTIGATION

The present investigation was undertaken (1) to compile the vast amount of data that had been accumulated by Government and company geologists since the last published study of the area before World War II, (2) to study the accessible mine workings, and (3) to determine the mineralogy of the ore. My work was concerned principally with the part of the district that is underlain by sedimentary rocks (pl. 1) and adds little to the older descriptions of the outlying areas (Emmons and Calkins, 1913).

In the summers of 1959 and 1960, all readily accessible mine workings were studied and mapped where necessary. Company maps at various scales were used as bases on which to plot geology; and where suitable base maps were not available, workings were mapped with Brunton compass and tape at a scale of 1 inch=100 feet. These maps, and maps of now-inaccessible workings from company and Government files, were reduced to 1 inch=200 feet and compiled into a series of 12 level maps at 100-foot intervals through the central part of the district. Five of these level maps were selected for inclusion with this report (pls. 2-6), but to better illustrate the geologic features, some workings as much as 100 feet above or below the chosen levels are also shown. Mine openings and the geology mapped in them are shown in their true position. Away from the workings, gently dipping features (principally formational contacts) are shown projected to the plane of the map. To provide a better fit with the topographic base map used by Goddard (1940, pl. 26), the altitudes of the workings, as determined by company engineers, have been reduced by 35 feet for the mines in the southwestern part of the map area and by 10 feet for the mines in the rest of the area. Although several coordinate systems have been employed in the district, the

maps with this report show only the two that are now in more general use—the Taylor-Knapp Co. coordinates in the northern part of the area and the Trout Mining Co. coordinates in the south.

In addition to the underground work, some surface mapping was also done. However, very little exploration work has been done near the surface since 1939, and the surface geologic map prepared by Goddard (1940, pl. 26) requires very few changes. Therefore, only a simplified and reduced map of the surface geology is published here (pl. 1). No surface mapping was done outside the area shown on plate 1.

Laboratory work consisted of microscopic study of the ores and wallrocks and X-ray study of the manganese ores. The determinative tables prepared by Tröger (1952) were used in the study of thin sections. Measurements of index of refraction were made in white light. Microchemical techniques described by Short (1940) and by Chamot and Mason (1938) were used to identify some ore minerals.

The manganese oxide minerals are not amenable to study by microscopic techniques alone, and identification of the various minerals required use of X-ray powder methods. Because the oxide ores are commonly fine-grained mixtures of several minerals, small samples for X-ray study were excavated from the surfaces of polished samples and mounted by the method described by Hildebrand (1953). Goniometer charts were used to obtain X-ray data for some minerals but were found to be unsatisfactory for the manganese oxides.

ACKNOWLEDGMENTS

The support and assistance of the mine operators within the district are gratefully acknowledged; without their cooperation, this study would not have been possible. Records and maps furnished by the Taylor-Knapp Co., the Trout Mining Co., Frank Antonioli, and Phil Salois were most useful, and published and unpublished reports and field notes of Geological Survey geologists who worked in the area previously were extensively consulted. Particular thanks go to J. J. Quinlan, formerly with the Geological Survey, for many hours of stimulating discussion regarding the genesis of the Philipsburg ore deposits.

GEOLOGIC SETTING

The Philipsburg district is in an area of folded and faulted Precambrian, Paleozoic, and Mesozoic sedimentary rocks that have been intruded by early Tertiary batholiths (Emmons and Calkins, 1913; Goddard, 1940). The eastern and southern parts of the district are underlain by the west end of one of these batholiths (fig. 2), and the

northwestern part is underlain by Precambrian and Paleozoic sedimentary rocks which form a broad north-plunging anticline. The sedimentary rocks in the district consist mainly of limestone, dolomite, shale, quartzite, and phosphatic quartzite (table 1), which near the margin of the batholith have been metamorphosed to marble, tactite, and hornfels (Holser, 1950).

SEDIMENTARY ROCKS

The sequence of sedimentary rocks exposed in the Philipsburg district and the general characteristics of these rocks are shown in table 1.

TABLE 1.—*Stratigraphic succession in the Philipsburg district*

[Modified from Goddard (1940) and Holser (1950)]

Age		Formation	Thickness (feet)	Character
Permian		Undifferentiated	180	Yellowish-brown to gray sandstone and quartzite, red to brown shale, and phosphate rock.
Carboniferous	Pennsylvanian	Quadrant Quartzite	300-325	Massive white to brown quartzite.
	Mississippian	Madison Limestone	1,000-1,500	Fine-grained dark-gray limestone with some chert.
Devonian		Jefferson Limestone	1,000-1,300	Fine-grained gray, blue-gray, or brown calcitic and dolomitic limestone; metamorphosed to medium-grained white to gray marble near batholith.
		Maywood Formation	210-490	Fine-grained greenish- or brownish-gray and purple dolomitic limestone, siltstone, and sandy limestone. Gray shale at base. Some silicates and hornfels formed during metamorphism.
		Unconformity		
Cambrian	Upper	Red Lion Formation	225-350	Thin-bedded light- to dark-gray limestone with thin shaly and siliceous layers. Partly metamorphosed to marble, hornfels, and tactite. Uppermost 2-3 ft is nearly pure marble (headlight bed).
		Hasmark Formation	300-1,300 (average 900)	Medium- to coarse-grained white to buff thick-bedded dolomitic marble with a few thin beds of shale.
	Middle	Silver Hill Formation	280-320	Limestone with irregular beds of siliceous shale. Lower third predominantly shale. Metamorphosed to marble, tactite, and hornfels. Locally called garnet rock.
		Flathead Quartzite	135	White to gray quartzite with some interbedded dark-gray shaly quartzite.
		Unconformity		
Precambrian (Belt Series)		Missoula Group (undifferentiated)		Gray to greenish-gray impure quartzite with some shaly beds; similar to Flathead Quartzite.

Quartzite of the Belt Series of Precambrian age, the uppermost few hundred feet of which is exposed in the core of the anticline, is the oldest unit in the district. These rocks were formerly included in the "Spokane Formation" (Emmons and Calkins, 1913), which Ross (1963, p. 29-30) showed is equivalent to almost the entire Missoula Group. The overlying Flathead Quartzite of Middle Cambrian age is very similar to the Precambrian quartzite; and although an unconformity separates the two units, the angular discordance between them is small. In many places the two units are inseparable. The middle of the Silver Hill Formation contains more limestone and marble than the upper or lower parts, and, near the batholith, shaly beds have been metamorphosed to tactite and hornfels. The Hasmark Formation here consists almost wholly of marble and is much thinner on the east limb of the anticline than it is over the crest. According to Hanson (1952, pl. 5), the Hasmark is of both Middle and Late Cambrian age. The youngest Cambrian unit in the district is the Red Lion Formation, the top of which is marked by a bed of almost pure marble, locally called the Headlight bed, which is similar to marble of the Hasmark Formation.

The Maywood Formation disconformably overlies the Red Lion and is Devonian in age (Lochman, 1950, p. 2213). The Jefferson Limestone is the youngest unit that contains a significant amount of ore in the district. Except for a small amount of phosphate rock that occurs in the rocks of Permian age (Pardee, 1936), the younger rocks of the district are barren.

IGNEOUS ROCKS

The sedimentary rocks were intruded in early Tertiary time by the Philipsburg granodiorite batholith. The batholith is elliptical in plan and underlies an area of about 45 square miles. The Philipsburg district lies along the western margin of the batholith at a reverse l-shaped indentation (fig. 2).

Most of the batholith is medium-grained granodiorite that consists predominantly of plagioclase, quartz, orthoclase, biotite, and hornblende and contains accessory magnetite, sphene, apatite, and zircon. Pyroxene was identified in only a few samples. Plagioclase forms euhedral to subhedral grains and has an average composition of An_{40} - An_{45} . It is commonly zoned with cores as calcic as An_{52} and rims as sodic as An_{19} . The biotite is deep brown to light yellow, and the hornblende is green or rarely brown. Orthoclase tends to become less abundant toward the borders of the batholith, and locally the granodiorite grades into quartz diorite (Emmons and Calkins, 1913, p. 100). Aplite and pegmatite phases of the granodiorite are uncommon. The

rocks of the batholith are generally very fresh and show only slight alteration of feldspar to sericite or epidote and of mafic minerals to chlorite. Near veins, however, the rock is intensely altered, and only traces of the original feldspar, biotite, and hornblende remain.

STRUCTURE

The dominant structural feature of the Philipsburg district is a north-trending anticline that plunges 15° – 30° N. The relations along the southwest side of Franklin Hill (pl. 1) indicate that the fold is doubly plunging, but the southern part is cut off by the batholith. The fold is asymmetrical; the east limb dips 30° – 55° E., whereas the west limb dips 45° – 70° W. A small north-plunging syncline whose trough is marked by rocks of Permian age is present in the northwestern part of the district (pl. 1).

Granodiorite cuts off the east and south sides of the anticline. Along the east side the contact is almost parallel to bedding and dips eastward under the batholith. However, the granodiorite truncates bedding to the south and at depth (pls. 1–7). Dikes and sills of granodiorite cut the sedimentary rocks near the batholith, and small pods occur in the western part of the district.

A thrust fault along which Precambrian rocks were thrust eastward over Paleozoic and Cretaceous rocks underlies the valley immediately west of Philipsburg (fig. 2; Emmons and Calkins, 1913), but thrusts have not been recognized within the district. The faults that have been recognized in the district are steep reverse faults, mineralized fractures showing very small displacement, and bedding faults.

The best defined reverse fault in the district is the Redemption fault (pl. 1), which strikes northwest and dips steeply northeast. The northeast wall has moved upward in relation to the southwest wall, bringing Precambrian rocks, Flathead quartzite, and Silver Hill Formation against the Hasmark Formation (section *D-D'*, pl. 7). This fault dies out to the northwest in a zone of closely spaced joints. A parallel fault has been postulated beneath alluvium in the southwestern part of the district to explain the relation between the Hasmark Formation and Jefferson Limestone there (pl. 1; Goddard, 1940, p. 167).

Steeply dipping to vertical fractures that commonly strike east and that are filled with vein quartz cut the batholith and sedimentary rocks. Displacement along these fissures is small; normally beds on the north side are offset eastward less than 8 feet, but locally they are offset as much as 20 feet. A subordinate set of fractures that strike northwest and dip southwest is also present in the sedimentary rocks.

Bedding faults at several horizons displace the steeply dipping veins. These faults may be marked by a single plane or by a shear

zone as much as 60 feet thick. On the east limb of the anticline, offset of the veins along these bedding faults is almost everywhere east side to the north. Horizontal displacement of veins along the bedding fault between the Silver Hill and Hasmark Formations ranges from nearly 0 to 80 feet, and that along the fault between the Hasmark and Red Lion Formations is from 0 to 145 feet, generally showing an increase with depth and to the north. A wide zone of faults in the upper part of the Maywood Formation and the lower part of the Jefferson Limestone offsets the veins 200–250 feet (pls. 3–5). Bedding faults occur at various other horizons, but they are generally not persistent, and displacement along them has been small.

Net slip along the fault at the contact between the Hasmark and Red Lion Formations in the True Fissure mine was calculated from vein intersections on the 500, 600, and 800 levels. The horizontal displacement of the Mountain View vein along this fault is 125–145 feet, and that of the more steeply dipping Horton vein is 40–60 feet (pls. 5, 6). The actual movement was down the dip of the fault and had almost no horizontal component. The fault is normal; relative movement on the east or hanging-wall side was 100 feet downward. Movement along other bedding faults is probably also normal except where there is a large offset in nearly vertical veins, as along the fault zone in the upper part of the Maywood Formation and the lower part of the Jefferson Limestone (pls. 3–5). In these places, the east side of the fault appears to have moved northward.

Normal movement along the bedding faults should offset veins on opposite limbs of the anticline in opposite directions. This relation is exemplified by the Cliff vein on the Scratch Awl 500 level, where it is displaced by a fault at the contact between the Silver Hill and Hasmark Formations (pl. 4).

Postmineralization faulting along the contact between the batholith and the sedimentary rocks and along parallel faults within the batholith offset the veins on the east sides of the faults to the north (pl. 4, east end Scratch Awl 500 level).

SEQUENCE OF EVENTS

The earliest event recorded in the rocks of the Philipsburg district is deposition of Missoula Group rocks in Precambrian time. This was followed, after some tilting and warping of the Precambrian rocks (Maxwell, 1959), by deposition, mostly in a marine environment, of sedimentary rocks during much of the Paleozoic Era exclusive of the Ordovician and Silurian Periods. Although Jurassic and Cretaceous sedimentary rocks have not been found in the district, their presence to the north shows that sedimentation was taking place at these times too.

The principal structural features of the area originated in Late Cretaceous and early Tertiary time during the Laramide orogeny. After broad folding early in the orogeny (McGill, 1959), the Precambrian rocks were thrust eastward over younger rocks along the Philipsburg thrust fault. Folding continued, as is shown by the fact that the thrust fault is also folded. High-angle faults such as the Redemption displaced the sedimentary rocks after they were folded.

Intrusion of the Philipsburg batholith followed the folding and faulting, and after the batholith had consolidated enough to fracture, steeply dipping fissure veins were formed. The period of ore deposition continued after fissuring stopped, and it culminated in the deposition of manganese-rich replacement deposits. (See p. 62.) Normal faulting along bedding postdated mineralization and was the last event of the Laramide orogeny that can be recognized in the district.

The Laramide orogeny probably left southwestern Montana with considerable relief at or shortly after the beginning of Tertiary time. Crustal stability and erosion characterized most of Paleocene and Eocene time, and by Oligocene time the area had been reduced to a surface of moderate relief (Pardee, 1950) and the Philipsburg batholith probably unroofed. Slow crustal movements during the Oligocene and Miocene Epochs formed basins and ranges approximately in the present pattern. Erosion kept pace with uplift, and the ranges were reduced to low relief while the basins were filled with sand, clay, gravel, and volcanic ash. Pardee (1950) called the resulting surface the "Late Tertiary peneplain."

Crustal movements accelerated late in the Miocene, culminated in the Pliocene, and ended in the early or middle Pleistocene. The basin deposits were tilted and faulted, and most of them were removed by erosion; remnants crop out in the Philipsburg Valley south of the district (fig. 2; Alden, 1953, pl. 1). The present mountain ranges were uplifted at this time, some along faults and some by warping. Warping rather than faulting is believed to have formed the Flint Creek Range and the Philipsburg Valley (Pardee, 1950, p. 402).

A topography largely the same as today's was formed before glaciation in the Pleistocene Epoch (Pardee, 1950). The glaciers, which in the Philipsburg area extended from the crest of the Flint Creek range into the Philipsburg Valley, sharpened topographic features, formed moraines, and deposited outwash in many valleys. Since glaciation, there has been some erosion of the uplands and filling of the valleys and basins with alluvium.

ORE DEPOSITS

The metalliferous deposits near Philipsburg are divided into four groups:

1. Steeply dipping quartz veins.
2. Quartz veins along bedding.
3. Manganese-rich replacement deposits.
4. Contact metasomatic magnetite deposits.

Steeply dipping quartz veins occur in both granodiorite and sedimentary rocks, and they strike west or northwest. Quartz veins that follow bedding planes in limestone and marble are common in the northern part of the district and yielded the first ores mined in the area. Steeply dipping quartz veins have been mined principally for silver, zinc, and lead; bedding quartz veins have been mined for silver. Manganese-rich replacement deposits occur in favorable beds adjacent to or near steeply dipping quartz veins. In contrast with the quartz veins, they contain little quartz and are irregular in shape. They consist mainly of rhodochrosite and manganoan dolomite that have been altered near the surface to manganese oxide deposits—the source of most of the manganese mined in the district. In the southeastern part of the manganese-producing area, enough sulfides accompany the manganoan carbonates that some primary replacement deposits can be profitably mined for silver and zinc. Contact metasomatic deposits of magnetite that have yielded a small amount of iron ore occur along the Redemption fault and along the border of the batholith in the southwestern part of the district.

Emmons and Calkins (1913, p. 172, 202–220) classified the ore deposits near Philipsburg as follows:

1. Silver-bearing veins in granite.
2. Silver-bearing replacement veins in sedimentary rocks.
3. Silver-bearing deposits in bedding planes of calcareous rocks.
4. Replacement deposits of contact-metamorphic origin—magnetite deposits.

Together, their first two categories are equivalent to the steeply dipping quartz veins of their report, and their third category is equivalent to quartz veins along bedding. Their contact metamorphic deposits are the same as those here called contact metasomatic, and inasmuch as their work preceded the mining of significant quantities of manganese, they did not recognize the manganese-rich replacement deposits as a separate category.

STEEPLY DIPPING QUARTZ VEINS

Steeply dipping veins occur in the sedimentary rocks in the central part of the district and in the batholith. Those in the sedimentary

rocks can be divided into two sets—one that strikes west and one that strikes northwest (pls. 1–6). The west-striking veins dip north or are nearly vertical in the southern part of the district but in the northern part they dip steeply south (pl. 7, sections *E-E'*, *F-F'*). The average dip of the northernmost west-striking vein, the Two Percent, is 77° S. Northwest-striking veins dip 50° – 70° SW. and are more abundant to the north.

The junctions of west- and northwest-striking veins are peculiar. Instead of actually intersecting, the northwest-trending veins commonly swing westward and the west-trending ones swing northward, so that a gap is left between them (fig. 4.) Thus the two sets of veins apparently formed at the same time.

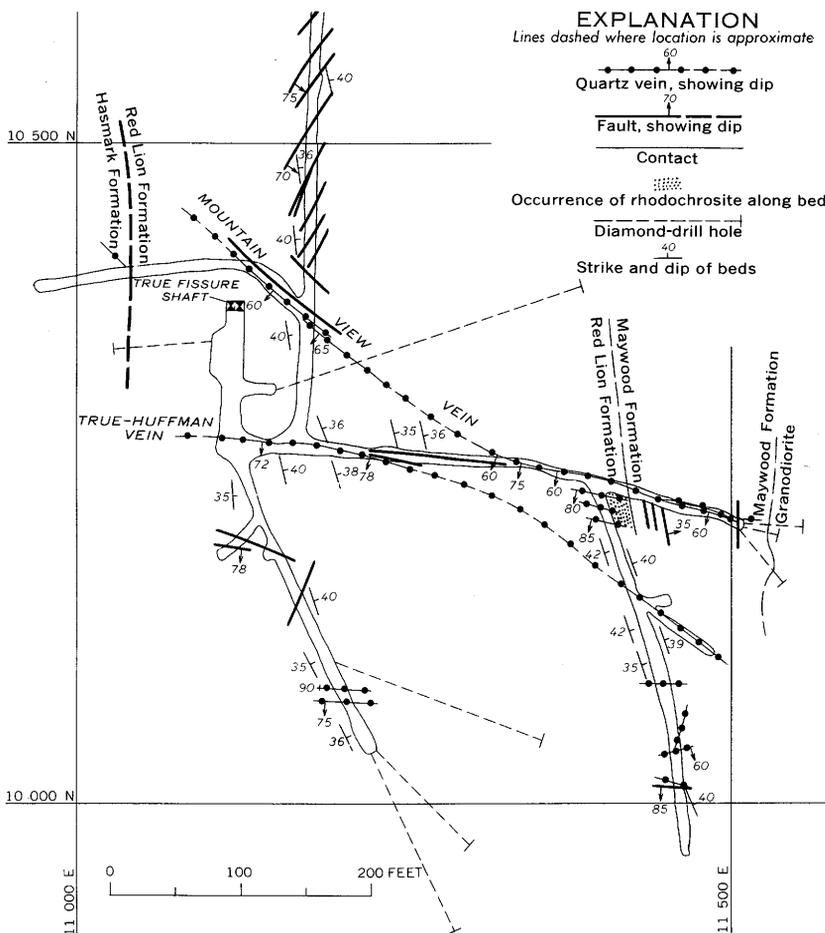


FIGURE 4.—Geology of part of the 900 level, True Fissure mine. Reduced from maps prepared by the Taylor-Knapp Co.

In general, the veins in the sedimentary rocks are largest and most productive in a belt 2,000 feet wide that trends N. 15°–20° W. from the intersection of coordinates 4,000 N. and 5,000 E. (pls. 2–6). To the west, the veins pinch or split into zones of small en echelon veins. Goddard (1940, p. 193) noted that the Cliff vein near the surface also splits into en echelon segments to the east. Projected northward, the trend of the belt crosses the crest of the Philipsburg anticline and includes the silver-rich bedding veins on Hope Hill. Perhaps the belt reflects some deep-seated structure that has influenced the localization of the veins.

Most steeply dipping veins in the batholith strike about east and dip south, but their strike is generally more variable than that of the veins in the sedimentary rocks. At the Granite-Bimetallic mine, the South vein, which strikes northwest and dips southwest (Emmons and Calkins, 1913, pl. 17), probably is a counterpart of the northwest-striking set of veins in the sedimentary rocks.

Veins in sedimentary rocks that have yielded the most ore (all silver-zinc) in recent years, or that seem most promising, are the Algonquin, Pocahontas, Cliff, Scratch Awl, Horton, Mountain View, and Two Percent (pls. 2–6). The only vein being mined in 1959 and 1960 was the Pocahontas above the 600 level of the Algonquin mine, but ore was blocked out in the Mountain View and Horton veins in the True Fissure mine and in the Cliff vein in the Scratch Awl mine. The Algonquin vein in the western part of the Algonquin mine appeared promising but had not yet been extensively explored when this report was written. Small production has also been reported from the Levi Burr, Headlight, and Saunders veins and from small veins in the Mystery tunnel that are on the trend of the Horton, True-Huffman, and Durango veins (Emmons and Calkins, 1913, p. 210–212).

No ore has been mined recently from veins in the batholith, but some production was reported from most of them in the past (Emmons and Calkins, 1913, p. 207–209); one—the Granite-Bimetallic vein—has yielded more ore than all the other veins in the district combined. Because most of the veins in the batholith were not accessible during the study, the discussion of steeply dipping quartz veins will be concerned primarily with those in the sedimentary rocks.

MINERALOGY

Quartz is the most abundant mineral in the veins, and some veins consist almost entirely of quartz. Rhodochrosite, barite, and mica are other common gangue minerals. Sphalerite is the most abundant sulfide mineral, followed in approximate order of abundance by galena, pyrite, tennantite, chalcopyrite, lead sulfosalts(?), ruby silver, and

enargite. The sulfide minerals chalcocite, bornite, covellite, realgar, and orpiment occur sparingly. In addition, veins in the batholith contain tetrahedrite, arsenopyrite, stibnite, and argentite (Emmons and Calkins, 1913, p. 153-155; Emmons, 1907, p. 40).

Quartz occurs in a wide variety of forms and sizes. Most is colorless or white and coarse grained; examples of later quartz cutting earlier deposited quartz are common. Sphalerite coats comb quartz, and some fine-grained quartz is mixed with fine-grained sphalerite to produce a rock resembling brown chert. Quartz forms veinlets in almost all the other vein minerals, and vugs in the veins are commonly lined with coarse-grained quartz.

Most of the sphalerite is resin colored, but some is red brown or red; a little is black or green. Coarse-grained sphalerite occurs in massive sulfide-rich bands in the veins or in leaner bands where it fills voids in and around quartz and barite. Some sphalerite shows growth bands marked by alternating light and dark layers, and some show polysynthetic octahedral twin lamellae. The replacement of sphalerite by later copper sulfides has, in a few places, been controlled by the twin planes; and where replacement was not complete, skeletal sphalerite crystals in copper sulfides resulted.

Generally, pyrite is not abundant in the Philipsburg sulfide ore and cannot be seen in hand specimen; however, it is present in almost all samples. Most pyrite occurs as microscopic euhedral to subhedral pyritohedrons that are surrounded by quartz and sphalerite; in very few places, veins contain large streaks or irregular blobs rich in pyrite. Irregular, embayed pyrite grains are replaced by copper sulfides and, less commonly, by sphalerite and galena. Pyrite has, to a limited degree, localized copper sulfides. A few crystals of pyrite contain grains of strongly anisotropic marcasite. Although most of the grains are irregular, some are pyritohedrons, thus indicating that marcasite postdates and replaces pyrite.

Galena is widespread in the quartz veins but is generally not as abundant as sphalerite. Most galena consists of fine to coarse grains that replace sphalerite and are scattered through the zinc ore; a very small amount occurs in relatively pure streaks. Near the surface most galena has been altered to cerussite, but unaltered galena has been found in outcrops of several quartz veins.

Tennantite and tetrahedrite are the most abundant copper minerals in the district; they are probably argentiferous and the source of some of the silver recovered from the sulfide ore. Samples from veins in the sedimentary rocks were tested for antimony with negative or only weakly positive results. Therefore, these veins probably contain tennantite but very little tetrahedrite. However, veins at the Granite-Bimetallic mine, in the batholith, contain appreciable amounts

of tetrahedrite and little tennantite (Emmons and Calkins, 1913, p. 155). Tennantite occurs as fracture-filling veinlets in sphalerite, commonly with chalcopyrite, and uncommonly as veinlets along galena cleavages. It veins and replaces enargite and, to a lesser extent, galena. Fracture fillings of tennantite in sphalerite commonly appear to end at a galena crystal but actually replace galena a short distance inward from the veinlet (fig. 5). Some tennantite contains tiny blebs

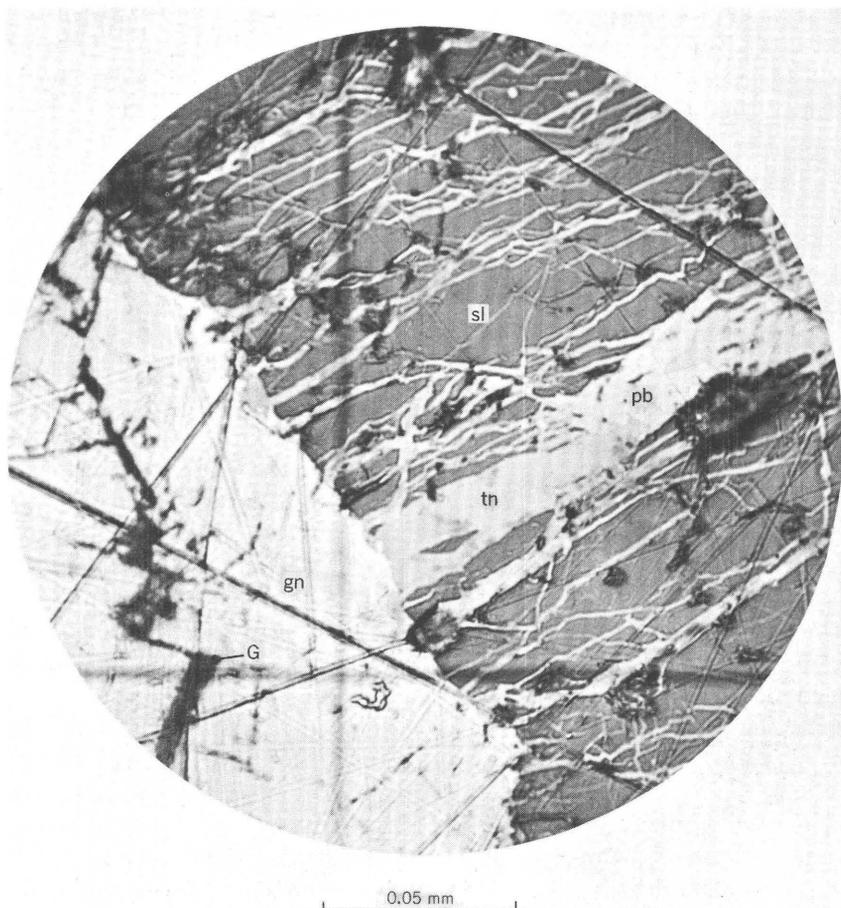


FIGURE 5.—Sphalerite (sl, dark gray) cut by veinlets of tennantite (tn, medium gray) and sparse lead sulfosalts (?) (pb, slightly lighter than tennantite). Note the matching walls indicative of fracture filling in many tennantite veinlets. Galena (gn, white) appears to truncate the veinlets, but some tennantite has replaced galena inward from the grain boundary. The dark nonopaque mineral (G) along galena cleavages is probably quartz. Horton vein, 500 level, True Fissure mine. Reflected light.

of chalcopyrite and a white mineral, possibly galena, that are probably due to exsolution, and much tennantite contains unreplaced remnants of enargite or galena.

Chalcopyrite is moderately abundant, and its habit is similar to that of tennantite. It occurs in veinlets in sphalerite (fig. 6) and along galena cleavages, and it replaces tennantite, enargite, and galena. Some also coats grain boundaries between quartz and other sulfides. Most enargite has been replaced by other copper sulfide minerals, and few grains are large enough to be identified in hand specimen. Bornite is scarce and is everywhere associated with chalcopyrite. It forms rims between chalcopyrite and tennantite or triangular replacement patterns in chalcopyrite where it has been partly replaced by other copper sulfides such as tennantite or covellite.

An unidentified mineral or group of minerals commonly is associated with galena and tennantite where those two minerals occur together. The material is pale green in polished section and ranges from shades nearly as dark as tennantite to those nearly as light as galena. It is moderately anisotropic and replaces or cuts galena along cleavage cracks or grain boundaries. Several lead sulfosalt minerals, some of which contain copper or silver, have these properties. The variation in color suggests that more than one sulfosalt is present.

The ruby silvers, proustite and pyrargyrite, are the principal source of silver in the high-grade silver sulfide ores in the district. All the hand specimens studied appear to contain the light ruby silver, proustite; however, much of the ruby silver is present in microscopic amounts where the two are inseparable. Goddard (1940, p. 172) listed pyrargyrite, proustite, and polybasite as occurring in small amounts in the unoxidized ore near Philipsburg, and Emmons and Calkins (1913, p. 154-155) stated that pyrargyrite is more abundant than proustite at the Granite-Bimetallic mine.

In the Philipsburg area, chalcocite is scarce and is associated with other copper sulfides in veinlets that cut sphalerite. It replaces tennantite and is cut by veinlets of covellite. In reflected light, the chalcocite appears gray with a slight blue cast and is anisotropic; some is twinned. Covellite is widespread but not abundant, and little is coarse enough to be identified in hand specimen; it forms tiny blebs or veinlets in other copper sulfide minerals or tiny veinlets in sphalerite and galena. Covellite has been found in a partially oxidized vein—the True vein in the Mystery tunnel—200 feet below the surface, and in the deepest levels studied—the Algonquin 800 level and True Fissure 800 level.

Barite is widespread and locally abundant in the veins near Philipsburg. Most forms platy crystals, some of which are bent and are cut

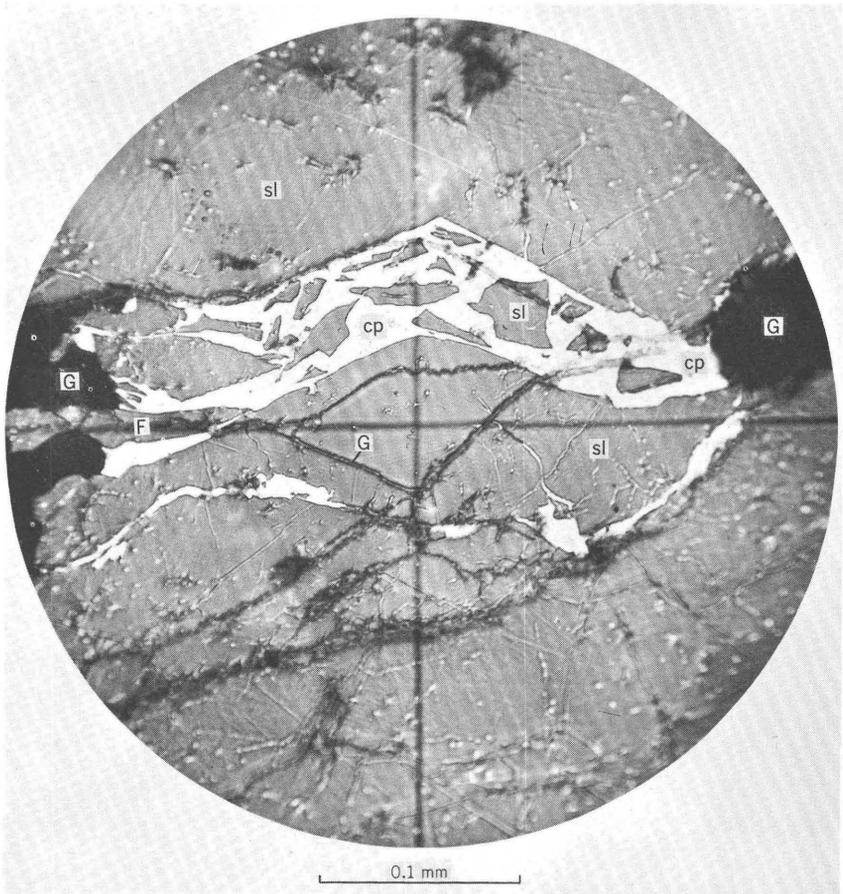


FIGURE 6.—Brecciated sphalerite (sl, dark gray) cut by chalcopyrite (cp, white). Sphalerite fragment (F) in left part of photograph has been torn from the wall of the veinlet and rotated slightly. Dark veinlets and black areas (G) are nonopaque gangue. Algonquin vein, 800 level, Algonquin mine. Reflected light.

by small veins of quartz. Locally, barite laths analogous to feldspar laths in basalts are set in a matrix of sphalerite and quartz (fig. 7). Much barite was dissolved after it was deposited, leaving platy-shaped cavities, some of which were filled or partly filled by carbonate, quartz, quartz and manganese oxide (fig. 8), or by later barite. In the sample shown in figure 8, a barite lath was surrounded by manganese oxide and the barite was dissolved. The void was lined with quartz, then partly filled with manganese oxide, and the filling later completed by coarser grained quartz. Late barite occupying old barite voids is recognized by the fact that the cleavages and optic axes of the later

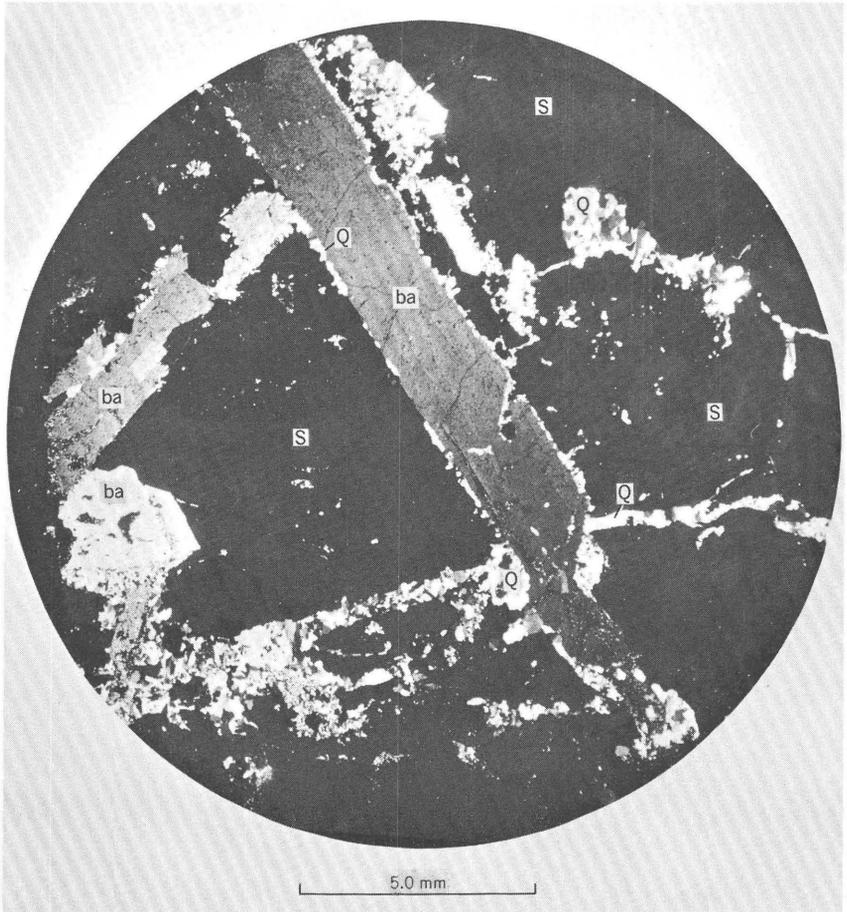


FIGURE 7.—Laths of barite (ba) with interstitial sulfide minerals (S), mainly sphalerite. Quartz (Q) cuts the sulfide minerals and barite and follows the boundary between barite and sulfide. Mountain View vein, 800 level, True Fissure mine. Crossed nicols.

barite do not parallel the elongation of the lath. Some laths are replaced by clear quartz that is in optical continuity with cloudy quartz outside of the lath (fig. 9). Late barite, possibly derived from early barite that has been dissolved and redeposited, cuts sphalerite and lines vugs in comb quartz.

Pale- to dark-pink medium- to coarse-grained rhodochrosite lines or fills vugs in the quartz-sulfide veins or cements brecciated vein material. In places pink bands of rhodochrosite alternate with white bands of manganoan dolomite or with bands of quartz. Some quartz veins adjacent to or enveloped by manganese-rich replacement de-

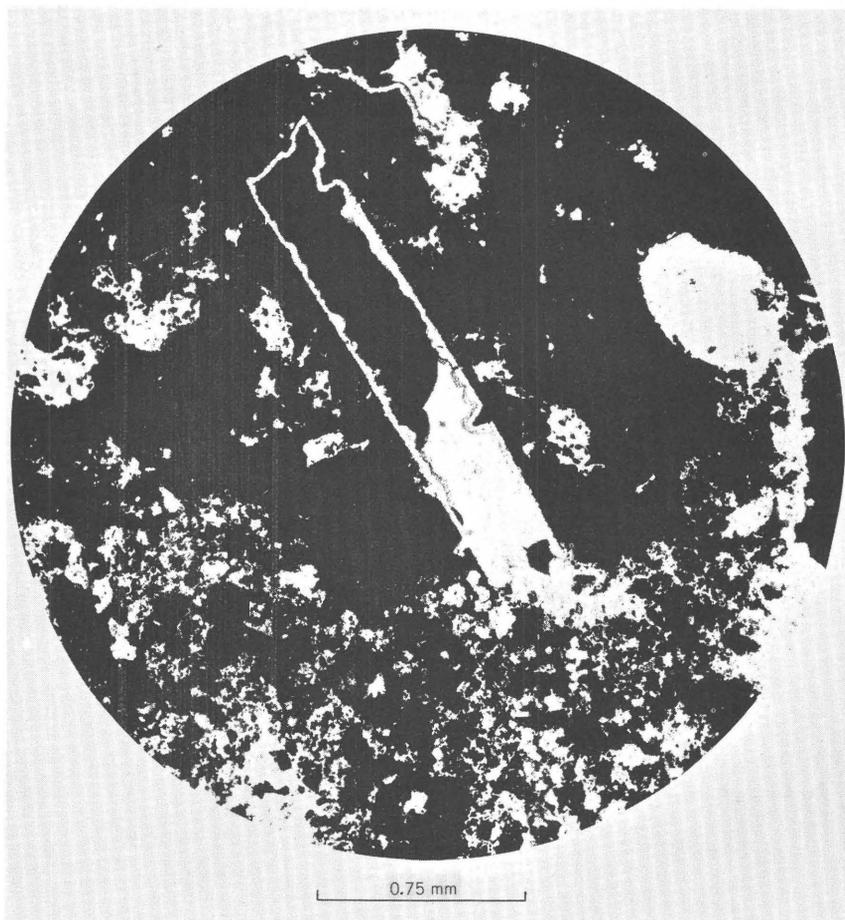


FIGURE 8.—Quartz and manganese oxide pseudomorphous after barite in oxidized manganese-rich quartz vein. White areas are quartz, and the black, manganese oxide minerals. Murphy adit, Mystery mine. Plane-polarized light.

posits are replaced by rhodochrosite that is characteristically bright pink. Optical and X-ray data for rhodochrosite and manganoan dolomite are plotted in figures 10 and 11. These data indicate that the rhodochrosite contains a minimum of 87 percent MnCO_3 and that the manganoan dolomite contains as much as 31 percent MnCO_3 . (See Prinz (1964) and p. 35 for discussions of this method of determining composition.) Calcite and ankerite have also been reported from the veins (Emmons and Calkins, 1913, p. 204; Goddard, 1940, p. 172).

The oxidized parts of the veins consist mainly of quartz and widespread but not abundant manganese oxide minerals, goethite, cerussite,

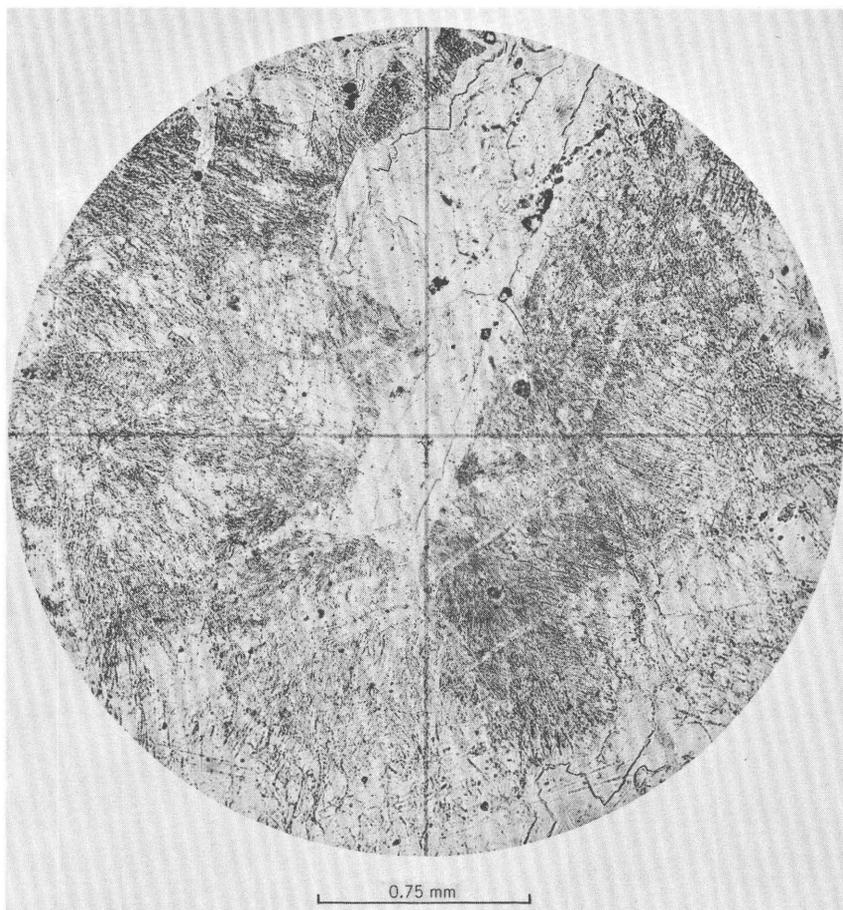


FIGURE 9.—Quartz pseudomorphous after barite. Above, former barite lath has been replaced by clear quartz; the remainder of the field is cloudy quartz. True-Huffman vein, 500 level, True Fissure mine. Plane-polarized light. Right, same as above but under crossed nicols. Note that the individual quartz grains are continuous across the border of the former lath.

malachite, pyromorphite, and remnants of sulfides. Cryptomelane, nsutite, pyrolusite, chalcophanite, and hetaerolite, which are described in more detail on pages 39–51, are the common manganese oxides present; coronadite showing an X-ray pattern almost identical with that given by Roy (1959, p. 1566) occurs with quartz, cerussite, galena, chalcophanite, and hetaerolite on the dump of a small shaft in an oxidized vein 650 feet east-southeast of the Scratch Awl mine. Goethite, identified by X-ray, includes material formerly called limonite (Emmons and Calkins, 1913, p. 156). Sparse chrysocolla



FIGURE 9.—Continued

and azurite occur with malachite; all three are most abundant in the western part of the district. Barite is abundant in some veins near the surface, and sparse hemimorphite occurs locally. Cerargyrite has been reported from the Granite-Bimetallic mine, and native silver from the Speckled Trout and Granite-Bimetallic mines (Emmons and Calkins, 1913, p. 205, 209).

DESCRIPTION

The steeply dipping quartz veins as a group range from a few inches to 20 feet in thickness; their average minable thickness is probably about 3-5 feet. Individual veins in the sedimentary rocks are thickest in carbonate units, somewhat narrower in shaly units, and thinnest in quartzite. The Silver Hill, Hasmark, and Red Lion Formations are

the most favorable host units, however, the degree to which each has been mineralized varies. For example, the Two Percent vein has been more productive in the Hasmark Formation than in the overlying Red Lion Formation, whereas at the True Fissure mine, 1,500 feet to the southeast, the Mountain View vein is thicker and richer in the Red Lion than in the Hasmark. Some ore has also been mined from veins in the Maywood and Jefferson Formations, but these formations are cut off by the batholith at depth and to the south, and fewer veins occur in them. Veins in the Flathead and in Belt quartzite tend to be narrow, but they contain irregularly distributed pods of high-grade sulfides.

The veins are banded; sulfides are generally concentrated in layers or pods that are parallel with vein walls. Sulfide-rich layers alternate with layers of gangue, and the distribution of the metallic minerals in individual veins is very erratic. At places or in single layers, sphalerite is the only sulfide mineral; whereas only a few feet away or in adjacent layers, the vein may contain abundant galena or copper sulfides with little sphalerite.

Breccia zones parallel the layering and the walls in many places in the veins. These zones consist of such combinations as brecciated early quartz cemented by later quartz, sphalerite cemented by quartz, sphalerite cemented by chalcopyrite, and quartz and sulfide vein material cemented by rhodochrosite.

The walls of the veins are either sharp, and commonly marked by fault gouge, or they are irregular. Irregular walls are probably caused by the replacement of wallrock away from the fissure. Minor veins that follow bedding, or that dip steeply, split from the main veins in many places.

Alteration of the wallrock along steeply dipping veins is negligible in sedimentary rocks; it is pronounced in granodiorite but extends only a few feet away from the vein. Mafic minerals in the granodiorite were altered in part to leucoxene, and feldspars were sericitized. Pyrite and secondary quartz were introduced. Closely spaced joints or sheeting commonly parallel the veins in both sedimentary and igneous rocks.

The Granite-Bimetallic vein consists of four zones roughly parallel with the land surface and caused by oxidation and secondary enrichment by descending water (Emmons and Calkins, 1913, p. 204-205). A lean oxidized zone extends from the surface to depths as great as 300 feet and is underlain by an enriched oxidized zone that is generally within 400 feet of the surface and contains cerargyrite and native silver. This is in turn underlain by an enriched sulfide zone, generally between 300 and 800 feet below the surface and characterized by ruby

silver and some argentite. Below this is the zone of primary sulfides—pyrite, arsenopyrite, tennantite, tetrahedrite, galena, and sphalerite.

No such regular zonation can be recognized in the veins in the sedimentary rocks because the depth of oxidation in those rocks varies considerably. For example, oxide-zone copper minerals occur in veins 800 feet below the surface, and galena has been seen in outcrop. This variation is probably due to differences in permeability of the veins and to variations in the iron sulfide content. Where iron sulfides were abundant and the vein was permeable, strongly acid solutions were formed that could migrate far below the surface. Where iron sulfides were scarce and the vein impermeable, oxidation was confined to relatively shallow depths.

TENOR OF ORE

Most of the ore from the steeply dipping veins has been silver-zinc sulfide ore. The oxidized parts of steeply dipping veins contain some silver ore, but little ore of this type has been mined except at the Granite-Bimetallic mine. The manganese content of the veins is generally not high enough to warrant mining, and these veins have contributed a very small part of the total manganese production of the district.

The enriched oxidized ore at the Granite-Bimetallic mine contained 300–400 oz per ton of silver; the enriched sulfide ore, 50–1,000 oz per ton of silver; and the primary sulfide ore, 20–30 oz per ton of silver (Emmons and Calkins, 1913, p. 204–205). The tenor of other veins in the batholith was much lower. The grade of ore mined in recent years from veins in the sedimentary rocks has probably averaged from 10–30 oz per ton of silver, 10–20 percent zinc, 1–3 percent lead, and a trace of copper and gold. Almost all was sulfide ore.

RELATION BETWEEN VEINS IN THE SEDIMENTARY ROCKS AND IN THE BATHOLITH

Zones of sheared and brecciated rock which have been recognized at several places along the contact between the batholith and the sedimentary rocks suggest that the contact is a major fault and that the veins on either side of the contact are faulted segments of once-continuous veins. However, the general lack of correlation between major veins on either side of the contact argues against this idea.

At the surface, exposures near the contact are poor, and no vein can be traced continuously across it. The contact has been cut at several places underground, but during the present study these places were inaccessible or tightly lagged. Emmons and Calkins (1913, p. 208) stated that the San Francisco vein has been explored both in the batholith and in the Jefferson Limestone on level 4. The contact

between the two units is disturbed and the vein on the west side is offset 25 feet to the south. If the Horton and Silver Chief veins are the same, then the offset along the border of the batholith on the 100 level of the True Fissure mine was on the west side 50 feet south (pl. 3). However, company maps of the True Fissure 300 level show the Horton vein extending into the granodiorite with no offset. Furthermore, old maps of the True Fissure 400 and 500 levels show that this vein was not offset along the contact but that the contact was offset along the vein with the north side offset 15–20 feet east (pls. 4, 5). The Cliff vein is shown extending from Jefferson marble into granodiorite on the Scratch Awl 300 and 500 levels, and the Footwall Scratch Awl vein crosses this contact on the 500 level (pls. 3, 4). Old maps show no offset at the contact, but several faults within the batholith displace the east side of the veins to the north. The Pocahontas vein is cut off by a fault at the border of the batholith on the 600, 800, and 1000 levels of the Algonquin mine and has not been located east of the fault (pls. 5, 6).

All the veins postdate the batholith. Evidence of this is found at several places underground where veins cut both the sedimentary rocks and dikes and sills which are presumably offshoots from the batholith. This relationship and the similarity in strike and dip of the veins on both sides of the contact indicate that the veins formed at about the same time. However, no vein has been traced from the sedimentary rocks for any great distance into the batholith or vice versa, and the pattern of the veins cannot be matched across the contact—no series of veins in the batholith corresponds to the persistent Algonquin, Pocahontas, Cliff, and Horton veins in the sedimentary rocks (pl. 1). Tracing of some veins across the contact precludes the possibility of faulting of large magnitude to explain this poor match.

The rough parallelism of the veins on both sides of the contact suggests that they were all formed by the same set of stresses. However, because the rocks are different on either side of the contact, they would have reacted differently to these stresses, producing one set of veins in the batholith and another set in the sedimentary rocks. Veins thus formed would be expected to extend only a short distance from one unit into the other, as is true of the Cliff and Horton veins. Shear zones along the contact may not be the result of a major fault but rather of minor and local faulting. The Horton and Silver Chief veins are probably not faulted segments of the same vein, and their present positions may be only fortuitous.

CONTINUITY IN THE SEDIMENTARY ROCKS

The Pocahontas vein is the most extensively explored vein in the sedimentary rocks; it has a strike length of 3,000 feet and extends to

a depth of at least 1,100 feet. Comparable dimensions would be expected for the other major west-striking veins in the district, but such dimensions have not yet been shown for the northwest-striking veins. However, the Mountain View and Scratch Awl veins become larger and more continuous at depth and may prove to be as extensive as their west-striking counterparts.

Even though some veins, such as the Headlight, apparently pinch out downward, the bulk of the evidence indicates that the present workings are near their tops. Goddard (1940, p. 193, 199) noted that en echelon segments of the Cliff vein near the surface converge downward to form a continuous vein on the 500 level of the Scratch Awl mine and that the Pocahontas vein horsetails or splits upward into several strands. The Mountain View is another vein that horsetails upward. At the surface, this vein cannot be recognized, and it is represented only by several small quartz stringers in the central part of the Headlight 500 level and northern part of the Headlight 700 level (pl. 4). However, 500 feet below the surface, on the True Fissure 500 level, the vein has been stoped for silver-zinc ore, and on the True Fissure 600 level it has been traced for 1,600 feet along strike.

This evidence suggests that the size and continuity of the veins will improve at depth; however, at depth they will enter quartzite, an unfavorable host rock in which the veins have generally been thin and discontinuous. Although several high-grade pods have been selectively mined from veins in quartzite, such veins generally have not been considered promising and have not been extensively explored. In the late 1950's, however, the Trout Mining Co. began exploiting the Pocahontas vein in quartzite above the 600 level of the Algonquin mine by using low-cost mining methods (shrinkage stoping) and removing both the lean and the high-grade parts of the vein. This work has been near the west edge of the belt of most productive veins (see p. 17) and has been within 600 feet of the surface; the veins should be better near the center of this belt and below the present deepest mine workings.

ORIGIN

The steeply dipping quartz veins consist mainly of minerals generally ascribed to deposition from hydrothermal solutions. The veins were formed in part by cavity filling in the fissures through which the solutions flowed, and in part by replacement of wallrocks. Displacement along the fissures has been small, but the presence of breccias of various ages indicates that movement either recurred during mineralization or was generally continuous throughout mineralization.

The ruby silvers, chalcocite, and covellite may have different origins. Mainly on the basis of their studies at the Granite-Bimetallic mine,

Emmons and Calkins (1913, p. 155) concluded that the ruby silvers were predominantly supergene and were deposited from descending waters. At the mines near Philipsburg, the evidence is not conclusive, but it suggests a hypogene origin. The ruby silvers are found on the True Fissure 800 level and Algonquin 800 level, and although the ruby silvers were among the latest sulfide minerals to form, they are everywhere associated with primary galena, enargite, tennantite, and chalcopyrite. This association, coupled with their presence in apparently unaltered veins 800 feet below the surface, indicates that the ruby silvers are hypogene. Sparse chalcocite and covellite are also found on the deep levels, but it is not known whether they are hypogene or supergene.

QUARTZ VEINS ALONG BEDDING

Quartz veins that follow bedding in the sedimentary rocks are common in the northern part of the district, and those in the Jefferson Limestone at the Hope mine (pl. 1) yielded considerable high-grade silver ore early in the history of the district. Because much of the mine has been closed for almost a century and the surface exposures and old dumps reveal little of the nature of the ore, most of the following information on the Hope mine has been abstracted from Emmons and Calkins (1913, p. 213-218).

The beds and the veins at the Hope mine strike N. 10°-60° E. and dip about 30° NW., but strike and dip are both variable; some of the largest ore bodies occur on the crests of small anticlines or in the saddles of small synclines. The veins are irregular in detail but roughly follow bedding in limestone or fine-grained marble. Veins occur at several horizons, and some are connected by thin stringers that parallel the west-striking steeply dipping veins to the south. In plan, the major veins are divided into two groups, called ore channels, that are separated by a 400-foot interval of barren rock (Cole, 1949, fig. 3). The ore channels trend about N. 80° E. and are thus parallel with the major group of steeply dipping veins and with the connecting stringers. The sulfide ore at the Hope mine consisted of quartz, calcite, fluorite, barite, rhodochrosite, argentite, chalcocite, and argentiferous "gray copper," and the rich oxidized ore contained cerargyrite, malachite, azurite, and chrysocolla. The average thickness of these bedding veins was probably less than 3 feet, but the ore, especially that in the oxidized zone, was very rich in silver.

In 1960, a bedding quartz vein at the Cadgie Taylor mine, which is northeast of the Hope mine (pl. 1), was being mined by open pit for silver and silica. This vein is 15-20 feet thick and consists of vuggy quartz and barite. Some of the vugs are lined by apparently well-formed crystals of manganite, which X-ray shows are actually a

pseudomorphous mixture of ramsdellite and pyrolusite. This is the only known occurrence of ramsdellite in the district.

The distribution of the bedding veins on Hope Hill suggests that they may pass into steeply dipping veins at depth. The U.S. Bureau of Mines found evidence of mineralization in two diamond-drill holes in this area (Cole, 1949); the objective of this drilling, however, was to penetrate the top of the Hasmark Formation below the old Hope workings, and further drilling is needed.

Many other bedding veins occur in the Red Lion, Maywood, and Jefferson Formations in the northern part of the district, but only the vein at the top of the Red Lion Formation at the Two Percent mine, which has been stoped for silver discontinuously downdip for about 400 feet (pl. 2), appears to have yielded much ore. These veins consist mainly of quartz but contain some barite, manganese oxide minerals, and sparse specks of sulfides or secondary copper minerals.

Sphalerite has not been noted in the veins in the northern part of the district nor in the deeper workings of the Hope mine (Emmons and Calkins, 1913, p. 214). However, it may be abundant at depth, as is indicated by (1) the presence of chalcophanite, a zinc-bearing manganese oxide mineral, in bedding veins on Poorman Hill (pl. 1) and in the No. 16 adit (pl. 2), (2) the small amount of zinc in diamond-drill holes below the Hope mine (Cole, 1949, tables 4, 5), and (3) the above-average zinc content of manganese oxide ore from the Marie and Little Dandy mines (Wells and others, 1947, p. 4).

In the western and northwestern parts of the district, a few shear zones, most of which parallel bedding, contain sparse secondary iron, copper, and manganese minerals, some quartz, and scattered scheelite crystals. These zones, which contain more iron and less quartz than most bedding veins, assay as much as 1.74 percent WO_3 (Walker, 1960, p. 23); but mineralization is spotty, and no production of tungsten has been reported. Powellite ($CaMoO_4$) has also been identified in some of these shear zones (Walker, 1960, p. 24).

MANGANESE-RICH REPLACEMENT DEPOSITS

DISTRIBUTION

Replacement deposits rich in manganese are irregularly distributed in favorable beds along steeply dipping quartz veins, the Redemption fault, and the border of the batholith. Most deposits are within the belt of the most productive steeply dipping veins (p. 17), and almost all deposits outside this area occur along the granodiorite contact or the Redemption fault, or in a belt parallel to and 1,500 feet northeast of the Redemption fault (pls. 1-6). The last-named belt includes the manganese ore in the Murphy drift, the Moore, White Horse, and

Mullen ore bodies, and the ore bodies in the western part of West Algonquin Hill (pls. 1-5). Alined groups of deposits within the main area of manganese replacement deposits are difficult to recognize, but two are suggested. One group trends parallel with the Redemption fault and includes the Durango, Huffman, Bryant, Cliff, Trout, Algonquin, Coyle, and Climax ore bodies and the ore bodies along the Horton vein between coordinates 9,000 E. and 10,000 E. The other group trends parallel with the border of the batholith and includes the Headlight, Mountain View, and Scratch Awl ore bodies and those along the Horton vein between coordinates 10,000 E. and 11,000 E. The two groups intersect at the Trout and Algonquin ore bodies.

There is some evidence that the manganese replacement deposits are alined vertically. The large Mountain View ore body in the Hasmark Formation on the 600 and 800 levels of the True Fissure mine (pls. 5, 6) is vertically below the biggest part of the Headlight ore body (pls. 3, 4; sections *A-A'*, *F-F'*, pl. 7), although the two are separated by 300 feet of mostly barren rock of the Red Lion Formation.

RELATION TO HOST ROCKS

Manganese-rich replacement deposits are restricted to relatively pure carbonate host rocks which are, in order of relative importance: (1) Hasmark marble, (2) Headlight bed at the top of the Red Lion Formation, (3) limestone beds in the middle of the Silver Hill Formation, (4) Jefferson marble, especially near the batholith, and (5) limestone beds in the Maywood Formation. Those associated with steeply dipping veins are commonly restricted to only one side of the vein, and in a few places barren rocks separates the vein and the replacement deposit. In favorable host rocks it is, therefore, necessary to drill the walls of drifts along veins in order to be certain that replacement ore has not been missed. Some veins are engulfed and replaced by manganese deposits, thereby making the vein difficult to recognize, especially in the oxidized zone.

Although the intersections of favorable beds and quartz veins controlled the distribution of the manganese deposits, most intersections are not replaced, and Goddard (1940, p. 171) has likened the distribution of replacement ore bodies along the veins to beads along a string. Furthermore, there is no relation between the size of the steeply dipping vein and the size of the associated manganese replacement deposits. For example, the Durango ore body is one of the largest manganese deposits in the district, but in many places in the Durango mine the vein is only a very narrow quartz stringer or cannot be recognized at all. Because of this, exploration for manganese-rich replacement deposits has been difficult and expensive.

The shapes of the manganese-rich replacement deposits are con-

trolled by the character of the host rocks. Where the host rocks are thin bedded, the deposits are tabular. In massive or thick-bedded host rocks, the deposits are irregular pipes that tend to be vertical.

The most favorable thin-bedded host rocks are the Headlight (or Scratch Awl) marble bed at the top of the Red Lion Formation, and the Silver Hill Formation. The Headlight bed is generally less than 8 feet thick and lies between shale, above, and impure limestone, below. The Headlight bed has been partly replaced by manganese near some steeply dipping veins. The contact between unreplaced host rock and mineralized rock in places is sharp, whereas in other places it is gradational and the ore fingers out along bedding into barren rock. The ore deposits in the Headlight bed are tabular and follow it closely but are very irregular in outline (pls. 2-4; Goddard, 1940, pl. 31). They have an average thickness of 3-5 feet, a maximum strike length of 500 feet, and dip length of 1,500 feet. Manganese deposits in the Headlight bed are present at the Headlight mine, where ore has been mined from the surface to the 600 level of the True Fissure shaft (pls. 2-5; section *A-A'*, pl. 7), and at the Scratch Awl mine, where the bed has been extensively replaced by manganese between the Cliff and the Scratch Awl veins (pl. 3).

In the middle of the Silver Hill Formation, several beds of relatively pure limestone that are separated by beds of impure limestone or tactite have been partly replaced by manganese near steeply dipping veins. The deposits commonly occur in layers that are separated by barren beds (pl. 2), and in many places they follow one bed for a short distance, end, and then continue in another bed above or below. Although the deposits in many beds are thin, locally those from several beds become thick enough to coalesce and form a single thick ore body. Deposits in the Silver Hill Formation are thus much more irregular than those in the Headlight bed. Manganese replacement deposits are abundant in the Silver Hill Formation on West Algonquin Hill, where several steeply dipping veins cut the formation at the crest of the anticline, and to the southeast at the Coyle mine (pls. 1-3).

Most of the manganese replacement deposits in the massive to thick-bedded Hasmark marble are irregular nearly vertical pipes. They occur, and tend to be elongated, along either steeply dipping veins or the Redemption fault. These deposits, like the Durango ore body, are extremely irregular; they swell in more favorable beds or below impermeable zones, such as a fault or a shale bed, and pinch in less favorable beds or above impermeable zones. The Durango deposit is rather uniform in size for most of the distance between the 4th and 5th levels (pl. 5 and section *A-A'*, pl. 7), but it pinches in one unfa-

avorable bed in this interval and above a fault between the 5th and 6th levels (section *A-A'*, pl. 7). It is much larger below this fault (pl. 6) and below a fault near the 3d level (pl. 4 and section *A-A'*, pl. 7). The petrographic differences between favorable and unfavorable beds are unknown; the whole formation is relatively uniform dolomitic marble.

Long fingers extend above the main part of many ore bodies, as above the Moore and White Horse ore bodies (section *B-B'*, pl. 7; Pardee, 1921, fig. 30), and there is little or no evidence at the surface to indicate the presence of an ore body below.

The nearly vertical pitch of these ore bodies is well shown by the Moore, White Horse, and Trout ore bodies. Near the surface, the Trout ore body is at the top of the east-dipping Hasmark Formation (pls. 1, 2); but because it is vertical, it cuts down nearly to the middle of the formation on the Trout 400 level (pl. 3) and to the base on the Trout 600 level (pl. 4). The Coyle ore body differs from most of the others in that it extends along the base of the Hasmark Formation; shoots within the ore body, however, are vertical or nearly so (pl. 8).

Manganese-rich replacement deposits in the Hasmark Formation range considerably in size. In plan, most have areas of less than 1,500 square feet, but areas of 4,000 square feet are common in the larger ore bodies. Some deposits have a limited vertical extent whereas others have been mined vertically for several hundred feet. The Coyle ore body extends down to 650 feet below the surface, or 900 feet along the rake.

Near the border of the batholith, the Jefferson Limestone contains some manganese replacement deposits. The Sharktown ore body, the largest of these, and a similar ore body on the True Fissure 400 level are more irregular than the typical deposits in thin-bedded host rocks, but they follow bedding more closely than do those in the massive Hasmark Formation (pls. 2, 4; Goddard, 1940, fig. 33). At the Marie, Chicago, Little Dandy, and Saunders mines in the northeastern part of the district, manganese-rich replacement deposits in the Jefferson Limestone follow bedding closely and are tabular like those in the Headlight bed (pls. 1-3). These deposits, however, are generally small.

Small tabular manganese replacement deposits also locally follow thin beds in the Red Lion and Maywood Formations in the central part of the district.

MINERALOGY

HYPOGENE MINERALS

The unoxidized manganese-rich replacement deposits consist mainly of varying amounts of two manganese-bearing carbonates—rhodo-

chrosite and high-index dolomite believed to be manganese bearing. Manganoan calcite was not found, perhaps because most carbonate-ore specimens available for study were from dolomitic host rocks.

Rhodochrosite is pale to deep pink, and ω ranges from 1.775 to 1.81 (fig. 10). The center of the strongest X-ray line (d_{211}) is between 2.82 and 2.84 Å, but this line is commonly a broad band representing a variation in spacing of as much as 0.06 Å.

Manganoan dolomite is gray, white, or pale pink, and ω ranges from 1.68 to 1.715 (fig. 10). Its X-ray pattern is similar to that of pure dolomite. The d -spacing of the strongest X-ray line ranges from 2.87 to 2.90 Å and shows no relation to the variation in index of refraction. The presence of manganese in this mineral has not been confirmed by chemical analysis. Both manganese and iron increase the index of refraction of dolomite; however, the low iron content of bulk samples of manganese carbonate ore (table 2) shows that the high index of refraction of this mineral cannot be due solely to iron. This fact, plus the invariable association of rhodochrosite with high-index dolomite, implies that the dolomite is manganese bearing.

The index of refraction, ω , was measured for all samples of manganoan carbonate collected during this study. These data are plotted in figure 10 along with X-ray data, color of mineral, and host rock. All samples having low indices of refraction (between 1.68 and 1.715) gave dolomite X-ray patterns and are white, pale pink, or gray. Those having high indices (between 1.775 and 1.81) gave rhodochrosite patterns and are pale to dark pink or gray. The lack of samples with ω between 1.715 and 1.775 and the distinctive X-ray patterns show that two minerals are present, and the difference in index of refraction provides a convenient means for distinguishing rhodochrosite from manganoan dolomite where both occur in the same thin section.

Rhodochrosite from the Philipsburg district has been analyzed chemically (Wayland, 1942, table 1; table 2, col. 1-3), but because manganoan dolomite cannot be readily separated from associated minerals, its composition must be deduced by other means. Variation of index of refraction with composition in the system $\text{CaCO}_3\text{-MgCO}_3\text{-MnCO}_3$ was presented by Wayland (1942, pl. 1) and by Winchell and Winchell (1951, fig. 61). Goldsmith and Graf (1960, fig. 6) showed the variation in the spacing of the d_{211} plane in the same system. These data were combined (Prinz, 1964), and samples of manganoan carbonates from Philipsburg for which both X-ray and optical data are available were plotted on the resultant diagram (fig. 11). Samples were plotted as parallelograms rather than points because of the wide range in values for individual samples (fig. 10). The composition of manganoan dolomite determined in this way is 27-48 percent

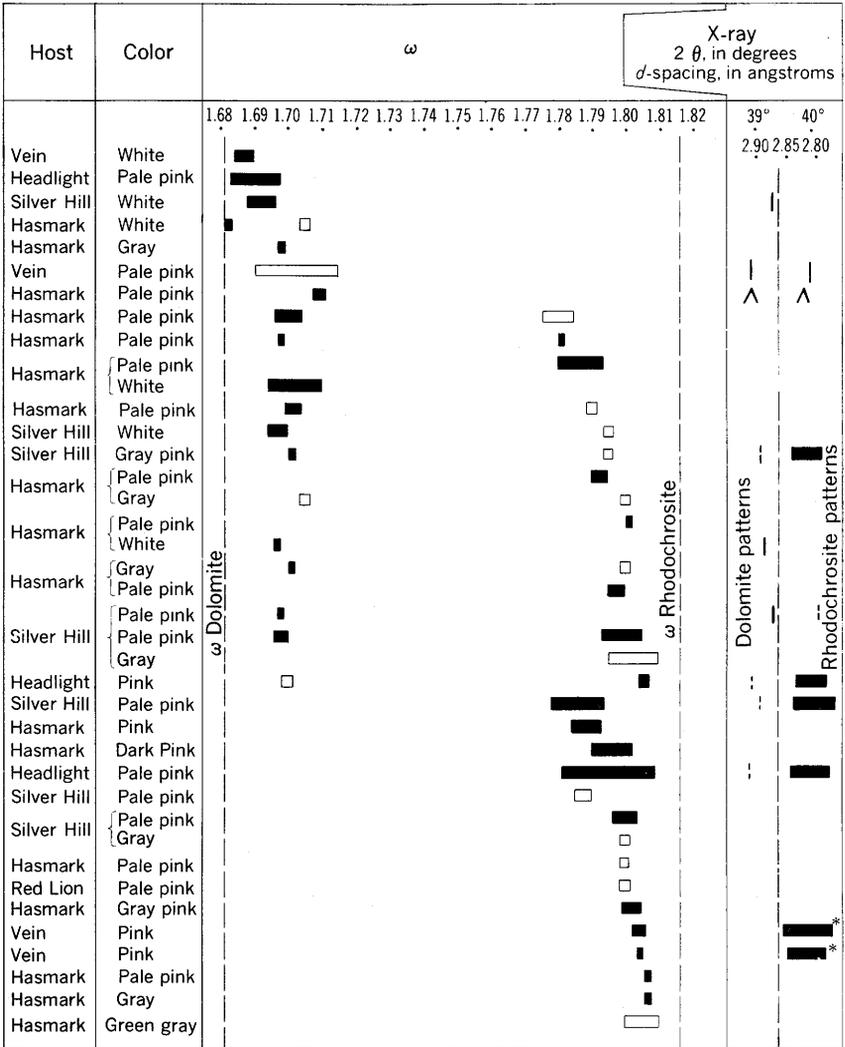


FIGURE 10.—Index of refraction, ω , and position of the strongest X-ray line (d_{211}) in manganous carbonates. Open bars indicate poor index of refraction determinations because the carbonate is fine grained, altered, or not abundant. Carets indicate the position of X-ray lines determined by goniometer; all other determinations were by film. Asterisks indicate abnormally large spindles, and dashed bars indicate very weak lines. All X-ray data taken in manganese-filtered iron radiation.

MgCO₃, 39–52 percent CaCO₃, and 6–28 percent MnCO₃. The diagram also indicates that rhodochrosite from Philipsburg contains a minimum of about 70 percent MnCO₃, and that it contains more MgCO₃ than CaCO₃.

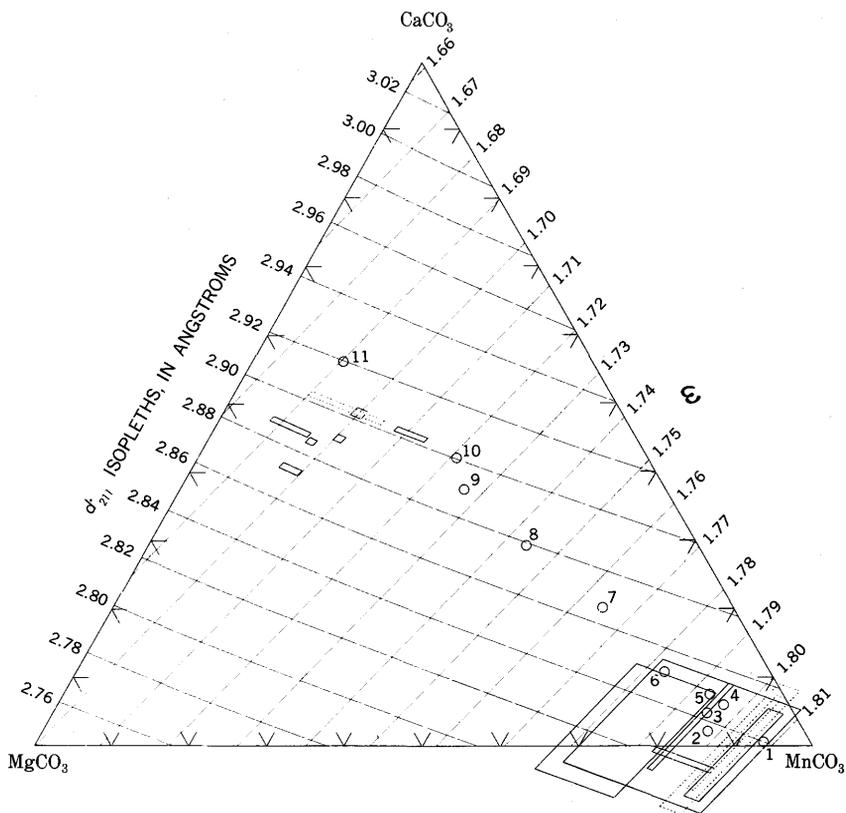


FIGURE 11.—Variation in ω and spacing of the d_{211} plane in the system $\text{MnCO}_3\text{-CaCO}_3\text{-MgCO}_3$. Parallelograms are plots of manganian carbonate samples from the Philipsburg district for which both optical and X-ray data are available. Dotted lines indicate samples from steeply dipping veins; the remainder are from manganese-rich replacement deposits. Circles and numbers are from the analytical data in table 2. All except Nos. 1-3 were calculated from bulk analyses of ores and concentrates and are not, therefore, representative of an individual mineral.

The approximate composition of the manganian carbonates can also be calculated from analyses of ores and concentrates. All the calcium and magnesium in the analyses in table 2 is calculated as carbonate, and where only total manganese is reported, it is all calculated as carbonate. Some iron is undoubtedly present as carbonate in all the samples, but it is not calculated as such because pyrite was found in most of the carbonate ore and the iron cannot be distributed between pyrite and FeCO_3 except in analysis 5. In analysis 5, enough iron to use the sulfur remaining after calculating sphalerite was assigned to pyrite; the remaining iron was calculated as FeCO_3 . The calculated

end-member compositions are shown in table 2 and are plotted in figure 11 along with the three rhodochrosite analyses from Wayland (1942, table 1). The carbonate in the ore and concentrate represented by analyses 4-6 is probably almost all rhodochrosite; that in analyses 7-10 is a mixture of rhodochrosite and manganoan dolomite; and analysis 11 probably represents manganoan dolomite.

TABLE 2.—Analytical data for manganoan carbonates from the Philipsburg district

[n.d., not determined]											
	1	2	3	4	5	6	7	8	9	10	11
Partial chemical analyses											
Mn (Total).....				26.00	26.2	31.81	19.71	19.3	9.16	12.8	4.26
Mn as carbonate.....				n.d.	n.d.	30.93	18.96	n.d.	n.d.	n.d.	n.d.
Mn as MnO ₂.....				.90	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO.....				1.81	2.15	4.06	3.68	6.40	4.71	6.85	8.09
CaO.....				1.91	2.5	4.55	6.14	11.8	9.52	16.4	20.3
Fe.....				.66	1.7	.73	1.04	.9	3.10	1.98	2.91
Cu.....				n.d.	<.05	n.d.	n.d.	.11	.01	<.01	<.01
Pb.....				.11	<.05	n.d.	n.d.	.02	<.02	<.02	.02
Zn.....				n.d.	.95	n.d.	n.d.	.06	.58	.05	.24
Al ₂ O ₃				2.75	2.2	n.d.	n.d.	3	8.24	2.36	7.36
SiO ₂				32.10	25.3	n.d.	n.d.	13.2	33.2	18.6	21.0
CO ₂				n.d.	n.d.	n.d.	n.d.	n.d.	21.6	31.9	26.9
P.....				.084	.040	n.d.	n.d.	.065	.06	.025	.02
S.....				n.d.	1.45	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Insoluble.....				n.d.	31.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
End member composition of carbonates ¹											
MnCO ₃	94.3	88.6	87.0	88.1	84.2	79.6	68.0	53.9	41.6	38.1	14.4
MgCO ₃	4.5	9.4	8.3	6.3	6.9	10.4	13.2	17.9	21.4	20.3	27.2
CaCO ₃	.4	1.9	4.4	5.6	6.8	10.0	18.8	28.2	37.0	41.6	58.4
FeCO ₃	.8	.1	.3	(²)	³ 2.1	(²)	(^{2})	(^{2})	(^{2})	(^{2})	(^{2})

¹ Nos. 4-11 calculated from the analyses assuming all Ca and Mg are present as carbonate. Where only total Mn is reported, it is all calculated as carbonate.

² Iron not calculated as carbonate.

³ Iron remaining after sulfur used up to form sphalerite and pyrite calculated as carbonate.

1. Rhodochrosite, Scratch Awl mine. Wayland (1942, table 1, analysis W).
2. Rhodochrosite, Algonquin mine. Wayland (1942, table 1, analysis V).
3. Rhodochrosite, Algonquin mine. Wayland (1942, table 1, analysis U).
4. Carbonate ore, True Fissure mine, 624 stope. Analysis by the Taylor-Knapp Co.
5. Carbonate ore, Metals Reserve Co. stockpile. Wells, Ispen, and Vincent (1947, table 1).
6. Carbonate concentrate, average grade of material sold to government stockpile by the Taylor-Knapp Co. from April 1953 to June 1955. Analyses by General Services Adm.
7. Low-grade carbonate ore, average grade of material sold to government stockpile by the Taylor-Knapp Co. from April 1954 to August 1954. Analyses by General Services Adm.
8. Rhodochrosite and dolomite, middling fraction from Taylor-Knapp Co. magnetic separator. Stickney and Sanders (1960, table 1).
9. Low-grade dolomitic carbonate ore, Mullen mine. Sullivan, Brown, and Peterson (1962, table 4).
10. Low-grade dolomitic carbonate ore, "Moorlight mines" (probably True Fissure mine). Sullivan, Brown, and Peterson (1962, table 4).
11. Low-grade dolomitic carbonate ore, Mullen mine. Sullivan, Brown, and Peterson (1962, table 4).

The mixture of rhodochrosite and manganoan dolomite is gray to pale pink and commonly has a slight purplish cast. Except for slight differences in color and specific gravity, much of the manganoan carbonate ore looks like unreplaced marble and could easily be overlooked. Original textures commonly are well preserved. Fine-grained rhodochrosite outlines original grains of the dolomitic marble host, coarser grained rhodochrosite extends inward from the margins

of the grain (fig. 12), and the centers of many grains consist of manganean dolomite. Evidently during replacement of the marble, manganese was accommodated in the dolomite structure to the limit of stability of the structure, then rhodochrosite started to form and partly replaced the manganean dolomite. In many places the carbonate in the centers of the grains was later partly or wholly removed, leaving a cellular structure consisting of rhodochrosite that outlines original grains (fig. 12, right). Some of these voids were later filled or partly filled by quartz. In a few specimens the sequence is reversed, and rhodochrosite is cut by later manganean dolomite.

Vugs, some of which may be solution cavities, are commonly lined with bright-pink medium to very coarse grained rhodochrosite and alternating white and pink bands of manganean dolomite and rhodochrosite, or with coarse-grained quartz. In some samples, quartz-lined vugs were filled with later manganean carbonates; in others, quartz grew on rhodochrosite and was the last mineral to form.

Some manganean carbonates are brecciated, and the fragments recemented by quartz, later carbonate, or quartz and mica. In some places, the carbonate ore is shattered badly, and it is impossible to collect specimens more than 1 inch across.

The primary manganese replacement deposits also contain some pyrite, clay minerals, and fluorite. The pyrite forms tiny cubes, pyritohedrons, or rounded grains in manganean carbonates and associated quartz; although it is generally not abundant, it occurs in almost all specimens. The clay mineral is montmorillonite-illite (Larson, 1964, p. 61). Many primary manganese-rich replacement deposits in the southern part of the district, particularly in the Scratch Awl, Trout, and Algonquin mines, also contain sphalerite, galena, and other sulfide minerals. In very few deposits, however, is rhodochrosite subordinate to sulfides in quantity.

Sheets of native silver coat joints, and wire silver occurs in vugs in a sulfide-bearing manganese-rich replacement deposit in the Silver Hill Formation along the Coyle vein above the Algonquin 300 level. Although the native silver occurs about 400 feet below the surface and 250 feet below the bottom of abundant manganese oxides in the ore-bearing horizon, sparse manganese oxides extend at least 150 feet below the occurrence, and the native silver is probably secondary, having formed in, or a short distance below, the zone of oxidation.

SUPERGENE MINERALS

The oxidized manganese deposits consists mainly of cryptomelane, todorokite, nsutite, pyrolusite, and manganite, probably in that order of abundance. Some amorphous manganese oxide is present, but its

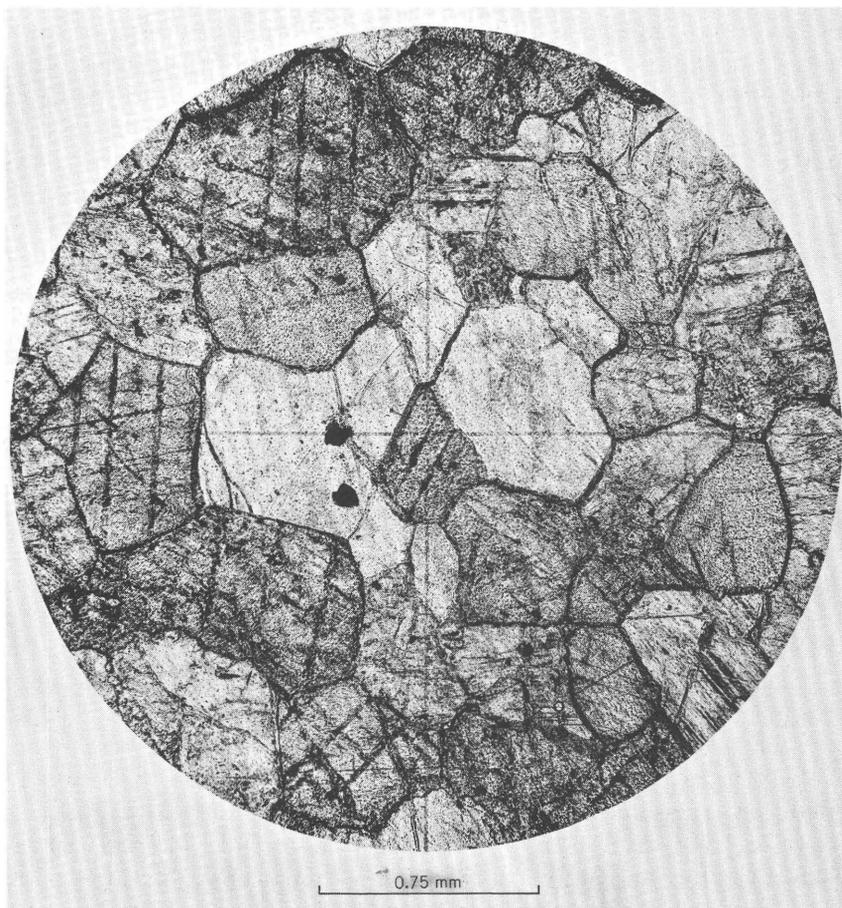


FIGURE 12.—Hasmark marble. Above: Unreplaced Hasmark marble adjacent to manganese carbonate ore. Dolomite containing unidentified opaque dust forms a uniform-textured mosaic. 500 level, True Fissure mine. Plane-polarized light. Right: Hasmark marble replaced by rhodochrosite and manganoan dolomite. Original dolomite grains are outlined by fine-grained rhodochrosite (dark gray). The interior of the grains consists of rhodochrosite and manganoan dolomite in optical continuity. The rhodochrosite forms an outer band and the manganoan dolomite an inner band. (See the large grain in the southeast quadrant.) The white areas in the center of many grains are voids. 600 level, True Fissure mine. Plane-polarized light.

relative abundance is impossible to determine. Chalcophanite and sparse hetaerolite occur in the oxide deposits adjacent to veins and where sphalerite is known or suspected to be present in the primary manganese carbonate deposit. Birnessite was tentatively identified by Larson (1964, p. 69). Gangue minerals in the oxidized ore include quartz, goethite, mica, clay minerals, calcite, and fluorite.



FIGURE 12.—Continued

CRYPTOMELANE

Cryptomelane (KR_8O_{16} , $R=Mn^{II}, Mn^{IV}$) is one of the most abundant manganese oxide minerals in the Philipsburg district. Some of it is soft, does not polish well, and is anisotropic where the polish is good enough to show this property. The remainder is hard (5-6), takes a good polish, and in reflected light is white to light gray, locally with a slight cream cast. This type is anisotropic and faintly pleochroic, but some is very fine grained and appears to be isotropic. Most hard cryptomelane is distinctly grayer than nsutite, but the cream-colored varieties cannot be distinguished from nsutite in polished specimens unless both are present.

Cryptomelane is commonly mixed with nsutite, todorokite, or chalcophanite as a mass of irregular small grains or in banded or

botryoidal structures (fig. 13). With nsutite, cryptomelane forms pseudomorphs after carbonate (fig. 14), and some shows a peculiar microscopic structure similar in appearance to tiny buns or pillows stacked on top of each other (fig. 15). The surface on one side of this structure is rounded and very regular, whereas that on the other side appears to have been molded to fit the surfaces of the adjacent structures. Hard cryptomelane and nsutite constitute the bulk of the material called "psilomelane" in hand specimen.

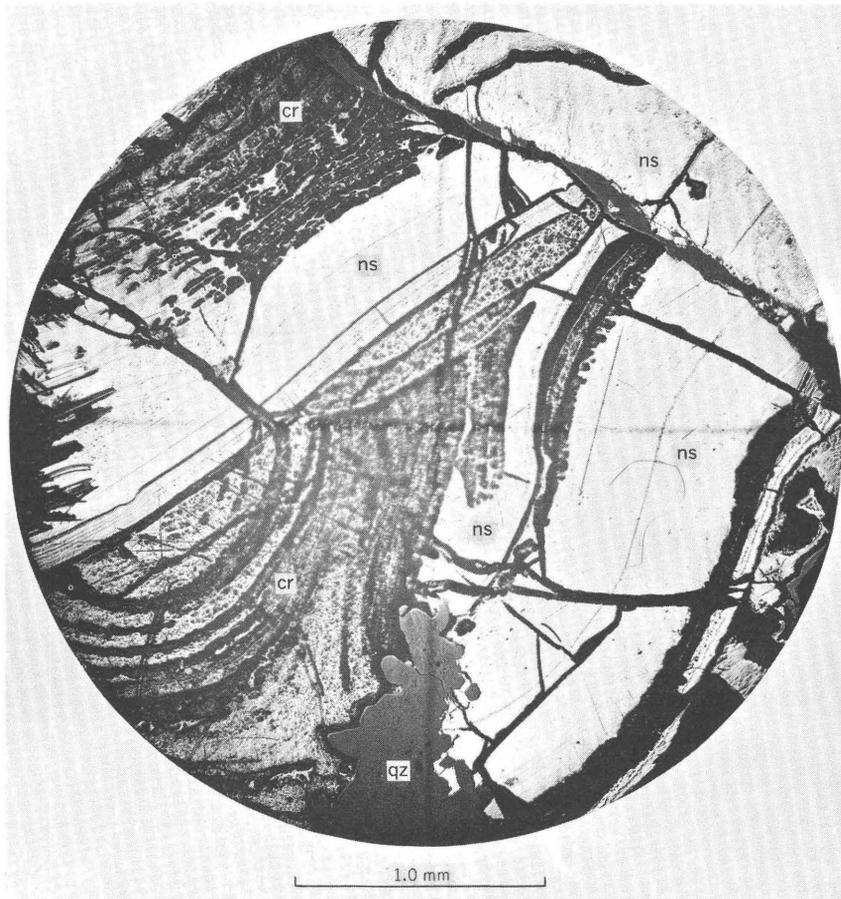


FIGURE 13.—Banded texture in manganese oxides. White well-polished bands (ns) are nsutite, and dark poorly polished bands (cr) are cryptomelane with some thin harder bands of nsutite. Quartz (qz) gangue is in lower part of photograph. 500 level, Trout mine. Reflected light.

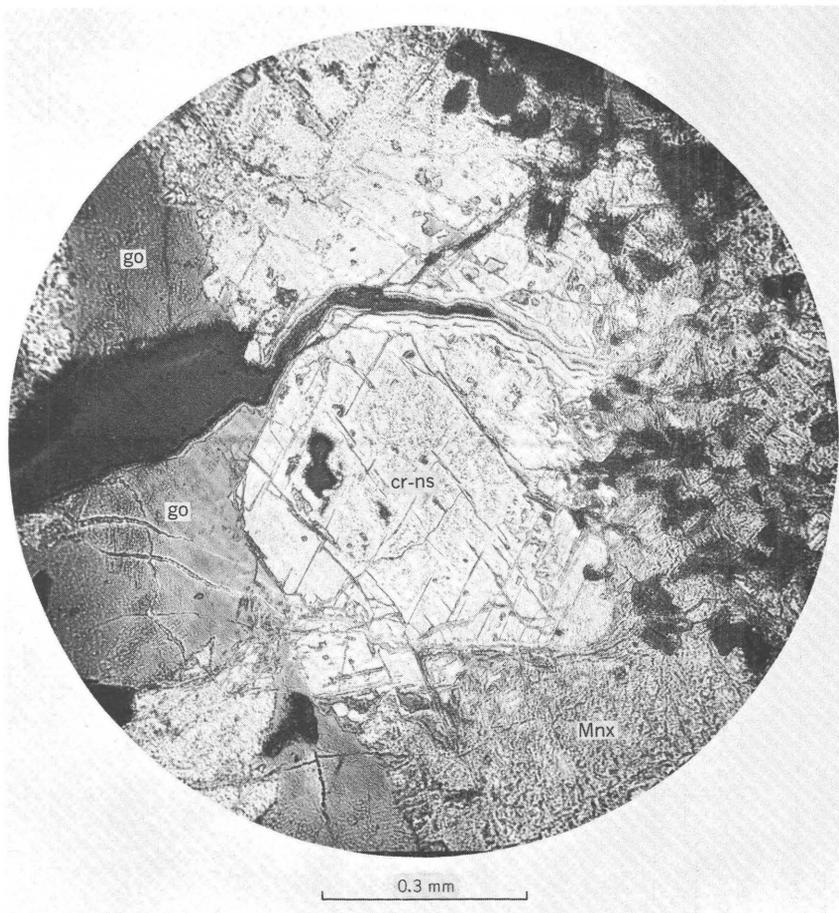


FIGURE 14.—Cryptomelane and nsutite pseudomorphous after carbonate. Cryptomelane and nsutite (*cr-ns*, light gray) preserve the trace of the carbonate cleavage and the shape of the original grain (compare with fig. 12). The dark-gray mineral to the left (*go*) is goethite, and the mottled dark-gray area to the right and at the bottom (*Mnx*) is poorly polished manganese oxide, probably also cryptomelane and nsutite. The black areas are pits in the sample. West Algonquin Hill, adit 200 feet southwest of Powder tunnel. Reflected light.

X-ray powder data for typical Philipsburg cryptomelane are given in table 3 with a recently published cryptomelane pattern for comparison. A chemical analysis of cryptomelane from Philipsburg was published by Richmond and Fleischer (1942, table 1, analysis 4, p. 610). No additional analyses were made of cryptomelane from Philipsburg; however, except for one specimen (probably coronadite), all "psilomelane" samples studied gave similar X-ray powder patterns



FIGURE 15.—Cryptomelane. The material with the bun or pillow structures is entirely cryptomelane, and the mineral outlining some of the structures is quartz. 200 level, Algonquin mine. Reflected light.

and are therefore all cryptomelane, rather than some other member of the psilomelane group.

TODOROKITE

Todorokite ($(\text{Ca}, \text{Na}, \text{Mn}^{\text{II}}, \text{K}) (\text{Mn}^{\text{IV}}, \text{Mn}^{\text{II}}, \text{Mg})_6 \text{O}_{12} \cdot 3\text{H}_2\text{O}$) is widely distributed and moderately abundant in the oxidized replacement deposits, probably because of the availability of calcium there, but it has not been found in the oxidized veins. It has a considerable vertical distribution, from outcrops to small pods of oxidized ore in predominantly carbonate stopes 700 feet below the surface.

Todorokite is soft to moderately hard (3–4.5) and forms a dark-brown powder. In reflected light it is white to medium gray; pleo-

chromism is faint, and anisotropism is moderately strong. Commonly it as an aggregate of radiating fibers or occurs as felted masses. It also occurs as irregular fine grains. It forms banded and botryoidal textures with cryptomelane, nsutite, and pyrolusite, and with pyrolusite it occurs as pseudomorphs after carbonate.

X-ray powder patterns of typical todorokite from Philipsburg and of "delatorreite," which has been shown to be identical with todorokite (Fron del and others, 1960, p. 1167), are similar (table 4) except for the extra broad band on the pattern of Philipsburg ore at 4.3 Å. This is probably due to lines indexed by Straczek, Horen, Ross, and Warsaw (1960, table 5) as (201) and (102) but absent on their pattern.

TABLE 3.—X-ray powder data for cryptomelane

Algonquin mine, 200 level Philipsburg district, Montana ¹		Western Australia (from Faulring, Zwicker, and Forgeng, 1960, table 2)		Algonquin mine, 200 level, Philipsburg district, Montana ¹		Western Australia (from Faulring, Zwicker, and Forgeng, 1960, table 2)	
d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I
6.96	10	6.94	S	1.64	2VB	1.64	M
4.94	7	4.92	S	-----	-----	1.61	VW
3.49	3	3.48	W	1.545	5	1.54	M
3.12	9	3.10	S	1.427	4	1.43	W
2.47	2	2.45	W	1.40	1	1.402	VW
2.40	8	2.39	M	-----	-----	1.39	VVW
-----	-----	2.32	VW	1.36	4VB	1.350	VW
2.21	3	2.20	W	1.299	3	1.297	VW
2.16	6	2.15	M	1.24	1	1.232	VW
1.99	1	1.97	VW	1.22	1	1.215	VW
1.83	1	1.92	W	1.20	1	1.193	VW
1.837	5	1.83	M	-----	-----	1.158	VW
-----	-----	1.73	VW	-----	-----	1.116	VW
-----	-----	1.69	VW	1.08	2	1.075	W

¹ FeK_{α1} radiation, Mn filter (λ=1.93597 Å). Camera diameter: 114.6 mm. VB=very broad.

TABLE 4.—X-ray powder data for todorokite

Algonquin mine, 700 level, Philipsburg district, Montana ¹		Oriente Province, Cuba ² (from Straczek and others, 1960, table 5)		Algonquin mine, 700 level, Philipsburg district, Montana ¹		Oriente Province, Cuba ² (from Straczek and others, 1960, table 5)	
d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I
9.55	10	9.6	s	2.22	4	2.21	m
4.77	8	4.77	s	-----	-----	2.16	f-b
4.3	4B	-----	-----	-----	-----	2.11	f-b
3.34	2	-----	-----	1.98	4	1.98	m
3.18	3 ³	3.19	w	-----	-----	1.92	w
-----	-----	3.11-2.95	band	1.74	2	1.74	wm
-----	-----	2.7	band	-----	-----	1.69	f-b
2.48	5)	2.448	m	1.53	2	1.53	w
2.40	6)VB	2.398	s	1.43	5	1.423	m
2.32	4)	2.34	m	-----	-----	-----	-----

¹ FeK_{α1} radiation, Mn filter (λ=1.93597 Å). Camera diameter: 114.6 mm. B=broad, VB=very broad.

² "Delatorreite."

³ Quartz contamination.

Todorokite from the True Fissure mine has been studied in detail by Larson, who presented two chemical analyses of the mineral (Larson, 1962, table 2). His samples contain from 4.65 to 4.99 percent

ZnO, and he concluded that the todorokite is zinc bearing. An analysis of todorokite-bearing manganese oxide ore, also from the True Fissure mine, showed less than 0.1 percent ZnO (table 10). Thus, this todorokite is not zinc bearing unless todorokite is only a very minor constituent of the sample, which X-ray analysis indicates is not so.

NSUTITE

Nsutite ($\text{Mn}^{\text{IV}}_{1-x}\text{Mn}^{\text{II}}_x\text{O}_{2-2x}(\text{OH})_{2x}$) is widely distributed and moderately abundant in the Philipsburg oxide ore. It gives X-ray powder patterns similar to those of synthetic gamma- or rho- MnO_2 ; previously I called it gamma- MnO_2 (Prinz, 1961) and indicated that it probably was the same mineral that Sorem and Cameron, in their report (1960) on the Nsuta, Ghana, ores, called Nsuta- MnO_2 . Recently this mineral has been named "nsutite," and a variety with a lower MnO_2 : MnO ratio has been referred to as manganoan nsutite (Zwicker and others, 1962). Judged from the data presented by McMurdie and Golovato (1948, table 3, p. 593), the Philipsburg oxide ore is especially well suited for use in dry cells because of its nsutite and cryptomelane content.

Nsutite is generally hard (about 6) but locally may be very soft, and it forms a dark-brown powder. In reflected light it is white with a faint cream or tan cast. It is normally anisotropic but commonly is very fine grained and apparently isotropic. It occurs in bands with cryptomelane and todorokite, forms pseudomorphs after carbonate (fig. 14), forms late veinlets that cut earlier formed manganese oxide minerals, or occurs in masses of irregular small grains. Some banded nsutite was brecciated and recemented or cut by later manganese oxide minerals or quartz. Some nsutite shows shrinkage cracks indicative of colloidal deposition.

Nsutite from Philipsburg gives weak X-ray powder patterns; thus abnormally long exposures were necessary to bring out the weaker lines. Comparison of these patterns with those of samples from Nsuta, Ghana (table 5), shows that the Philipsburg ores contain both nsutite and manganoan nsutite. Some Philipsburg nsutite shows a weak line at 2.82 or 2.83 Å, a line that is not present on other patterns of nsutite, gamma- MnO_2 , or rho- MnO_2 . This line is probably not due to a contaminant, because it is shown by samples containing various impurities.

PYROLUSITE

Pyrolusite (MnO_2) is commonly a late-formed mineral and lines vugs in earlier manganese oxides. As such it is readily recognized in hand specimen, a fact that led previous workers to overestimate its relative abundance. Much of the fine-grained fibrous manganese oxide

that was previously identified as pyrolusite is todorokite. Some pyrolusite also formed with the other manganese oxides and occurs in botryoidal ore or as pseudomorphs after carbonate. The grain size of pyrolusite is variable, even in a single specimen and tends to be coarser in vugs (fig. 16). Some pyrolusite is prismatic, commonly with the prisms oriented perpendicular to banding. It may also be poikilitic, where sieved with quartz, or show growth bands (fig. 16).

Two types of X-ray powder patterns were noted for pyrolusite (table 6): one is almost identical with the pattern published by Ramdohr (1956, p. 48-49); the other contains extra lines at 4.13 and 3.72 Å and is similar to the pattern published by Roy (1959, table 1).

TABLE 5.—X-ray powder data for nsutite

Nsuta, Ghana ¹		Algonquin mine, 200 level, Philipsburg district, Montana ²		West Algonquin Hill, adit 200 ft southwest of Powder tunnel, Philipsburg district, Montana ²		True Fissure mine, 800 level, Philipsburg district, Montana ²		Cliff Millsite mine 4th level, Philipsburg district, Montana ²		Nsuta, Ghana ³	
d (Å)	4 I	d (Å)	I	d (Å)	I	d (Å)	I	d (Å)	I	d (Å)	4 I
				⁶ 7.00	2	⁵ 9.60	10	⁶ 6.99	6		
				⁶ 4.94	1	⁵ 5.27	5	⁶ 4.98	1		
						⁵ 4.71	5 VB				
4.36	VW	3.98	10	4.01	10	4.00	10	4.09	10	4.46	VW
3.96	VS	⁸ 3.33	4	⁷ 3.33	2					4.10	VS
				⁶ 3.13	1 VB			⁶ 3.13	4		
						2.83	1	2.82	2		
2.69	Tr	2.58	3	2.68	4			2.67	4	2.66	M
2.59	VW										
								2.46	7	2.45	M
2.43	S	2.42	8	2.425	7 VB	2.43	9 VB	2.41	7 VB	2.39	VW
2.34	M	2.33	5	2.33	4 VB	2.32	7 VB	2.35	5 VB	2.36	M
2.22	VVW										
								2.17	9	2.16	S
2.13	S	2.13	9 VB	2.13	8 VB	2.14	8			2.13	M
2.07	VW	2.06	2 VB	2.06	2 VB	2.08	1				
										1.924	VW
										1.880	VVW
1.892	VVW	1.883	1	1.900	2						
1.831	Tr	1.8175	1	1.82	1						
1.706	Tr										
1.638	S	1.645	7 VB	1.642	6 VB	1.648	4 VB	1.679	8	1.667	S
1.615	W	1.61	5 VB	1.61	4 VB	1.597	2 VB			1.517	W
		1.541	1								
1.488	VVW	1.483	1	1.48	2					1.426	W
1.425	W	1.421	3	1.423	3	1.423	2	1.430	4	1.394	M
								1.40	2	1.372	VW
1.362	VW	1.365	3 VB	1.37	3	1.371	1			1.330	W
										1.292	VVW
1.306	VVW	1.305	1	1.305	1					1.257	VW
1.250	Tr			1.25	1					1.225	VVW
1.212	Tr									1.187	VW
1.165	Tr			1.17	1					1.136	VVW
										1.107	Tr
1.116	Tr									1.082	W
1.067	VW	1.066	2 VB	1.067	2						

¹ Nsutite; Zwicker, Groeneveld Meijer, and Jaffe (1962, table 2A).
² FeK α_1 radiation, Mn filter ($\lambda=1.93597$ Å). Camera diameter: 114.6 mm. VB, very broad.
³ Manganosan nsutite; Zwicker, Groeneveld Meyer, and Jaffe (1962, table 2A).
⁴ VS, very strong; S, strong; M, medium; W, weak; VW, very weak; VVW, very, very weak.
⁵ Line due to an unknown impurity.
⁶ Line due to contamination by cryptomelane.
⁷ Line due to contamination by quartz.

This variation in X-ray patterns does not appear to be related to the physical properties of the mineral. A partial analysis of pyrolusite from Philipsburg was published by Hewett and Fleischer (1960, table 3).

CHALCOPHANITE

Chalcophanite ($(\text{Mn}^{\text{II}}, \text{Zn})\text{Mn}^{\text{IV}}_2\text{O}_5 \cdot 2\text{H}_2\text{O}$) is widely distributed and locally moderately abundant in manganese oxide deposits derived from primary ore known or suspected to contain sphalerite, and it may prove useful as a guide to the search for deeper zinc-bearing primary ore.

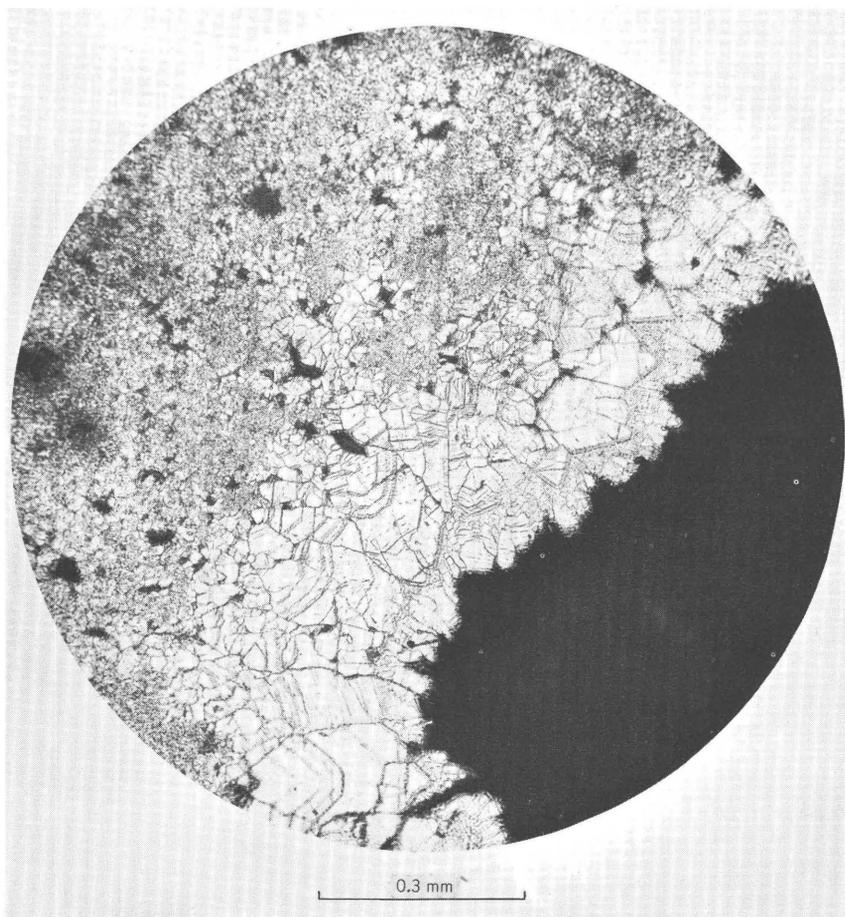


FIGURE 16.—Pyrolusite showing growth bands and coarsening of texture toward center of vug (black is open space). 800 level, True Fissure mine. Reflected light.

TABLE 6.—X-ray powder data for pyrolusite

Cliff mine, 100 level Philipsburg district, Montana ¹		True Fissure mine, 800 level, Philipsburg dis- trict, Montana ¹		Dongari Buzurg, Bhandara district, India ²		Niedertefenbach, Nassau, Germany ³	
d (A)	I	d (A)	I	d (A)	I	d (A)	⁴ I
		4.13	3	4.13	3		
		3.72	2	3.74	2		
						3.43	W
						3.13	VS
⁵ 3.34	1						
3.11	10	3.12	10	3.11	10		
⁵ 2.94	1						
2.64	1	2.63	1	2.648	2		
2.40	8	2.41	8	2.41	9	2.41	S
2.20	3	2.21	1 B	2.19	3	2.20	W
2.11	7	2.11	6	2.10	8	2.12	M
1.969	4	1.978	2	1.97	4	1.97	M
1.624	9	1.626	7	1.63	9	1.62	VS
1.558	5	1.561	4	1.55	5	1.56	S
1.434	4	1.434	4			1.44	W
1.393	3	1.40	1 VB			1.39	W
⁵ 1.37	1						
1.303	6	1.304	5			1.31	S
1.25	1					1.25	VW
1.202	2	1.20	1			1.20	VW
1.159	2	1.16	1			1.16	VW
1.124	2	1.125	1			1.12	VW
1.100	1					1.10	VW
1.056	5	1.056	3			1.05	M
1.038	3	1.04	1			1.04	W
1.000	4	1.00	1			1.00	W

¹ FeK α_1 radiation, Mn filter ($\lambda=1.93597$ A). Camera diameter: 114.6 mm. B, broad; VB, very broad.

² Roy (1959, table 1).

³ Ramdohr (1956, p. 43-49).

⁴ VS, very strong; S, strong; M, medium; W, weak; VW, very weak.

⁵ Lines due to a contaminant.

Chalcophanite commonly fills vugs in, or forms veinlets that cut, other manganese oxides. It also may be interbanded with cryptomelane and form tiny prisms set in a fine-grained matrix of todorokite. Chalcophanite, hetaerolite, and todorokite form stalactites (fig. 17) in vugs at the boundary between the Mountain View vein and an oxidized manganese replacement deposit on the 600 level of the True Fissure mine.

X-ray patterns for chalcophanite from Philipsburg differ from ASTM card 15-807 (table 7) in that extra lines are present at 3.76, 3.12, and 2.17 A in Philipsburg samples, regardless of impurities. Unfortunately, no samples of pure chalcophanite from Philipsburg could be obtained.

HETAEROLITE

Hetaerolite (ZnMn₂O₄) was found, generally with chalcophanite, in only a few samples from or near oxidized quartz veins. X-ray powder patterns of hetaerolite from Philipsburg and Sterling Hill, N.J., are almost identical (table 8). Larson (1964, p. 68), however, identified hydrohetaerolite in samples from the district, but not hetaerolite.



FIGURE 17.—Stalactites consisting of todorokite, chalcophanite, hetaerolite, and amorphous MnO₂. 600 level, True Fissure mine. Scale is in inches.

TABLE 7.—X-ray powder data for chalcophanite

Trout mine, 500 level, Philipsburg district, Montana ¹		Sterling Hill, N.J. ²		Trout mine, 500 level, Philipsburg district, Montana ¹		Sterling Hill, N.J. ²	
<i>d</i> (Å)	I	<i>d</i> (Å)	I	<i>d</i> (Å)	I	<i>d</i> (Å)	I
6.92	10	6.96	100	1.656	2	1.668	10
6.20	5	6.23	10	1.590	5	1.597	40
³ 5.52	1	-----	-----	1.555	1	1.563	5
³ 4.93	1	4.08	50	1.501	3	1.507	10
4.06	7	-----	-----	³ 1.438	1	-----	-----
3.76	1	3.50	60	1.425	5	1.431	30
3.49	6	3.32	10	³ 1.41	1	-----	-----
3.31	2	3.23	5	1.394	3	1.402	5
3.22	1	-----	-----	1.317	2	1.324	5
3.12	2	2.77	20	1.30	1	1.308	5
2.76	4	2.71	5	1.273	2	1.279	10
2.71	1	2.57	40	1.23	1	-----	-----
2.55	6	2.46	20	1.200	1	-----	-----
2.45	5	2.41	20	1.18	1	-----	-----
2.40	5	2.24	50	1.168	1	-----	-----
2.22	7	-----	-----	1.156	1	-----	-----
2.17	1	2.13	20	1.139	1	-----	-----
2.12	3	1.986	5	1.115	1	-----	-----
1.97	1	1.900	30	1.1	1	-----	-----
1.896	4	1.849	10	1.061	2	-----	-----
1.841	3	1.795	20	1.039	1	-----	-----
1.787	3	1.750	5	1.033	2	-----	-----
-----	-----	1.715	5	1.001	1	-----	-----
1.709	2	-----	-----	-----	-----	-----	-----

¹ FeK_{α1} radiation, Mn filter (λ=1.93597Å). Camera diameter: 1146 mm.

² ASTM card 15-807.

³ Lines probably due to a contaminant.

TABLE 8.—X-ray powder data for heterolite

Algonquin mine, 300 level, Philipsburg district, Montana ¹		Sterling Hill, N.J. ²		Algonquin mine, 300 level, Philipsburg district, Montana ¹		Sterling Hill, N.J. ²	
d(A)	I	d(A)	I	d(A)	I	d(A)	I
6.95	2			1.517	6	1.518	8
4.84	1	4.871	1	1.430	4	1.430	4
4.03	1/2					1.350	1
3.03	8	3.045	7	1.32	1	1.323	3
2.85	5	2.855	4			1.277	2
2.69	9	2.698	9	1.262	2	1.263	3
2.46	10	2.460	10			1.212	1
2.29	2	2.300	3	1.167	1	1.169	5
2.23	1/2					1.151	4
2.02	2	2.017	3	1.12	1 1/2 VB	1.107	4
1.789	2	1.792	3	1.106	1 1/2	1.089	3
1.748	3	1.752	5	1.089	1 1/2	1.089	3
1.682	3	1.683	4	1.072	1		
1.618	2	1.616	3			1.053	2
1.562	4	1.560	5	1.011	1		

¹ FeK α_1 radiation, Mn filter ($\lambda=1.93597$ A). Camera diameter: 114.6 mm. VB=very broad.

² Frondel and Heinrich (1942, table 3).

³ Lines probably due to contamination by chalcophanite.

MANGANITE

Manganite (Mn₂O₃·H₂O) is uncommon at Philipsburg. At one place it is veined by later manganese oxides, and at another it lines vugs in earlier formed oxides. X-ray powder data for manganite from Philipsburg and from Germany are listed in table 9.

TABLE 9.—X-ray powder data for manganite

Cliff Mill site mine, 4th level, Philipsburg district, Montana ¹		Ihlfeld Harz, Germany ²		Ihlfeld Harz, Germany ²		Cliff Mill site mine, 4th level, Philipsburg district, Montana ¹		Ihlfeld Harz, Germany ²		Ihlfeld Harz, Germany ²	
d(A)	I	d(A)	I	d(A)	I	d(A)	I	d(A)	I	d(A)	I
3.40	10	3.40	100	3.700	1	1.322	3	1.326	10	1.316	4
				3.385	10	1.294	1	1.297	10	1.287	2
				3.096	1	1.280	1			1.275	1
				2.833	1	1.260	2	1.256	5	1.257	1
2.63	7	2.64	60	2.616	9	1.243	1	1.24	20	1.239	2
2.52	3	2.53	5	2.506	2	1.212	1	1.21	20	1.208	1
2.41	9	2.41	20	2.406	6	1.180	2	1.183	10	1.179	4
				2.359	5	1.170	1				
				2.310	5	1.156	2	1.162	10	1.152	4
2.27	5	2.28	50	2.263	7	1.134	2	1.139	40	1.130	8
2.19	5	2.20	5	2.186	3	1.114	1	1.116	20	1.109	4
2.02	3					1.098	2	1.10	20	1.094	3
1.779	6	1.783	20	1.771	6	1.079	2	1.08	20	1.076	3
1.701	3	1.708	40	1.694	5					1.052	1
1.669	9	1.672	30	1.661	9	1.026	1	1.029	30	1.024	8
1.634	2	1.636	40	1.629	5					1.022	2
1.499	4	1.502	20	1.493	5	1.014	2	1.01			
1.433	3	1.437	30	1.428	1	.992	2	.993	10		
				1.424	4						
				1.414	1						
1.420	1										

¹ FeK α_1 radiation, Mn filter ($\lambda=1.93597$ A). Camera diameter. 114.6 mm.

² ASTM card 8-99.

³ Fleischer and Richmond (1943, table 1).

⁴ Line due to an unknown contaminant.

WAD

Soft dark-brown to black earthy wad is common in the Philipsburg district. X-ray analysis shows that it is a mechanical mixture of one or more of the following minerals: Todorokite, cryptomelane, chalcophanite, pyrolusite, or goethite.

AMORPHOUS MANGANESE OXIDE (?)

Some manganese oxide specimens contain material that is hard (5-6), white in reflected light, and apparently isotropic. X-ray patterns of this material are very weak and show only the stronger cryptomelane, nsutite, or todorokite lines. Todorokite does not fit the properties of this material; samples giving a todorokite pattern are probably a mixture of amorphous material and todorokite. Because some fine-grained cryptomelane and nsutite have the same physical properties, weak patterns of these minerals may represent either poorly crystallized cryptomelane or nsutite, or mixtures of these minerals and amorphous material.

BRAUNITE

Braunite ($3(\text{Mn}^{\text{III}}, \text{Fe}^{\text{III}})_2\text{O}_3 \cdot \text{Mn}^{\text{II}}\text{SiO}_3$) was identified at Philipsburg by Pardee (1921, p. 153) and by Goddard (1940, p. 176), but none was found during this study. Pardee's statement (1921, p. 153) that it shows rhombohedral cleavage suggests that the material identified as braunite may be cryptomelane, nsutite, and perhaps pyrolusite pseudomorphic after carbonate.

GANGUE MINERALS

Quartz, goethite, mica, clay minerals, and calcite are common gangue minerals in the oxidized manganese deposits; sparse fluorite, which is possibly a primary mineral that has been preserved and perhaps somewhat redistributed during oxidation, occurs in a few places. Some quartz was inherited from the primary deposits, but other quartz is supergene, as is shown in the manganese oxide ore where alternating bands of quartz and manganese oxide minerals fill a veinlet or void (fig. 8). Some vugs and veinlets are filled with late chalcedonic quartz, which like coarser grained quartz, forms alternating bands with manganese oxide minerals. Goethite is found in most oxidized ore bodies but is scarce in all except those along the Redemption fault. White to brown calcite is common in the oxidized manganese deposits as linings in vugs and small veins. It is most likely a supergene by-product from oxidation of manganous carbonates.

RELATION BETWEEN OXIDIZED AND UNOXIDIZED DEPOSITS

Unoxidized manganese carbonate deposits are overlain by manganese oxide deposits at depths ranging from 100 feet in relatively impervious hosts such as the Silver Hill Formation to at least 850 feet in highly permeable ones such as the Hasmark Formation; the bottom of the deepest known oxidized ore body, the Mountain View ore body (section *F-F'*, pl. 7), has not yet been explored. The base of the oxidized deposits is very irregular, and remnants of unoxidized ore occur within or alongside some oxidized ore bodies and below impermeable beds where protected from downward percolating water.

The shapes of the deposits in both the oxidized and unoxidized zones are similar, as is well illustrated by deposits in the Silver Hill Formation at the Coyle mine. Thin beds rich in manganese oxide minerals can be traced to the surface and are identical in habit with thin beds of manganese carbonate in workings below.

The carbonate deposits are generally devoid of vugs; the few vugs present tend to be small. By contrast, the oxidized deposits are extremely cavernous, the size of individual open spaces ranging from tiny pores to cavities several tens of feet across. The margins of many large cavities consist of botryoidal manganese oxide minerals; stalactites (fig. 17) of manganese oxides occur in a few cavities. Circular or tabular solution cavities, locally called "water courses," are common in marble above or adjacent to oxidized deposits. These cavities generally lack manganese minerals, although small amounts of manganese oxides occur in cracks and veinlets near most oxide deposits.

GRADE OF ORE

The bulk of the ore mined from the replacement deposits has been manganese oxide, and since World War I, most of it has been used in the manufacture of dry-cell batteries. The grade of ore has ranged considerably. Most contained between 30 and 43 percent manganese, but in recent years lower grade material has been extracted, some averaging as low as 15 percent manganese. For battery use, the ore is milled to concentrates containing 65–72 percent MnO_2 (equivalent to 41–45.5 percent manganese).

A relatively small amount of manganoan carbonate ore has been mined from the Philipsburg district, almost all of which was sold to Government stockpiles. The manganese content of the carbonate ore ranged from 14 to 35 percent and probably averaged about 20–25 percent; high-grade carbonate ore is uncommon. Production of manganese carbonate has been inhibited not only by the low grade of the ore but by milling difficulties. Much of the manganese is in manganoan

dolomite, which is fine grained and difficult to concentrate by normal ore-dressing techniques.

Although steeply dipping quartz veins and manganese-rich replacement deposits are generally not both of ore grade in the same places, locally the veins have been mined for silver and zinc and the adjacent walls for manganese. Some unoxidized manganese replacement deposits are rich enough in silver, zinc, and lead to have been mined for these metals, but the amount of ore mined from deposits of this type has been comparatively small. The ore in the Silver Hill Formation in the Coyle area above the 300 level of the Algonquin mine is an example of this type of deposit (pls. 3, 8).

Chemical and spectographic analyses of two samples of manganese ore from the Mountain View ore body (True Fissure mine) are given in table 10. The carbonate ore sample is a split from a 100-pound channel sample that was collected by the Taylor-Knapp Co. from an unoxidized remnant that occurs in oxide ore above the 600 level of the mine. The sample consists of manganoan carbonates, quartz, sphalerite, sparse galena, pyrite, clay minerals, and probably some copper sulfides. The presence of the quartz and sulfides indicates that some vein material was included with the sample. The oxide sample is a composite of millfeed that represents several hundred tons of oxide ore produced from this same ore body from a stope above the 800 level of the True Fissure mine and about 200 feet below the area where the carbonate sample was collected. The oxide sample consisted of assayer's pulp and was therefore not amenable to detailed mineralogic study. However, cryptomelane, todorokite, quartz, and calcite were identified in an X-ray powder photograph of this material, and study of other samples from the same stope indicates that it may have also contained nsutite and pyrolusite.

ORIGIN

The primary manganese deposits formed mainly by replacement of original carbonate rocks; cavity filling was of only minor importance, and much of that probably occurred in cavities that originated by dissolution during replacement. Some deposits spread laterally below impervious beds; the ore-bearing solutions that formed these must have been ascending. The solutions that formed the manganese deposits were later than those that formed the sulfide deposits but were probably a later stage of the same period of hydrothermal activity.

Structural conditions were different during deposition of manganese ore than during deposition of silver-zinc ore in the veins. Manganoan carbonates line or fill some vugs in the veins and in a few places cement brecciated vein material; however, the great bulk of the manganese

TABLE 10.—*Partial chemical and semiquantitative spectrographic analyses of manganese ore, True Fissure mine*

[Chemical analyses by S. M. Berthold and J. I. Dinnin, U.S. Geol. Survey; semiquantitative spectrographic analyses by Helen W. Worthing, U.S. Geol. Survey]

	Manganese carbonate ore, 624 stope	Manganese oxide ore, 803 stope		Manganese carbonate ore, 624 stope	Manganese oxide ore, 803 stope
Chemical analyses					
MnO.....	37.60	30.66	K ₂ O.....	.55	1.45
MnO ₂	None	17.74	H ₂ O ⁺60	3.43
Equivalent Mn.....	(29.1)	(35.0)	H ₂ O ⁻20	1.38
SiO ₂	28.46	18.50	TiO ₂.....	.06	.06
Al ₂ O ₃	2.44	4.28	P ₂ O ₅.....	.28	.16
Total Fe as Fe ₂ O ₃.....	.52	1.42	CO ₂	21.10	6.10
CaO.....	1.17	10.08	SrO.....	<.1	.15
MgO.....	2.19	2.09	ZnO.....	5.08	<.1
Na ₂ O.....	.19	.27			
Semiquantitative spectrographic analyses ¹					
Ag.....	0.003	0.0015	Mo.....	0	.0015
Ba.....	.0007	.05	Ni.....	.0007	.0007
Be.....	.0001	.0003	Pb.....	.05	.015
Cr.....	.0003	.001	V.....	.007	.01
Cu.....	.015	.01	Y.....	.0015	.002
Ga.....	.001	0	Zr.....	.005	.002
In.....	.002	0			

¹ Spectrographic results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, etc.; which represent approximate midpoints of group data on a geometric scale. The assigned group for semiquantitative results includes the quantitative value about 30 percent of the time.

Looked for but not found: As, Au, B, Bi, Ce, Co, Ge, Hf, Hg, La, Li, Nb, Pd, Pt, Re, Sb, Sc, Sn, Ta, Te, Th, Tl, U, W, and Yb.

is in the walls. By the time manganese minerals began to be deposited, the fissures were nearly filled and were being opened only locally. With the fissures closed, the solutions were channeled into the wall-rocks and flowed up through them, perhaps working their way upward along grain boundaries and small fractures. The deposits in massive hosts tend to have a vertical pitch even though there are no structures within or adjacent to the deposit that could have served as a control for such a pitch. This suggests that the solutions rose vertically through the rocks. Solutions may have passed vertically through unfavorable host rocks without depositing ore. This is indicated by the fact that the Headlight ore body is separated from the Mountain View ore body below it by barren impure limestone of the Red Lion Formation. (See p. 32.)

Although the intersections of favorable beds and structures were a major factor in controlling the location of manganese-rich replacement deposits, the fact that many such intersections are not replaced indicates that there was yet another ore control. The fact that these deposits tend to be alined parallel with the Redemption fault or with the border of the batholith suggests that this control was a series of deep-seated structures below the present mine workings that carried

the ore solutions from their source and channeled them into the areas where the major ore deposits were formed.

Toward the surface, the primary manganoan carbonate deposits were in part altered to manganese oxides. This oxidation was caused by descending ground water, as shown by (1) carbonate remnants below impervious beds and (2) the relation between depth of oxidation and permeability of the host rock. The vuggy nature of the oxide ore indicates that the alteration was accomplished mainly by the removal of materials such as CO_2 that are found in the carbonate ore but are absent, or are present in smaller amounts, in the oxide ore.

Migration of manganese during oxidation was limited. Facts that point to this conclusion are: (1) on a microscopic scale, some manganese oxide minerals retain such primary textures as the grain outlines of the primary marble and cleavage cracks of the primary carbonate (fig. 14); (2) the overall shapes of primary and oxidized ore bodies are the same; (3) individual manganese-rich beds retain their identity right to the surface; and (4) the content of manganese per unit volume of both types of deposits is approximately the same. Although the grade of oxide ore is higher than that of primary carbonate ore, both contain the same amount of manganese per unit volume in place because of the cavernous nature of the oxide ore. Fritzberg (1927, p. 646) noted that 1 short ton of ore in place at the Trout mine occupied 16 cubic feet, whereas Pardee (1921, p. 156), who apparently examined more cavernous ore, placed this value at 20 cubic feet. Assuming these values and grades of 30–40 percent manganese, each cubic foot of oxide ore in place contains 30–50 pounds of manganese. Precise data for the volume occupied by 1 ton of carbonate ore are not available. However, the specific gravities of the minerals that make up the ore are known, and from these the specific gravity of the carbonate ore was calculated as 3.2. This is equivalent to 10 cubic feet per ton and, allowing for some cavities, the value may be as high as 13 cubic feet per ton. Using these values and grades of 20–25 percent, the amount of manganese per cubic foot of carbonate ore was also calculated to be 30–50 pounds.

Although oxidation has probably been going on for a long time, perhaps since early Tertiary time, late Tertiary events prevented the development of extensive enriched residual deposits at the surface. Mountain building that started late in the Miocene Epoch kept the topography of the area steep, so that residual materials were removed by erosion about as rapidly as they were formed. Any that did remain were removed by the Pleistocene glaciation.

That oxidized ore extends to depths greater than 850 feet is not surprising. Host rocks that were permeable enough to provide access

for the ascending solutions were also permeable enough to allow free circulation of the descending solutions. Solution cavities or water courses that formed in the more soluble host rocks permitted even wider and freer circulation of the ground water.

CONTACT METASOMATIC MAGNETITE DEPOSITS

Irregular small magnetite-rich pods occur in relatively pure marble of the Hasmark Formation in the southwestern part of the district. At the Silver Lode and Old Kentucky mines, these pods occur along the batholith contact, whereas at the Redemption mine they occur along the Redemption fault about 1,000 feet north of the contact (pls. 1, 3; Holser, 1950, pl. 1 and fig. 3). Magnetite was also seen along the Redemption fault on the 4th level of the Cliff Millsite mine about 1,500 feet north of the batholith and on the dump of the H & H shaft 1,000 feet farther north. In addition to magnetite, these deposits contain olivine (in part serpentinized), chondrodite, dolomite, quartz, and, at the Redemption pit, ludwigite; near the surface, limonite is common. The deposits are probably of contact metasomatic origin, having been formed by emanations from the batholith shortly after its intrusion. Emmons and Calkins (1913, p. 219) reported that car-load shipments from the Redemption mine contained from 27–47 percent Fe; the grade of the other deposits is probably similar. Little magnetite has been produced—probably less than 50,000 tons—and the prospects for future production appear poor.

A similar magnetite deposit has been reported in Jefferson marble at the Henry Clay claim, which is about three-quarters of a mile southwest of the Silver Lode mine (Holser, 1950, p. 1061).

PARAGENESIS

The paragenesis of the primary minerals is indicated in figure 18. Magnetite was the first to form; it is probably contact metasomatic mineral. The rest of the hypogene minerals formed later and include minerals that are generally ascribed to deposition from hydrothermal solutions. Paragenetic studies indicate that they were formed during a single period of mineralization. The sequence beginning with barite, pyrite, and sphalerite and ending with rhodochrosite and more pyrite was noted in many vein and replacement deposits, and I saw no sulfides later than rhodochrosite except pyrite, nor evidence that the sequence was repeated. Previous workers, however, have noted sulfides that formed after rhodochrosite in two places. One is the Scratch Awl mine, where Pardee (1921, p. 154) reported “rhodochrosite, quartz, and sulfides of one generation cut by the same minerals of a later generation.” Pardee did not state what sulfides are included in the later

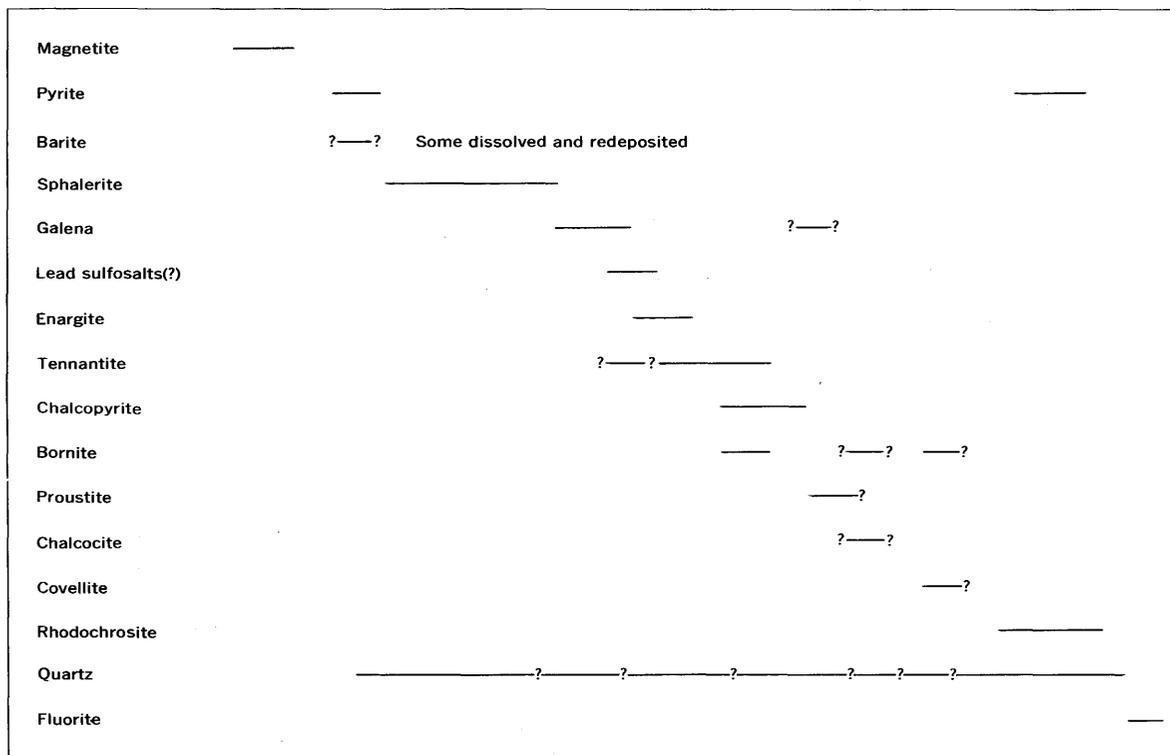


FIGURE 18.—Paragenesis of selected hypogene minerals.

generation, but if they are all pyrite, his statement would not affect my conclusion. The other occurrence of sulfides later than rhodochrosite is at the Granite-Bimetallic mine, where sphalerite, quartz, and chalcopyrite cement a rhodochrosite breccia and ruby silver cuts rhodochrosite (Emmons and Calkins, 1913, p. 205, fig. 37, and p. 177, fig. 23).

From the paragenesis of the primary minerals, several stages of mineralization can be recognized. From oldest to youngest, these were characterized by deposition of iron oxide, iron sulfide, zinc, lead, copper-silver, and manganese (fig. 19). Arsenic and some iron accompany some of the lead and copper-silver, and iron (sulfide) also accompanies manganese. Little silica was deposited during deposition of iron oxide and manganese; however, minerals formed during the intervening stages are associated with abundant quartz.

The relative importance of the various stages of mineralization in the formation of the different types of deposits is shown in figure 19. Minerals associated with the deposition of iron oxide form contact metasomatic deposits but do not occur in the veins or in the manganese-rich replacement deposits. Pyrite (iron sulfide stage of mineralization) and sphalerite (zinc stage) occur mainly in steeply dipping veins and are scarce in bedding veins. Lead minerals occur in both types of veins but are not abundant in either. Bedding veins are richer in silver than the steep veins. Manganese minerals occur in veins of both types, but the bulk of the manganese is in replacement deposits. Some manganese-rich replacement deposits also contain zinc, lead, silver, and copper minerals that formed during the earlier stages of mineralization.

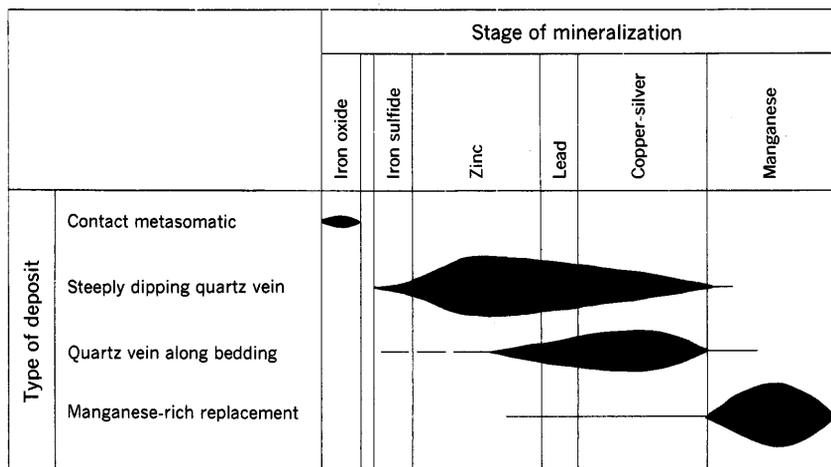


FIGURE 19.—Relationship between stage of mineralization and type of deposit.

ZONING

Although clear-cut zoning, like that shown in many mining areas, cannot be recognized in the Philipsburg district, there is a rude compositional zoning in the quartz veins and manganese-rich replacement deposits, and a structural zoning in the distribution of the various types of deposits. Quartz veins in the sedimentary rocks contain more secondary copper minerals at and near the surface west of a line extending approximately from Hope Hill southward through the Cliff Millsite shaft than they do to the east of this line. However, the veins to the east do contain copper sulfides at depth, and perhaps their copper content increases with depth.

Manganese-rich replacement deposits contain less silver, zinc, and lead in the vicinity of the True Fissure mine than they do to the south and perhaps to the north also. In the True Fissure mine the primary manganese ore consists mainly of manganoan carbonate and sparse pyrite, whereas to the south, in the Algonquin, Trout, and Scratch Awl mines, the manganoan carbonate ore commonly contains other sulfide minerals and has been mined for its silver and zinc content. The primary manganoan carbonate ore to the north may also contain sphalerite, as is suggested by the fact that the zinc content of oxidized manganese deposits there is abnormally high (Wells and others, 1947, p. 4) and the zinc-bearing manganese oxide mineral chalcophanite occurs in those deposits.

Structural zoning is reflected in the distribution of the various types of deposits in the part of the district that is underlain by sedimentary rocks. In the southern and central parts of this area, most of the quartz-sulfide ore is in steep fissure veins. The ore along bedding is dominantly manganiferous and is quartz poor. On Hope Hill to the north, the quartz-sulfide ore follows bedding, and steep fissure veins are few. The dividing line between these two types of ore is about at the Two Percent mine, where a bedding quartz vein was mined near the surface and a steeply dipping fissure vein was mined at depth.

Mineral zoning in the Philipsburg district is too irregular and erratic to be used as an indication of "hot spots" during ore deposition and therefore cannot be used to indicate the source area of the ore-forming fluids. Mineralizing fluids at each stage of mineralization probably were available throughout the district. Whether ore formed at a particular place during a given stage of mineralization depended upon whether structures were open to receive the fluids and whether there were channels to transport the ore fluids from their source to the open structures. The rude zoning is due to interaction between stage of mineralization and stage of structural evolution of the area.

STRUCTURAL HISTORY OF THE ORE DEPOSITS

Before intrusion of the Philipsburg batholith, the rocks in the district had been folded, and thrust faulting had occurred in the valley to the west. The fold axes and the thrust fault both trend north to northeast and were probably the result of compression oriented west-northwest. Northwest-trending high-angle reverse faulting, represented in the district by the Redemption fault, postdates the folding and thrusting.

During intrusion of the batholith the nearby sedimentary rocks were metamorphosed, and at this time or perhaps slightly later, metasomatic deposits of magnetite formed at several places along the border of the batholith and along the Redemption fault.

After consolidation of at least the border of the batholith, compressive forces were renewed, probably oriented in about the same direction, and steeply dipping fissures formed in both the batholith and the sedimentary rocks. The most prominent set of fissures strikes west; apparent displacement is north side to the east, which is to be expected along shear planes resulting from the postulated compressive forces. A subsidiary set of fissures strikes northwest.

Quartz veins along bedding contain the same minerals as the steeply dipping quartz veins; both types were probably formed during a single period of mineralization, and the fissures in which they occur probably resulted from the same compressive forces. However, the bedding veins are richer in silver and poorer in zinc than the steeply dipping veins, and thus fissuring along bedding was most active later than the most active period of fissuring along steeply dipping planes (fig. 19).

That bedding fissures, rather than steeply dipping fissures formed in certain places and at certain times is probably due to differences in (1) the direction of least pressure and (2) the character of the host rock. Bedding fissures would be expected to form where or when the minimum pressure (or easiest relief) was upward or vertical, whereas steeply dipping fissures would form if the minimum pressure was horizontal and normal to compression (Anderson, 1951, p. 15; and Sitter, 1956, p. 119-120). Most bedding veins occur in rocks higher in the section, where the load of overlying rocks is less; and many bedding veins formed later, after some unloading from above by erosion or by decrease in magmatic pressure from below. For these reasons, bedding-plane veins could be expected to give way in depth to steeply dipping veins. This is supported (1) by the fact that the bedding veins on Hope Hill are divisible into two groups, or ore channels, whose trends are parallel to the steeply dipping veins, and (2) by the presence of numerous bedding veins in the sedimentary

rocks on the strike of the persistent San Francisco vein in the granodiorite. In the Two Percent mine there may be an example of a bedding vein giving way in depth to a steeply dipping vein. There, a bedding vein along the Headlight bed was mined near the surface, but the associated steeply dipping vein was weak. However, the steeply dipping vein contained minable ore at depth.

Most of the bedding-plane veins occur in the Jefferson Limestone or along the Headlight bed, which suggests that the character of the host rock may also have been a factor in determining whether bedding or steeply dipping fissures formed.

By the manganese stage of mineralization very little fissuring was taking place, and the ore solutions were, for the most part, forming replacement deposits in the wallrocks; only a small amount of material was being deposited in the veins. Two reasons for the change in loci of deposition are suggested—one structural and one chemical. While under compression the grains in the host rocks were possibly held tightly together. With relaxation of compression, enough space opened up around the grains to provide access for the ore solutions, which, with fissuring no longer active and the fissures nearly filled, moved principally through the wallrocks. The localization of replacement ore along fissure veins, the Redemption fault, and the border of the batholith was probably due to previous weakening of the wallrock near these older structures. Once started, solution by the ore-forming fluids probably opened the walls even more and channeled the fluids along particular pathways.

The change in loci of deposition was probably also due in part to changes in the composition of the mineralizing solutions. The character of the manganese-bearing solutions was such that they reacted with the carbonate wallrocks to produce replacement deposits, whereas the early sulfide- and silica-rich solutions did not.

Structural adjustments after mineralization, perhaps caused by subsidence of the magma chamber, produced normal bedding faults that offset many steeply dipping veins.

SUGGESTIONS FOR FURTHER EXPLORATION

Steeply dipping quartz veins.—Although a few steeply dipping quartz veins pinch out at depth, many do not. In fact, some pinch upward and cannot be recognized at the surface or at shallow depths. Therefore, deep diamond drilling and crosscutting, especially between adjacent properties, should be done to search for veins that do not extend to the surface or to currently explored levels. For example, several potentially valuable veins cut by diamond drill hole 1-AU (see section *E-E'*, pl. 7) have not been adequately explored.

Exploration for steeply dipping veins should probably be concentrated within the 2,000-foot-wide belt of most productive veins. (See p. 17.) Although the more favorable host rocks at depth are in the northern part of this belt, the southern part, which is in quartzite, should also be considered. As noted earlier (p. 29), veins in quartzite have been mined, but they have not been extensively explored.

Little deep exploration has been done north of the Two Percent mine. Areas below bedding veins, especially below groups of bedding veins trending parallel with the strike of steeply dipping veins, should be explored to see if bedding veins pass in depth into steep veins. (See p. 31.)

Veins in the batholith should be tested from the deeper levels of nearby mines in the sedimentary rocks. These veins have been explored near the surface, but very little work has been done on them at depth.

Manganese-rich replacement deposits.—All manganese deposits that crop out have probably been found, and since these deposits pinch out both up and down, future exploration will have to be directed toward finding concealed ore bodies. The tendency of replacement deposits to be aligned parallel with the Redemption fault or the border of the batholith has been noted (p. 31); thus, exploration for this type of deposit should be concentrated along these trends away from or between major ore bodies. Because of the vertical pitch of these ore bodies, the area below large ore bodies should be tested thoroughly even though the ore body may appear to have bottomed in barren rock. Barren zones separate veins from the adjacent replacement deposits in many places, thereby making it imperative that the walls of drifts along veins be tested in favorable host beds.

The postulated fault beneath alluvium southwest of and parallel with the Redemption fault (pl. 1) cuts favorable host beds and may contain ore bodies similar to those found along the Redemption fault. No record of exploration of this fault could be found.

Many favorable areas have not been adequately explored at depth, and I believe that given a high enough price and stable marketing conditions, mine operators in the district would be able to find enough manganese oxide ore to sustain production for many years to come. However, the costs of exploration and of mining are high, and under present market conditions there is very little incentive to explore for new ore bodies. Therefore, little ore is developed ahead of production and proven reserves are small.

At present, none of the primary carbonate deposits can be exploited for manganese alone, and only those rich in rhodochrosite and poor in manganoan dolomite hold much promise of being valuable in the

near future. However, if a way is found to treat manganoan dolomite economically, large quantities of this type of ore could be found in the lower levels of the present workings and below.

The manganese carbonate deposits are a potentially valuable source of silver and zinc. To date, few deposits of this type have been exploited, but the distribution of the zinc-bearing manganese oxide minerals, which can be used as an indicator of sulfide-bearing primary replacement deposits, suggests that they may be more widespread at depth than has been suspected, especially in the northeastern and southeastern parts of the manganese-rich part of the district.

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