Geology and Ore Deposits of the Eureka and Adjoining Districts San Juan Mountains, Colorado

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A study of part of the western San Juan Mountains eruptive center, its related cauldron subsidence structures, altered volcanic rocks, and ore deposits

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GEOLOGY AND ORE DEPOSITS OF THE EUREKA AND ADJOINING DISTRICTS, SAN JUAN MOUNTAINS, COLORADO

By Wilbur S. Burbank and Robert G. Luedke

ABSTRACT

The Eureka mining district is in the western San Juan Mountains in southwestern Colorado and includes an area of about 30 square miles from which ores of gold, silver, copper, lead, and zinc have had a gross value of more than $63 million. Two mines, the Sunnyside and Gold King, yielded more than 90 percent of the dollar value of production.

This report, although centered on the Eureka district, also deals with parts of several adjoining mining districts, all of which are genetically related to the same center of volcanism and periods of mineralization.

Chiefly volcanic rocks are exposed in the area; they have accumulated to a thickness of more than a mile on a basement of Precambrian, Paleozoic, and Mesozoic rocks. This complex of eruptive rocks, which is divisible into three major and several minor units, consists of lava flows, breccias, tuff-breccias, tuffs, and welded ash-flow tuffs that in composition average rhyodacite-quartz latite but range from andesite-basalt to rhyolite. Associated with and intruded into these eruptive rocks are many small dikes, sills, and irregularly shaped plutons.

The San Juan Formation at the base of the volcanic succession is exposed almost entirely outside a large volcanic depression called herein the San Juan depression. Next higher in the succession and confined mostly within this depression is the Silverton Volcanic Group, which has been subdivided in order of decreasing age into the Picayune Formation, Eureka Tuff, Burns Formation, and Henson Formation. At the top of the succession is the Potosi Volcanic Group, which is widespread in the western San Juan Mountains and subdivided into several formational units, only one of which is exposed within the area of this report.

The dominant structural feature of the Eureka district and environs is the Silverton cauldron, about 10 miles in diameter, which lies within the western half of the San Juan volcanic depression, about 15 miles wide and 30 miles long. Outward from the Silverton cauldron, the volcanic and basement rocks are broken by systems of radial and concentric fractures; the rocks within and adjacent to the cauldron site are broken, tilted, and irregularly faulted. The central-east part of the Silverton cauldron coincides approximately with the Eureka district; the district thus has intersecting major ring faults bounding a subsided cauldron block and radial graben faults that extend northeast outward from the cauldron center.

Coincident with or just following later stages of eruptive activity, the volcanic rocks throughout and around the San Juan volcanic depression were intensely altered propylitically. Subsequently, the metalliferous deposits were formed within and along the numerous fissure and fault systems.

Two major types of mineral deposits and associated alteration products are recognized within and around the Silverton cauldron: (1) chimney or pipelike deposits with intensely leached and decomposed walls consisting of clays, alunite, diaspore, and other minerals that formed in a relatively acid environment and (2) normal vein deposits with sericitized wallrocks that were altered in a neutral to alkaline environment. The local dominance of one or the other type of deposit was conditioned by the structural evolution and by local features of the volcanic environment.

The chimney deposits with their leached and ore-filled caves are typical chiefly of the arcuate peripheral fault belts of the cauldron where the highly fractured rocks are intensely altered solfatarically. These deposits are sealed by siliceous caps that formed by rock decomposition during escape of hot volcanic waters and gases from underlying sources. Open cavities leached in the rocks were later filled with masses of sulfides and minor quantities of gangues.

The vein deposits and associated ore shoots were formed in repeatedly reopened fissures that were localized by broad structural features—intersections of major fault systems and belts of tensional fissuring due to crustal distention and collapse about the cauldron. The complex low-grade ores in the veins are chiefly base metals, gold, and silver in quartz and locally manganese silicates and carbonate gangues, which commonly constitute from 85 percent to more than 95 percent of the fissure fillings. Gold occurs chiefly in the late quartz veins, whereas silver occurs in both the early base-metal ores and the late quartz veins. A general but definite paragenetic sequence is recognized throughout much of the Eureka district.

Inferences from comparison of the two types of deposits are that the solutions that deposited sulfide-rich assemblages of minerals low in gangues were initially richer in sulfur than the hydrothermal solutions that deposited the abundant gangues of the veins and that probably also formed some hot-spring deposits of the western San Juan region. The primitive sulfide solutions are interpreted to have been derived from magmatic sources at depths generally below the shallow altered rocks, which are believed to be the source of some of the major gangues of the vein. The effects of repeated opening of fractures and formation of spaces by physical action were minimal as compared with chemical leaching in forming the chimney deposits. This leaching contrasts with the major effects of fissure reopening in vein evolution. Thus, the solutions forming the veins were repeatedly mixed with shallow meteoric waters and with waters contaminated with soluble substances of wallrock alteration. The earliest openings of the fissures were marked by violent injections of clastic debris from great depths. Later reopenings tended to concentrate residual solutions of the altered rocks in the open spaces, where these mixed with the shallow meteoric waters. Further evolution of sulfide solutions from greater depths resulted in the complex vein assemblages of gangues and sulfides.

The structural and textural conditions of the rocks had a profound effect upon the chemical processes that played an important role in the differentation of ore- and gangue-forming

solutions. Nevertheless, the different rock units cannot be classed arbitrarily as favorable or unfavorable without regard to particular local conditions.

Supergene leaching and enrichment of the ores around and within the Silverton cauldron are negligible. Most enrichment of ores at depth is related to hypogene processes that caused fractional leaching and redeposition of the metals.

INTRODUCTION AND ACKNOWLEDGMENTS

The Eureka district, one of the major mining areas in the western San Juan Mountains of southwestern Colorado (fig. 1), has been an important contributor to the mineral economy of San Juan County and the State of Colorado. Gold, silver, copper, lead, and zinc were the principal metals recovered from the mining operations. A small amount of tungsten was also produced.

The geology and mineral deposits of the district were examined at different times after the late 1890's, notably by Ransome (1901) and by Cross, Howe, and Ransome (1905), but many problems relating to geologic environment and associations of the ore deposits remained to be investigated. Accordingly, the western San Juan project, started in the late 1920's, was charged with the study of the more strongly mineralized areas of the Ouray, Silverton, and Telluride quadrangles. One of the objectives was to furnish guidance in exploration and discovery of base- and precious-metal ores.

Early in the investigations, fieldwork by Burbank (1930) in the Ouray area (pl. 1) revealed that ore deposition in the western San Juan region occurred during two metallogenetic epochs instead of one, as had been previously believed. The hydrothermal activity occurred in two main centers of different ages—an older one of Late Cretaceous and early Tertiary age centered near the town of Ouray and a younger one of late Tertiary age centered within and around the Silverton cauldron. The older mineral deposits are related to plutonic bodies intruded into Paleozoic and Mesozoic sedimentary rocks, which are the principal host rocks of the ore deposits. These early deposits were formed and partly eroded before eruption of the volcanic material. The younger ore deposits are related to structural features and intrusive activity of the Silverton cauldron and, although found in the basement rocks, occur chiefly in the overlying volcanic rocks. This report deals entirely with the geology and ore deposits of middle and late Tertiary age and chiefly with those deposits found in the volcanic rocks near the center of the Silverton cauldron.

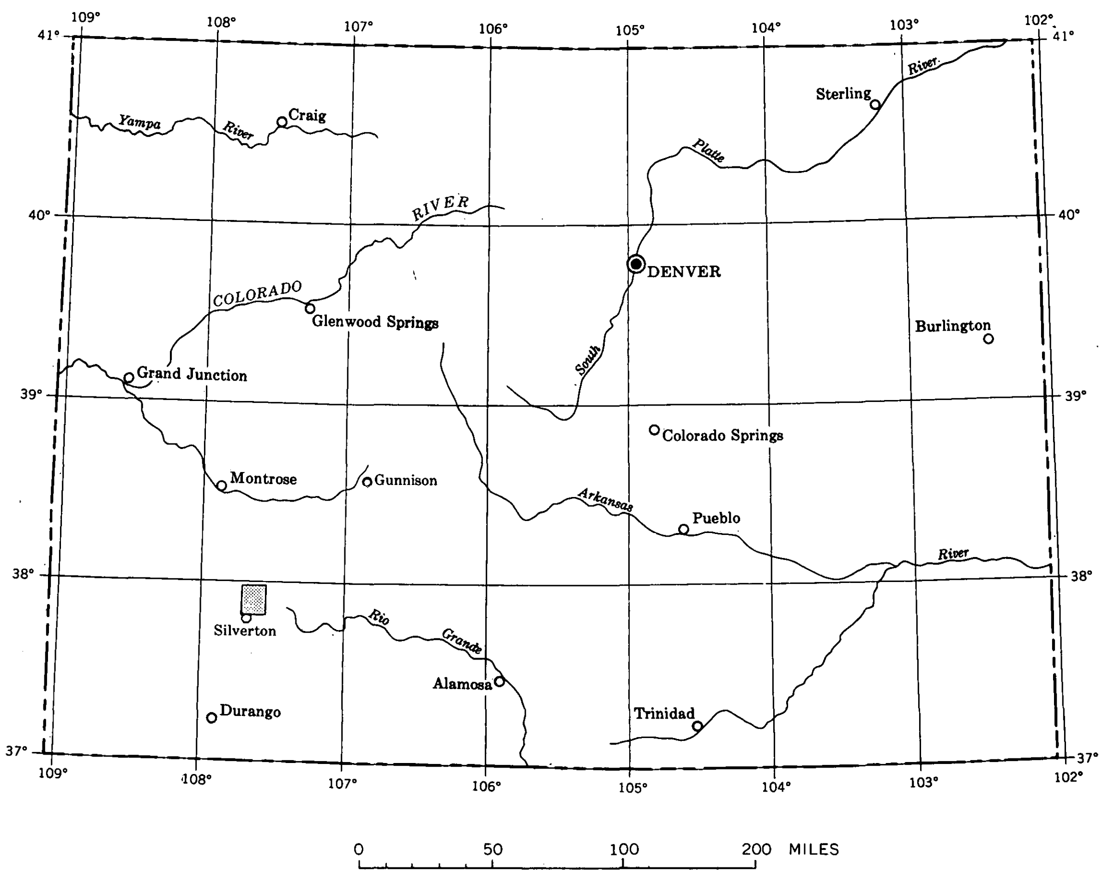

FIGURE 1.—Map of Colorado showing area of this report.

This report is one of a series prepared by the U.S. Geological Survey in cooperation with the Colorado State Mining Industrial Development Board and a predecessor agency, the Colorado State Metal Mining Fund Board. Seven progress maps have been published (Burbank, 1933b, 1941; Burbank and Luedke, 1964; Kelley, 1946; Luedke and Burbank, 1962; Varnes, 1948, 1963) as well as a number of geologic reports. Parts of two of these maps (Burbank, 1941; Kelley, 1946) are included on plates 2 and 3 to demonstrate certain structural features more clearly. Some areas on these included maps were revised in the course of fieldwork between 1958 and 1962 by R. G. Luedke and W. S. Burbank, and some of the rock units originally mapped by V. C. Kelley and W. S. Burbank were reclassified.

An index map on plate 2 indicates those persons who were responsible for the several parts mapped; their assistance was invaluable. In addition, D. J. Varnes and J. S. Vhay have provided data on nearby areas valuable in solving many field problems.

Grateful acknowledgement is made to the property owners and mine operators of the area for their generous cooperation in premitting access to mines and in providing information on operations.

GEOGRAPHY

The Eureka district includes all the area shown on plate 2 except those parts in Poughkeepsie Gulch and west of the Brown Mountain divide, which are parts of the Uncompahgre and Red Mountain districts, respectively, and the American Flats part in Hinsdale County, which is part of the Galena district. The area north of the townsite of Eureka and east of the Animas River to the Hinsdale County line (pl. 1) also is normally included in the Eureka district, as is some of the area tributary to Cement Creek south and west of Gladstone.

The four abandoned townsites within the map area (pl. 2) of about 30 square miles covered by this report are Eureka, in the Animas River canyon at the mouth of Eureka Gulch; Animas Forks, at the junction of the Animas River canyon and California Gulch; Gladstone, in Cement Creek canyon in the southwestern part; and Mineral Point, in the north-central part. Silverton, the county seat of San Juan County, lies about 6 miles southwest of the district and is the principal center from which most of the local mining operations have been carried out. Ouray, the county seat of Ouray County, is 5 miles northwest of the map area and serves those parts of the country adjacent to Poughkeepsie Gulch and Ironton Park. The main road serving the district is State Highway 110 from Animas Forks to Silverton; it joins U.S. Highway 550 extending from Montrose south through Ouray and Silverton to Durango. Although rugged, the area is readily accessible during the summer months over secondary roads, but travel is limited largely to four-wheel drive vehicles of short turning radius. These roads were constructed for access to mining properties and to various parts of the National Forest; the road up the Animas River canyon as far as Animas Forks and the road up Cement Creek canyon as far as Gladstone have been kept open some winters because of mining activities.

The topography of the district is alpine; the high sharp peaks, narrow rugged divides, steep-walled basins and amphitheaters, and deep U-shaped canyons are a result of vigorous glacial and interglacial erosion. Altitudes range from 9,900 feet at the townsite of Eureka in the southeastern part of the district and 9,600 feet in Ironton Park in the northwestern part to 13,733 feet on Wood Mountain in the northeastern part. Most peaks in the area are between 12,500 and 13,200 feet in altitude, but 1–3 miles east are several peaks higher than 13,800 feet, including Handies Peak, which reaches 14,048 feet. The mining area, which averages well over 11,000 feet in altitude, is one of the highest in the San Juan region.

The headwaters of the Uncompahgre and Animas Rivers are within the map area, and a small part of the drainage basin of Henson Creek is in the extreme northeastern part. These streams are all ultimately tributary to the Colorado River. The divides separating the three watersheds are spurs from the Continental Divide only a few miles to the southeast (pl. 1). The drainage pattern of the Silverton region is controlled by the major structural features of the Silverton cauldron (pl. 1). The Animas River follows the east and southeast boundary of the downfaulted central block, and some minor tributary canyons, such as Eureka and Poughkeepsie Gulches, follow strong subsidiary structures of the cauldron; other minor tributary canyons are less directly controlled.

Annual precipitation in the Eureka area is about 40 inches. Winter snowfall is commonly heavy, and rain and hailstorms, sometimes of considerable severity, occur frequently during summer months. Because of the high precipitation, the ground is well saturated with water, and small to heavy flows of water are encountered in most mining operations. Soil and talus are subject to widespread creep, and rockfalls from precipitous slopes are frequent, particularly in spring and early summer. Landslides are common. Bodies of perpetual ice commonly occur beneath talus and rock glaciers in some cirques.

Small but dense stands of fir, spruce, and aspen cover the protected lower slopes of the canyons, but a large proportion of the country is above timberline, which is at about 11,500 feet, and thus is relatively bare except for alpine shrubs, grasses, and flowering plants.

Mining has been the chief industry of the area, but at the time fieldwork was done for this report, only a few mines had operations in progress, and these were mainly exploratory and developmental. Besides mining, the grazing of sheep is an industry of some importance. Some lumbering has been done, but much of the original timber resource has been used in connection with past mining operations.

HISTORY AND PRODUCTION

Ransome (1901, p. 19–25) and Henderson (1926, p. 48–50) stated in their excellent summaries of the early mining history of the Silverton quadrangle and San Juan County that the rugged and inaccessible western San Juan Mountains were not prospected until rather late in the history of the West. The first real attempt at prospecting in the region was by the Baker party in 1860, which penetrated the mountains to the park where Silverton now stands. Harassment by Indians and severe winter conditions discouraged them, and incited little further prospecting until the early 1870's, after the revision of a treaty with the Ute Indians. When prospecting was resumed, many important discoveries were made; real mining began in 1874. A smelter was put in operation in Silverton in 1875, and at about the same time one was constructed in Lake City to the northeast to treat ores from the area. There were no wagon roads or rail transportation into this region until the late 1870's and early 1880's respectively, and consequently, the high costs and difficulties of transporting ores and equipment by pack train and wagon resulted in slow development of the new discoveries. The total production for the Silverton area from the beginning of activity to the close of 1876 has been estimated at a little over $1 million.

In 1879, the first road into the area was completed from Del Norte via the Rio Grande Canyon and Stony Pass southeast of Silverton. Also, a road was completed from Silverton up Cement Creek canyon to the head of Poughkeepsie Gulch where several of the more productive deposits then were being mined. Completion of the Silverton branch of the Denver and Rio Grande narrow-gauge railroad in 1882 and establishment of a smelter in Durango gave new impetus to the treatment of lower grade ores. The future of the region still was not assured, however, until 1890, when J. H. Terry at the Sunnyside mine in the Eureka district and E. G. Stoiber at the Silver Lake mine (southeast of Silverton) in the Animas district both successfully developed methods of concentrating low-grade ores of the area. Extension of the railroad from Silverton up the Animas River canyon through Eureka to Animas Forks in the mid-1890's and up Cement Creek canyon to Gladstone in 1899 permitted further cost reductions in ore treatment. A great improvement in treating the low-grade complex ores of the area was made in 1917 when the first commercial lead-zinc selective flotation plant in North America was introduced at the Sunnyside mine.

Mining activities in the Eureka district have fluctuated considerably throughout the district's history, as many of the operations were small and thus easily affected by the market price. The decline of the price of silver in 1892 and 1893, as well as the smaller declines in lead and copper prices that followed, caused mining activity to decrease and forced many of the smaller operations to close. The major activity in the district, particularly to the late 1930's in the district's history, centered about the operations of the Sunnyside and Gold King mines. These and other concurrent or later operations are reviewed in the section on mining (p. 55). Mining operations in the district are treated annually in the United States Bureau of Mines Minerals Yearbook and the Mining Yearbook of the Colorado Mining Association.

Production records (table 1) for the Eureka district are available only for the years 1932 through 1957 and hence give only the more recent trend of production; for earlier and later years the district's output is included under the total San Juan County records. The figures for the year 1926 are given, however, to illustrate a typical year of operation at the Sunnyside mine and mill; although the output is for all San Juan County during this year, only small-lot shipments were made from a few other mines in the county.

Many of the earlier production records fail to reveal the metal content of the average complex ore mined and milled. The dollar value of payments for the gold and silver recovered from ores not uncommonly exceeded that for the base metals recovered, even though the value of the total base metals present in the ores was considerably larger. Both Robie (1926) and McQuiston (1948) described the progress and improvement made in the treatment of the complex ores of the area before and after 1917.

The production figures in table 1 represent about 20–25 different operations throughout the district. The output came mostly from lode mining, but a little came from cleanup of old mine dumps and placer mining. The more active producers during this period were the Columbus Group near Animas Forks, the Lead Carbonate mines on the mountain slope east of Gladstone, and the Mountain Queen lease at the extreme head of California Gulch. The increased production in 1937–38

TABLE 1.—*Eureka district, mine production of gold, silver, copper, lead, and zinc in terms of recovered metals, 1926 and 1932–57 inclusive*

[Source: U.S. Bur. Mines, Mineral Resources of the United States and Minerals Yearbook, annual volumes]

Year	Producing mines: Lode	Producing mines: Placer	Ore sold or treated (short tons)	Gold (fine oz)	Silver (fine oz)	Copper (lb)	Lead (lb)	Zinc (lb)	Total value
1926 [1]	15		289,401	14,309	869,963	1,560,400	18,460,600	22,423,000	$4,215,674
1932	1		28	93	18				1,923
1933	2		1	20	10				409
1934	5		68	303	1,773	100	3,000	2,000	11,945
1935	2	1	111	[2] 1,443	[3] 5,437		2,700		54,535
1936	2	1	172	[4] 583	4,036	100	2,500		23,637
1937	4		64,010	2,595	105,174	234,000	2,438,000	3,668,000	582,760
1938	3		112,358	5,841	267,953	660,000	5,982,700	8,286,000	1,115,269
1939	4		442	781	6,298	6,800	28,400	19,000	34,640
1940	13		5,358	917	42,369	17,000	154,600	93,100	77,740
1941	7		967	279	5,172	2,000	48,600	12,000	17,349
1942	3		288	8	2,039	1,400	39,200	23,400	6,701
1943	7		741	26	3,084	4,900	78,800	53,000	15,374
1944	3		1,376	60	3,527	8,000	92,500	92,000	23,576
1945	4		1,062	39	2,915	10,600	117,500	86,000	24,956
1946	6		6,214	1,475	18,469	55,600	599,200	546,500	207,541
1947	6		14,880	1,614	51,144	156,900	1,260,300	964,200	433,875
1948	12		28,181	3,033	123,465	241,000	2,214,000	1,826,000	909,358
1949	12		16,905	891	44,666	97,000	1,156,000	1,140,000	414,727
1950	11		16,296	1,028	31,828	68,000	645,300	669,000	261,043
1951	17		18,601	591	37,451	130,000	1,138,000	1,318,000	522,790
1952	8		13,960	544	41,969	166,000	1,517,000	970,300	502,503
1953	3		4,186	471	22,843	23,500	534,000	182,400	134,833
1954	6		3,355	179	8,483	12,000	145,000	135,200	52,032
1955	4		1,086	83	3,623	7,800	85,200	68,400	30,201
1956	4		3,802	84	8,338	19,400	176,100	159,700	68,258
1957	4		2,558	36	3,958	28,600	109,800	94,100	40,068

[1] Includes small-lot shipments from 13 mines outside Eureka district.
[2] Includes 334 fine ounces of placer gold.
[3] Includes 175 fine ounces of placer silver.
[4] Includes 2 fine ounces of placer gold.

came largely from the renewed operation (reactivated in 1937 and shut down in 1938) of the Sunnyside mine and mill which had been inactive since 1930.

The total production from the area shown on plate 2 is estimated to be $60–65 million, on the basis of the gross value of recovered metals. Ninety percent or more of this total represents production from the Sunnyside and Gold King mines. The Eureka district thus has provided about half the little more than $123 million worth of recovered metals credited to San Juan County from 1873 through 1948. From this district alone, gold has yielded about 30 percent, lead about 24 percent, and zinc about 14 percent of the total county production.

Reserves of ore in the district, including only those bodies that may be geologically inferred from moderate extensions of known productive ore bodies, are estimated at roughly a million tons. The potential resources of complex ores aggregate many times these reserves if estimated on the known vertical and lateral extent of the many mineralized but relatively undeveloped veins, but the value of much of these resources so estimated might be well below current costs of exploitation. Despite the present marginal or uneconomic value of much of this potential ore and the difficult operating conditions during winter months, a sustained demand for lead and zinc should revitalize mining in the district. Gold and silver byproducts of base-metal mining locally enhance chances of successful operations.

REGIONAL GEOLOGY

Volcanic rocks of middle and late Tertiary age cover most of the western San Juan Mountains region and are the principal materials making up the high mountains (pls. 1, 4). The volcanic accumulations form a blanket 4,000–6,000 feet thick resting on a basement of eroded metamorphic, sedimentary, and igneous rocks of Precambrian, Paleozoic and Mesozoic ages. The erosion surface beneath the volcanic rocks bevels older structural features and rises gradually from an altitude of 8,500 feet just north of Ouray to more than 12,000 feet south of Silverton and in the area between Silverton and Lake City. This erosion surface forms an important separation between the formations and ore deposits of pre-Tertiary age and those of Tertiary age. It is fairly smooth, but is locally surmounted by former uplands or local prominent monadnocks of more resistent rocks; it is covered locally by a thin sedimentary formation, the Telluride Conglomerate, of early or middle Tertiary age.

The lower part of the Tertiary volcanic succession consists of several thousand feet of tuff-breccia, collectively called the San Juan Formation. This is overlain by the Silverton Volcanic Group, a complex accumulation of flows, breccias, tuffs, and welded ash-flow tuffs, which erupted from a number of centers within the site of the San Juan volcanic depression (pl. 4). Intervals of erosion and local deformation demarcate several formations within the Silverton Group. The San Juan Formation and Silverton Volcanic Group together accumulated to a thickness of more than a mile. Eruptive materials of these groups are overlain locally by widespread welded ash-flow tuffs, breccias, and tuffs of the Potosi Volcanic Group corresponding to part of the Potosi Volcanic Series of Larsen and Cross (1956, p. 90). (See Luedke and Burbank, 1963.)

Late during the eruption of the volcanic material composing the San Juan Formation and during most of the eruption of the material composing the Silverton Volcanic Group, the large oval San Juan volcanic depression—about 15 miles wide and 30 miles long—was formed around some of the centers from which the materials were erupted. The Silverton and Lake City cauldrons, now marked by downfaulted central blocks each about 10 miles in diameter, were formed within this depression. Adjacent volcanic rocks, particularly around the Silverton cauldron (pl. 1), are broken by systems of radial and concentric fissures and are intruded by several large stocks, many smaller plugs, and numerous dikes. A series of graben faults join the two cauldrons (pl. 4).

The fissure and fault systems, many of which were directly related to subsidence and resurgence of these central blocks and to the intrusive activity, constitute the principal sites of ore deposition. The most productive deposits of late Tertiary age have been veins in the San Juan Formation and in some units of the Silverton Group. Ore deposits in the form of chimneylike shoots, a few of which yielded very rich ore, occur along the west and north margins of the Silverton cauldron (Burbank, 1941).

The only rock units of the region that are younger than the volcanic rocks are scattered glacial and alluvial deposits of Quaternary age.

This report deals principally with a mineralized area of intense faulting and fissuring in the vicinity of the series of graben faults within the Silverton cauldron. For discussions of broader regional and petrologic features of the San Juan Mountains, the reader is referred to the published reports by Cross and Larsen (1935) and Larsen and Cross (1956).

STRATIGRAPHY

PRECAMBRIAN ROCKS

Precambrian rocks in the map area crop out only near the northwest corner (pl. 2) near the Saratoga mine at the east edge of Ironton Park. These exposures, locally fractured and iron stained, consist only of quartzite of the Uncompahgre Formation, the youngest formation of the Needle Mountains Group. The Uncompahgre Formation is also exposed north of Ironton Park in the Uncompahgre River canyon and tributary gulches (pl. 1). Neither the top nor the bottom of the formation is exposed at either locality, but about 8,000 feet of interbedded thick units of white to gray quartzite and dark gray to black argillite, slate, and some phyllite are exposed in the canyon.

The quartzites and slates probably underlie the volcanic rocks throughout much of the western and northwestern parts of the map area. Toward the east, however, the Precambrian rocks underlying the volcanic rocks are granites; to the south, they are gneisses, schists, amphibolites and granites (pls. 1, 4).

PALEOZOIC SEDIMENTARY ROCKS

Paleozoic and locally younger sedimentary rocks in a thin wedge overlie the Precambrian rocks bordering the west front of the San Juan Mountains (pls. 1, 4). Some of the Paleozoic rocks only are exposed near the northwest corner of the map area at the east edge of Ironton Park and seem to be near the present east limit of this wedge, denoted by a line projected from near Ouray south through the head of Ironton Park to the vicinity of Silverton (pl. 4); these rocks, consisting of Devonian, Mississippian, and Pennsylvanian formations, overlie the Precambrian quartzite.

The highly indurated and altered limestone exposed near and in the workings of the Saratoga mine includes certainly the Leadville Limestone of Mississippian age. Very likely the Ouray Limestone of Devonian age is present, but it was not recognized owing to the alteration and relatively poor exposures. Unconformably overlying the limestone are red calcareous shale and conglomerate beds corresponding to the Molas and Hermosa Formations of Pennsylvanian age. Both the limestone and the calcareous shale are locally replaced by pyrite and ore minerals near fissures.

TERTIARY SEDIMENTARY ROCKS

The only Tertiary formation of nonvolcanic sedimentary origin found with the area shown on plate 2 crops out near the Saratoga mine in patches too small for designation on the map. Beds a few feet thick, consisting of Precambrian debris, lie unconformably on older sedimentary rocks at the base of the volcanic formations and probably represent the Telluride Conglomerate or partly reworked remnants of it, considered of Oligocene(?) age by Larsen and Cross (1956, p. 60), although the evidence cited is admittedly tenuous.

TERTIARY VOLCANIC ROCKS

The bulk of the exposed rocks composing the western San Juan Mountains region consists of layered volcanic materials of middle and late Tertiary age (pls. 2, 4). The eruptive materials are divided from older to younger into three principal units: the San Juan Formation, the Silverton Volcanic Group, and the Potosi Volcanic Group. The latter two units are each divided into several formations. Changes in nomenclature of these volcanic units throughout the period of geologic investigations in the western San Juan Mountains have been discussed by Luedke and Burbank (1963) and are shown in table 2. Most of the units discussed were renamed or redefined.

The layered succession of these eruptive materials in the western San Juans aggregates nearly 1½ miles thick and has a volume greater than 1,000 cubic miles. Tuff-breccia, welded ash-flow tuffs, and lava flows predominate, but there are also some air-fall tuffs, flow breccias, and volcanic conglomerates. The eruptive materials, on the basis of meager chemical data, are dominantly calc-alkalic but have weak alkalic affinities. They range in composition from probable andesite-basalt to rhyolite, but are predominantly intermediate—rhyodacite and quartz latite.

The Tertiary volcanic formations in the western San Juans have been considered to be Miocene(?), Miocene, and Pliocene in age (Larsen and Cross, 1956, p. 61–64); however, these ages have been assigned from inadequate and meager fossil evidence. Only a few poorly preserved plant and animal fossils have been found, and these do not permit age assignments closer than middle to late Tertiary. Thus, the ages of the volcanic formations in this report are based entirely upon their relative positions in the sequence of rocks.

Most of the volcanic formations or parts thereof discussed in the following pages are genetically related to the western San Juan region and are represented within the Eureka district (pl. 2).

SAN JUAN FORMATION

The San Juan Formation, the oldest of the local volcanic units and the principal unit west and north of the map area (pl. 2), crops out only in the northwest corner of the map area and rests upon an erosion surface of moderate to low relief cut on prevolcanic rocks. Typically it is exposed in steep rounded slopes and cliffs. The formation is propylitically altered and is characteristically gray to greenish gray and locally red, purple, or bluish gray depending on the degree of alteration. When the formation is viewed from a distance, rude bedding can be discerned, but at close range, bedding is locally obscure. The maximum thickness of the San Juan Formation is more than 3,000 feet at Ouray, 2 miles north of the map area; however, within the map area the thickness decreases within a distance of about a mile, from 1,000 feet at the northwest edge to 200 feet or less at Albany Gulch.

TABLE 2.—*Nomenclature of Tertiary volcanic units in the western San Juan Mountains*

Telluride quadrangle [1]	Silverton quadrangle [2]	Ouray quadrangle [3]	San Juan region [4]	San Juan region [5]	Western San Juan region [6]
Potosi rhyolite series	Potosi volcanic series	Potosi volcanic series	Potosi volcanic series: Piedra rhyolite Huerto andesite Alboroto quartz latite Sheep Mountain andesite Treasure Mountain quartz latite Conejos andesite	Potosi volcanic series: Piedra rhyolite Huerto quartz latite Alboroto rhyolite Sheep Mountain quartz latite Treasure Mountain rhyolite Conejos quartz latite	Potosi Volcanic Group: Sunshine Peak Rhyolite Gilpin Peak Tuff
			Sunshine Peak rhyolite	Sunshine Peak rhyolite	
Intermediate series	Silverton volcanic series: Pyroxene andesite flows and tuffs Burns latite complex Eureka rhyolite Picayune andesite	Silverton volcanic series: Henson tuff Pyroxene andesite Burns latite Eureka rhyolite Picayune andesite	Silverton volcanic series: Henson tuff Pyroxene andesite Burns latite Eureka rhyolite Picayune volcanic group	Silverton volcanic series: Henson tuff Pyroxene-quartz latite Burns quartz latite Eureka rhyolite Picayune quartz latite	Silverton Volcanic Group: Henson Formation Burns Formation Eureka Tuff Picayune Formation
San Juan Formation	San Juan tuff	San Juan tuff	San Juan tuff	San Juan tuff	San Juan Formation

[1] Cross and Purington (1899).
[2] Cross, Howe, and Ransome (1905).
[3] Cross, Howe, and Irving (1907).
[4] Cross, and Larsen (1935).
[5] Larsen and Cross (1956).
[6] This report and Luedke and Burbank (1963).

The San Juan Formation is predominantly composed of a chaotic accumulation of moderately to well-indurated rhyodacitic tuff-breccia. The lower few hundred feet of the formation contains erratically distributed foreign fragments consisting mainly of pre-Tertiary metamorphic and igneous rocks that were derived in part from erosion of the pre-Tertiary terrane and in part from reworking of material in the Telluride Conglomerate.

The finely comminuted matrix and the fragments in the tuff-breccias seem to be composed of the same finely porphyritic rock; this rock has a typical salt-and-pepper texture. Phenocrysts, averaging 1 millimeter in size, are plagioclase and mafic minerals; plagioclase phenocrysts predominate. The plagioclase is andesine or labradorite and may or may not be altered. Of the mafic minerals, hornblende is more common than either augite or biotite; the mafic minerals usually are altered. The groundmass is cryptocrystalline, fine grained, and felted, and is composed of quartz, potassic feldspar and (or) sodic plagioclase, apatite, and specks of iron ores; where felted, the microlites are andesine. Alteration products are carbonate minerals, chlorite, epidote, iron oxides, sericite, clay, secondary silica, and pyrite. The bulk of the material extruded is probably rhyodacite, but ranges from rhyobasalt to quartz latite.

The San Juan Formation was deposited originally over an estimated 2,400 square miles. The tuff-breccias probably were deposited as mudflows, but the mode of accumulation has not been satisfactorily determined in all respects.

The formation is the principal host rock of veins in the areas west and northwest of Ironton Park; possibly the formation may be found at depth elsewhere in the Eureka district in drill holes or deep mine workings.

SILVERTON VOLCANIC GROUP

The Silverton Volcanic Group of middle to late Tertiary age is an accumulation of volcanic materials mostly confined to and occupying the large San Juan volcanic depression (pl. 4). Particularly around the west rim of the depression, and possibly at other places, some material overflowed the contemporary rims for at least 6–8 miles. The total volume of materials erupted and now composing this group is estimated to be about 400 cubic miles, of which only 15–20 cubic miles overflowed. The intradepression materials occupy an area of about 425 square miles, as compared with the 2,400 square miles occupied by the San Juan Formation.

The Silverton Volcanic Group is divided into four formations: from the base upwards, the Picayune Formation, Eureka Tuff, Burns Formation, and Henson Formation (table 2). Each of the individual formations represents one sequence of a succession of major eruptions. The Picayune, Burns, and Henson sequences represent the bulk of the Silverton and consist of thin to thick flows interbedded with some air-fall and partly reworked tuffs, local volcanic piles and domes, and related intrusive bodies. Together, the volume of the Picayune, Burns, and Henson Formations is about three times the volume of the Eureka Tuff. The Eureka episode is characterized by welded ash-flow tuffs; minor ash-flow tuffs, of only local consequence, occur in the Burns and Henson Formations. A few fossiliferous limestone and calcareous shale beds occur within the Burns Formation, but neither the fossil plants nor the animal remains permit an age assignment of the Silverton Group closer than middle to late Tertiary.

PICAYUNE FORMATION

The Picayune Formation consists of both fine-grained and porphyritic rocks in flows, breccias, and tuffs of wide compositional range exposed in the Animas River valley adjacent to Picayune Gulch on the east edge of the map area. All the rocks are indurated and moderately to intensely altered to bluish or greenish gray. They weather brownish gray to olive gray. Some of the rocks are interpreted as hornfelses which have resulted from deep burial and volcanic heat. Some breccia and tuff beds in this layered sequence are localy disturbed, and the sequence is locally intruded by dikes and irregular masses and sheets of felsitic rock. Only the upper part of the formation, 500–600 feet thick, is exposed.

The flow rocks in the formation are sparsely to conspicuously porphyritic with both felsic and mafic phenocrysts in a dense aphanitic groundmass. Commonly the rocks are amygdular; the chlorite- and carbonate-filled amygdules vary in shape and range in size from less than 1 millimeter to more than 1 centimeter.

Most of the felsic phenocrysts and all the mafic phenocrysts are completely altered. The anhedral to euhedral plagioclase phenocrysts are as much as 7.5 mm long, but are mostly less than 3 mm long. Most are complexly twinned and have resorbed margins, and more sodic rims. The plagioclase phenocrysts are partly to considerably albitized or sassuritized. Of the few crystals for which any optical data could be obtained, the anorthite content averaged An_{45}. The mafic phenocrysts, identified by relict shapes only, consisted of pyroxene, amphibole, and biotite; pyroxene predominated. The anhedral to subhedral casts of the mafic phenocrysts are as much as 4 mm long but generally average nearer 1.5 mm. Carbonate minerals, quartz, iron oxides, epidote, and chlorite, commonly penninite variety, are the common alteration products of the mafic phenocrysts. Mica and clay minerals also are alteration products of the feldspars. The accessory minerals in the rocks are apatite, magnetite, and ilmenite; the two oxides commonly are altered to, or have reaction rims of, hematite and leucoxene respectively.

In contrast to these Picayune rocks at the type section, much fresher rocks in a few thin amygdular flows of the Picayune Formation outside the west flank of the depression west of Ironton Park (pl. 1) are medium dark gray and moderately porphyritic. Phenocrysts of plagioclase (An_{35-65}), clinopyroxene, orthopyroxene, and a little olivine are in a dense groundmass of plagioclase microlites with pilotaxitic to trachytic texture.

The Picayune eruptive materials range from quite mafic to silicic in composition, but most are mafic. Too little of the materials is exposed to determine with any assurance the type and location of the source vents.

EUREKA TUFF

Exposures of the Eureka Tuff, the second oldest formational unit of the Silverton Volcanic Group, are mostly limited to the lower slopes and bottoms of the deep valleys. The Eureka Tuff consists predominantly of a succession of evenly bedded welded ash-flow tuffs that have been moderately to intensively indurated and altered over wide areas. The gray to greenish-gray welded tuffs are conspicuously speckled owing to abundant white feldspar crystals, have a prominent eutaxitic structure, and contain many inclusions of certain accidental materials. Andesitic and latitic fragments are commonly the most abundant, but locally quartzite and other foreign materials dominate.

The base of the formation is exposed within the map area on the west side of the Animas River valley, where it rests upon the Picayune Formation, and also at the mouth of Poughkeepsie Gulch, where it rests upon the San Juan Formation. The thickest section of the Eureka is exposed on the slopes of Wood Mountain and on the east slope of Eureka Mountain, where it exceeds 1,200 feet. In parts of the map area, some of the very highly altered rocks mapped as Eureka include bodies of rock that may belong to the overlying Burns Formation and possibly also to the underlying Picayune Formation.

The welded tuffs contain moderately abundant fragmental intratelluric crystals of feldspar and biotite in a fine-grained to cryptocrystalline matrix of quartz, potassic feldspar, iron oxides, and alteration products. Crystals of both orthoclase, locally microperthitic, and plagioclase (about An_{30}) are present; the orthoclase is estimated to be as abundant as or slightly more abundant than the plagioclase. The feldspar crystals range from 0.5 mm to about 6 mm in length and range from fresh to partly altered. Biotite crystals are bent and broken thin sheets 2 mm across and are completely altered. Quartz crystals are scattered here and there, but quartz seems to be only a minor phenocrystic constituent. Magnetite and apatite are common through the rock, and pyrite cubes occur locally where the rock is more intensely altered.

Vitroclastic texture is not well preserved in the matrix because of the compaction, welding, and alteration. In general, the compaction of the pumice lapilli gives the excellently preserved eutaxitic structure. These flattened pumice lentils display digitate ends and are warped and bent around the crystals. In many outcrops, the pumice lentils have been replaced by a green clay or chlorite and thus present a sharp contrast to the gray of the matrix and white of the feldspar phenocrysts.

The Eureka Tuff may be rhyolitic in composition, as considered in the past, but it is more likely to be quartz latitic, in view of the high content of plagioclase and biotite and the low content of quartz. No reliable chemical information supporting this belief, however, is available.

The welded tuffs are the result of ash-flow eruptions (terminology of Smith, 1960a) or glowing avalanche-type eruptions of great magnitude. The Eureka Tuff seems to be an excellent example of Smith's (1960b, p. 158) composite sheet of ash-flow deposits and probably represents the great range in types of cooling units and cooling history that he suggests. The source vents are unknown but believed to be within the San Juan volcanic depression.

BURNS FORMATION

The Burns Formation of the Silverton Volcanic Group is a complex accumulation of lava flows, breccias, and tuffs associated with local volcanic cones and domelike eruptive masses; all lie for the most part within the volcanic depression. Although chiefly intradepression in origin, the Burns eruptive materials overflowed parts of the contemporary rims. The volume of the intradepression Burns materials is estimated to be roughly 100 cubic miles. Disregarding the local volcanic cones and domes, the Burns Formation in the map area thickens from a few hundred feet near the depression margin at the north to more than 1,500 feet along the south side of Eureka Gulch.

The formation contains rock units that differ considerably in their stratigraphic and structural relations from place to place and now includes some units that were formerly part of both the underlying and overlying formations of the Silverton Group. The presently understood interrelationships and correlations of the Burns units are thus based more upon stratigraphy and gross characteristics of the rocks than upon petrographic features. Nevertheless, with only minor exceptions, the lower part of the Burns tends to be characterized by amphibole and biotite, whereas the upper part tends to be characterized by pyroxene. The meager chemical data available indicate that the Burns lavas are fairly uniform in composition and probably average near rhyodacite.

Within the map area the Burns Formation has been divided into upper and lower members. These two members have been divided into several distinct units on the basis of the type of eruption and (or) mode of deposition.

Lower member

The lower member of the Burns Formation may be divided conveniently into four units. The lowest unit is an anomalous intensely altered rhyolitic rock mass having steeply dipping flow lines and is found beneath the base of typical Burns rocks in Gray Copper Gulch; we did not relate this unit with certainty to the Burns while mapping in the area. Subsequent fieldwork in adjacent areas to the west (Burbank and Luedke, 1964), however, suggests that these rhyolitic rocks are related to a rhyolitic flow lying conformably beneath a local Burns volcanic dome in the ring-fracture zone of the volcanic depression west of Red Mountain peaks (pl. 1). These rhyolitic rocks appear neither at the base of the Burns west of the depression's rim nor within the depression east of Gray Copper Gulch. It thus appears that most of the rhyolite was restricted to a moat or graben within the depression's ring-fault zone that developed between Eureka and Burns eruptive epochs. The flow lines in the rhyolite are truncated by the basal flows of the lower member of the Burns in Gray Copper Gulch, and thus some erosion and possibly some tilting and (or) faulting occurred between the early Burns eruptive phases. Certainly tilting, faulting, and erosion occurred between the Eureka and Burns eruptive epochs, for at the base of the Burns at many scattered localities are appreciable accumulations of breccias composed principally of all pre-Burns volcanic materials. These local accumulations of surficial debris are, not believed, however, to be indicative of any long interval of planation and erosion.

The other three units of the lower member of the Burns are separate but intertonguing local lava masses and volcanic domes which formed along the ring-fracture zone of the volcanic depression; two of these separate volcanic masses, the Poughkeepsie Gulch volcano and the Mineral Point dome, rest on Eureka Tuff in the northern part of the map area. Between these older rock masses and overlying or lapping onto them are younger flow-layered lavas, whose source is problematical but may be in part beneath Tuttle Mountain or elsewhere in the angle between Poughkeepsie and California Gulches. The flow-layered lavas of the lower member thicken south along Poughkeepsie Gulch and generally southeast of a line extending from Tuttle Mountain northeast through Houghton Mountain to Denver Pass (pl. 2). However, the strongly developed flow-layered structures typical of the flows in the north-central and northwestern parts of the area appear to decrease eastward and southward. In the southern and southeastern parts of the map area, a discontinuous basal sandy tuff occurs between the lower member of the Burns and the underlying Eureka Tuff and is best developed in Eureka Gulch opposite the Terry tunnel. At the head of Poughkeepsie Gulch, and generally throughout the area south of the previously mentioned line it rests on Eureka Tuff and is overlain by a partly welded pebble-rich tuff that forms the base of the upper member.

Poughkeepsie Gulch volcano.—Situated mostly under Mount Abrams at the north end of Brown Mountain, Poughkeepsie Gulch volcano is a composite mass of alternating rhyodacitic lava flows, tuffs, and flow breccias and (or) agglomerates resting upon welded tuffs of the Eureka and against the wall of tuff-breccia of the San Juan Formation; at the base of the volcano and north of the vents is a local thin laminated flow of rhyolite. The volcano has a diameter of about 2 miles, the vent or vents (?) being somewhat off center relative to the whole mass. Kelley (1946) mapped three small intrusive plutons on the west wall of Poughkeepsie Gulch which are interpreted as the plugged source vents of this volcano.

Except for the light-gray rhyolitic flow at the base, the eruptive materials are medium to dark gray and are porphyritic with phenocrysts in a dense aphanitic groundmass. Amphibole and plagioclase feldspar are the prominent phenocrysts.

Subhedral to euhedral blades of hornblende, averaging about 2 mm in length, and anhedral to euhedral, mostly equidimensional crystals, of calcic andesine, averaging about 1 mm in size, occur in a microcrystalline groundmass of quartz, potassic feldspar, apatite, magnetite, and alteration products.

Mineral Point dome.—An elongated dome-shaped mass, known as Mineral Point dome, extends northeast from Mineral Point through Seigal Mountain and beyond the northeastern part of the map area. The medium-gray rock composing the dome is remarkably uniform throughout, having only slight variations in general appearance, texture, and mineral content. It is moderately porphyritic, with phenocrysts of pyroxene and plagioclase feldspar embedded in an aphanitic groundmass; this texture imparts to the rock its identifiable character in the field. At two localities on the margin of the dome—one on the cliffs by the San Juan Chief mill on the northwest side and the other just north of the Red Cloud mine on the south side—there seem to be brecciated (?) rim remnants or marginal chilled selvages which are slightly coarser porphyritic facies of the Mineral Point rock. Deuteric and later hydrothermal alteration effects are common throughout the Mineral Point dome.

Augite, mostly altered to chlorite and a carbonate mineral, and a little biotite compose the mafic phenocrysts. The felsic phenocrysts include two generations of plagioclase feldspar; the earlier and larger, averaging 6 mm in length, has an approximate anorthite content of An_{60}, whereas the later and smaller, averaging 2.5 mm in length, has an approximate anorthite content of An_{30}. All the phenocrysts are in a fine-grained to holocrystalline groundmass consisting of feldspar microlites, averaging 0.5 mm in length, with felted to pilotaxitic texture. Interstices are filled with magnetite, apatite, quartz, and alteration products.

Flow-layered unit.—A unit characterized by the flow layers occurs throughout most of the map area; however, in the southern and eastern parts, the rocks have a more massive appearance. Flow layering is accentuated by alternating light and dark millimeter-thick laminae not more than several meters long.

The gray rock weathers olive to brownish gray and is moderately porphyritic, having felsic and mafic phenocrysts in an aphanitic to fine-grained groundmass. The rock is generally weakly altered; locally, alteration is intense. Plagioclase, averaging 1.5 mm in length, and amphibole, averaging 0.5 mm in length, predominate as phenocrysts, but some biotite and sporadic quartz are present. The phenocrysts occur in a groundmass that consists most commonly of either a cryptocrystalline aggregate of quartz and potassic feldspar or a pilotaxitic texture of feldspar laths, averaging less than 0.1 mm in length, the interstices between the feldspar laths being filled by opaque materials and alteration products. The groundmass probably averages about 75 percent of the total bulk of the rocks composing this unit.

Upper member

Like the lower member, the upper member is divided into units, principally because of different modes of emplacement and types of materials contained in each. The older of the two units consists of a pebble-rich tuff, which throughout the map area and probably much of the adjacent areas serves as an excellent horizon marker and divider unit between the flow units of the lower and upper members, even in localities of intensely altered rock. Within most of the map area this tuff is welded, but at the mouth of Placer Gulch and on Eureka Mountain, it has little or no welding and is more sandy. Eastward beyond the Animas River valley the sandy tuff grades into and intertongues with tuffaceous and pumiceous shale and limestone. The younger of the units of the upper member consists of thick lava flows and resembles in many respects the flow-layered unit of the lower member, except in the eastern part of the area where it contains some interbedded thin sandy and shaly tuffs.

Also like the lower member, the upper member thickens from north to south. Near the north end of Brown Mountain it is only about 100 feet thick, but at the south end of the mountain it is 600–800 feet thick. Throughout the map area the upper member is generally overlain by thin-bedded sandy tuffs at the base of the Henson Formation. Much of the rock now included in the upper member of the Burns Formation was formerly included in the Pyroxene Andesite of the Silverton Volcanic Series (Cross, Howe, and Ransome, 1905). The sources of the upper member's flows are problematical, but a thicker domelike body in the member west of Gladstone may represent one source.

Pebble tuff unit.—Throughout most of the map area is a thin persistent ledge-forming welded pumice-rich and pebble-rich tuff, which ranges in thickness from a few feet to more than 50 feet but averages about 25 feet. This tuff separates the Burns Formation into an upper and a lower part. Both the lower and the upper contacts of the tuff appear sharp wherever clearly observed and not necessarily conformable with the flows that underlie or overlie the tuff bed.

The greenish-gray rock is very fine grained or granular, and where welded, has excellent eutaxitic structure. The aphanitic matrix, almost totally obscured by alteration products, is moderately rich in lithic fragments and fragmental crystals. Lithic fragments as large as 1.5 cm in diameter consist of metamorphic and extrusive igneous rocks; among the accidental fragments, rounded to subrounded quartzite and irregular plates of slate predominate. The fragmental crystals, averaging less than 1 mm in diameter, are both felsic and mafic. Biotite is the most common mafic crystal present; andesine and orthoclase are the most common felsic crystals present. Also present but in very minor amounts are quartz, amphibole, and questionable pyroxene. Because the rock is badly altered throughout its exposures, the composition can only be assumed to be rather silicic.

Flow unit.—The upper member's lava flows are compositionally uniform and thick. In Ross Basin at the head of Cement Creek, they appear massive, but elsewhere they are streaked or have flow layering that varies in prominence. The medium-gray rock is porphyritic and contains felsic and mafic phenocrysts embedded in a dense aphanitic groundmass. The rocks weather brownish gray.

Much of the rock in this unit within the central and southern parts of the area, particularly where strongly deformed, has been intensely silicified, epidotized, and propylitized. Pyrite cubes are dispersed throughout.

Plagioclase and clinopyroxene phenocrysts, locally imparting a glomeroporphyritic texture to the rock and even penetrating one another, occur in a groundmass that ranges from a cryptocrystalline or fine-grained granular mass with a few feldspar microlites to a felted and in places pilotaxitic mass. The anhedral to euhedral plagioclase phenocrysts (An_{25-45}) average about 1 mm in length. The clinopyroxene (augite), averaging about 0.5 mm in diameter, is mostly altered to chlorite, epidote, quartz, and iron oxides in the thin sections examined. The remainder of the rock consists of minor amounts of orthopyroxene, biotite, quartz, apatite, magnetite, and alteration products.

HENSON FORMATION

The Henson Formation as redefined (Luedke and Burbank, 1963) now includes the former two upper units of the Silverton Volcanic Series as mapped by Cross, Howe, and Irving (1907): (1) an unnamed unit provisionally called the Pyroxene Andesite and (2) the Henson Tuff. The interbedded lava flows and tuffs in these two units are identical, and it is thus impracticable, and in many places impossible, to distinguish them, particularly in belts of structural complexity. Accordingly, the entire sequence of eruptive rocks in the Silverton Volcanic Group above the Burns Formation has been assigned to the Henson Formation.

The Henson Formation consists principally of interbedded andesitic to rhyodacitic lava flows, breccias, and tuffs, but also includes rhyolitic lava flows in the vicinity of Picayune Gulch, rhyolitic lava flows and tuffs in the vicinity of Red Mountain No. 1, rhyolitic tuffs along Mineral Creek west of the San Juan Chief mill site, and a quartz latitic welded ash-flow tuff (Luedke and Burbank, 1961) in the northern part of the area at Mount Abrams and Engineer Mountain. Local thicknesses of the formation are controlled possibly in part by structure, surface relief, and local subsidence during Henson time. The maximum known thickness of the Henson Formation in the southern part of the map area is about 800–1,000 feet. Possibly greater thicknesses exist in the northern part, particularly just north of the map area. There the accumulation of eruptive materials was confined in part by the Mineral Point dome of the Burns Formation which acted as a partial barrier to materials that originated in the ring-fault zone of the San Juan volcanic depression north of the dome (fig. 2) and to materials that came from centers south of the dome or in the central part of the depression. The ash-flow tuff has a preserved thickness of about 1,000 feet on Mount Abrams but thins northeastward to average about 200 feet. The rhyolitic mass in the vicinity of Red Mountain No. 1 possibly has a thickness far exceeding 1,000 feet.

Sources of the lavas and ash are mostly obscured, but one central-type vent is found near the head of Eureka Gulch beneath the slope of Bonita Peak, and another is suspected near the head of Picayune Gulch beneath the slopes of Eureka Mountain. Some flows may have erupted from fissures, because some dikes of material similar to that in the Henson flows cut the older formations. Fissure eruptions are assumed also for the thin flows of rhyolite and associated tuffs near the base of the Henson Formation and the similar rhyolite in dikes that cut the older rocks. The quartz latitic ash flow is believed to have erupted from a central vent just north of the map area west of Engineer Mountain (Luedke and Burbank, 1961).

The sandy reworked water or fine-grained gray tuffs reworked by water are thin bedded and locally are cross-stratified. They occur as layers, in places lenticular, that range in thickness from a few feet to more than 100 feet. The base of the Henson Formation is generally marked by a tuff layer which locally has a large proportion of embedded foreign fragments, mostly flow rocks; however, any of the tuff layers locally may have many rounded to subangular fragments of silicic and mafic rocks ranging from sand to boulder size. The bulk of the tuffs consists of grains of fragmental felsic and mafic crystals, magnetite, and lithic fragments cemented by secondary silica, clay, and carbonate minerals. The grains range from less than 0.05 to 1.7 mm in diameter. Vitroclastic texture is largely destroyed.

The dark-gray commonly amygdular lava flows and breccias are porphyritic and consist of two main types: (1) dense aphanitic rock containing phenocrysts 1–2 mm in length and (2) dense aphanitic rock containing phenocrysts 5–10 mm in length. The finer prophyritic rocks are found throughout exposures of the formation, but particularly south of the Mineral Point dome, whereas the coarser porphyritic rocks are found mostly north and east of the Mineral Point dome. In both types, plagioclase and pyroxene are the principal phenocrysts, but minor amounts of olivine are more common in the coarser type. The plagioclase feldspar phenocrysts are labradorite (An_{55-65}) and range from 0.2 mm to 1 cm in length. The pyroxene phenocrysts consist of both augite and hypersthene and range from 0.5 mm to 2.5 mm in length. These minerals are altered in

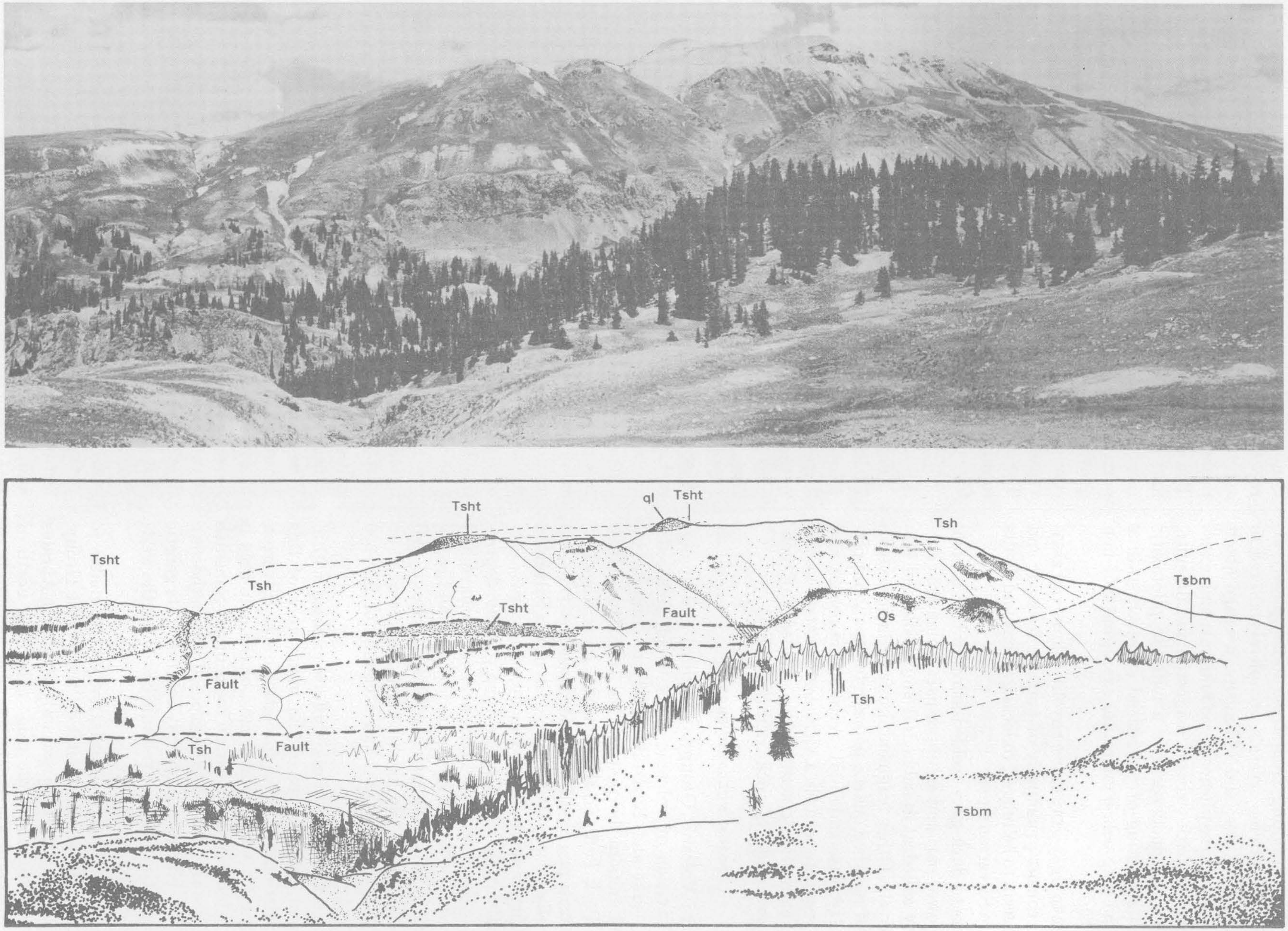

FIGURE 2.—View and sketch of the alternating flows and tuffs and the welded tuff of the Henson Formation lapping onto Mineral Point dome unit of the Burns Formation, and ring faults of the Silverton cauldron in the south side of Engineer Mountain. Timbered ridge (center right) underlain by rhyolitic flows and breccias at base of Henson Formation, which are dipping 25°–45° N. Crest of peak capped by porphyritic quartz latite, ql. Tsbm, Mineral Point dome unit of Burns Formation; Tsh, Henson Formation; Tsht, welded ash-flow tuff of Henson Formation; Qs, landslide. Sketch by B. N. Wahju.

varying degrees, ranging from fresh to completely altered. Subhedral olivine crystals, completely altered to serpentine, iron oxides, and iddingsite, average about 1 mm in length. These phenocrystic minerals and accessory minerals of apatite, zircon, magnetite and ilmenite, and alteration products occur in a felted to pilotaxitic groundmass consisting of interstitial cryptocrystalline materials and plagioclase microlites averaging 0.07 mm in length.

The white to light-gray dense rhyolitic flows and associated tuffs consist principally of potassic feldspar and quartz and seem to be related to local grabens and faults active in late Silverton time.

The light- to dark-gray welded ash-flow tuff is composed of a lower part and an upper part which are characterized by euhedral to subhedral amphibole and biotite respectively. Other fragmental intratelluric crystals consisting of resorbed quartz, potassic feldspar, and plagioclase (oligoclase-andesine), accessory minerals, and alteration products occur in a vitroclastic matrix locally exhibiting eutaxitic structure. The welded tuff contains very few accidental rock fragments.

POTOSI VOLCANIC GROUP

The Potosi Volcanic Group is the third and youngest major division of volcanic rocks which was redefined by Luedke and Burbank (1963) to contain two formational units in the western San Juan Mountains: the Gilpin Peak Tuff and the Sunshine Peak Rhyolite; the units consist principally of welded ash-flow tuffs and are genetically related to the formation of the Silverton and Lake City cauldrons, respectively, which are superimposed within and upon the San Juan volcanic depression (pl. 4). Other units are now believed to have had their source in the Lake City center and thus add to the formational units in the redefined Potosi Group. All these units possibly could have covered an area of more than 1,000 square miles and had a volume of 200–300 cubic miles.

No rocks of the Gilpin Peak Tuff are exposed within the map area, but because of the importance of this unit in its relationship to the formation of the Silverton cauldron (pl. 1), within which most of the map area is located, it is noteworthy. Also, no rocks of the Sunshine Peak Rhyolite are believed to be exposed within the map area, but it too is mentioned briefly because of its genetic relationship to the Tertiary volcanic history in the western San Juan Mountains.

Isolated bodies of welded tuffs, not yet assignable to any particular formational unit in the Potosi Group, are exposed within the map area only on Mount Abrams and at the north end of the ridge extending north of Engineer Mountain. On Mount Abrams the body has a minimum thickness of 400 feet. At both localities, the rocks are grayish-brown moderately crystal-rich welded ash-flow tuffs with prominent eutaxitic structure and probably have a composition of rhyolitic quartz latite. The rock contains accessory fragments of quartz latite, and particularly on Mount Abrams, accidental fragments of granite, quartzite, and slate in the lowermost part. The crystals and crystal fragments of andesine, quartz, augite, and minor hornblende and biotite are contained in a dense crystalline matrix in which the vitroclastic structure is almost or completely obliterated. The compacted pumice lapilli and matrix are devitrified to minute fibers or fine-grained aggregates of potassic feldspar and quartz.

QUATERNARY DEPOSITS

The Quaternary deposits of the map area include Pleistocene glacial and landslide deposits and Recent alluvial, talus, rock-glacier, and landslide deposits. Three advances of Pleistocene glaciers, were recognized in the San Juan region by Atwood and Mather (1932), who named them, from oldest to youngest, the Cerro, Durango, and Wisconsin glacial stages. Richmond (1954) has further suggested that the Durango and Wisconsin stages each represent two glacial advances rather than one and that the Cerro is of pre-Wisconsin age and the Durango and Wisconsin are of early Wisconsin and late Wisconsin ages, respectively. A few remnants of gravel on protected mountain shoulders, as on Houghton Mountain at an altitude of 12,400 feet, may represent remnants of pre-Wisconsin deposits, but for the most part, the earlier deposits, the Cerro stage of Atwood and Mather (1932), were destroyed during the Wisconsin Glaciation. Remnants of the Wisconsin glacial drift are found mostly near the cirques and on the slopes of the valleys at the junctions of valley glaciers.

Rock glaciers, or rock streams as they were previously called by Howe (1909), probably represent minor advances of ice, rock, and snow in glacial cirques in post-Wisconsin time rather than landslides as thought by Howe (1909) and Atwood and Mather (1932). After Pleistocene glaciations, the walls of the cirques must have remained high enough to permit more rock debris than ice and snow to accumulate in the cirques. At depth, the rock glaciers in some, if not all, cirques are still cemented with ice. Under present conditions, talus from the walls of the cirques is encroaching upon and covering the stagnant rock glaciers. The age of these rock glaciers is debatable, but they have advanced over the old Wisconsin glaciated floor of the cirque heads and, according to Richmond (1954), are of Recent rather than Pleistocene age.

Locally, talus entirely obscures the lower slopes of the cliffs and mountains. In places the talus is likewise cemented with ice at depth. In the mapping of talus, generally only those deposits are shown that effectively obscure the bedrock.

Small landslides, as represented, for example, by the deposit in Placer Gulch, have continued to take place in the area until recent years.

The valley alluvial deposits and alluvial cones in the map area are largely of Recent origin but locally may be partly reworked older debris of late Wisconsin age. Where cemented by bog iron and clayey material, the older gravels are resistant to erosion and consequently are preserved in their original position. These higher level gravels are found along Cement Creek, south and west of the map area; some are preserved also along the Middle Fork of Cement Creek and along Minnehaha Creek.

Alluvial cone or fan deposits are found at the mouths of most tributary streams and gullies, and coalescing alluvial cones effectively obscure the lower slopes of some of the cliffs and mountains.

Many of the small upland flats and locally valley bottoms are covered by colluvial deposits consisting in part of alluvial fill and in part of residual materials. Often these colluvial areas are extremely boggy.

The bearing of the physiographic development and glacial erosion on oxidation and enrichment of ores within the region will be considered briefly under the section "Supergene and hypogene enrichment."

INTRUSIVE ROCKS

Three and possibly more periods of intrusive activity are recorded in the western San Juans by (1) granitic to diabasic rocks of Precambrian age, (2) granodioritic and related hybrid rocks associated with the Laramide orogeny of Late Cretaceous and early Tertiary age, and (3) grabbroic to rhyolitic rocks of late Tertiary age. Clastic dikes, of intrusive origin but not of primary igneous composition, are also discussed in this section. Ore deposits of prevolcanic age (Burbank, 1930, 1935, 1940; Luedke and Burbank, 1962) are related to the granodioritic rocks, and centers of ore deposition similar to that at Ouray may be buried beneath the eruptive materials.

Intrusive rocks younger than the eruptive materials form numerous discordant and concordant masses throughout the Eureka district and adjoining areas. A few intrusive bodies in the Eureka district clearly represent lava conduits or feeder vents for some of the late surface eruptions. Generally, however, structural relations of these intrusive masses are obscured by faulting and overlapping eruptive rocks; where field relations are uncertain, the intrusive masses are included with surface volcanic accumulations with which they are associated. Dikes and small plugs or irregularly shaped plutons are common, and the fractures and vents they occupy are related structurally to the fissures occupied by the ore deposits. All the larger stocks lie outside the map area (pls. 1, 4).

The common intrusive igneous rocks, occurring mostly as dikes in the map area, are andesite, quartz latite, and rhyolite. The andesite (possibly latite) in dikes and sills is generally an inconspicuous dark fine- to medium-grained rock that closely resembles lava flows. Some of these intrusive bodies cut flows throughout the volcanic pile and may have been feeders to some of the flows. Some also occur along major fault lines which were active at different times during the eruptive cycles; at such places the intrusive rocks are associated with breccia bodies of similar composition, possibly representing repeated eruptions along active faults. Most of these intrusive and breccia bodies have vague boundaries and structural relations and have not been differentiated on the map from the main masses of flows. Possibly some unmapped sill-like bodies of these rocks exist, but on the whole very few true sills have been recognized. Some rock masses described as sills by Cross, Howe, and Ransome (1905) were shown by detailed mapping to be thick complex flows, whose internal structures, caused by fracturing and engulfment of lava crusts, give the false impression of local intrusive masses.

Porphyritic quartz latite is the most widespread of the intrusive rocks. It is a very conspicuous gray to light-brown rock with large phenocrysts of pink to white potassic feldspar, commonly about 1 cm long but as much as 4 cm long, and a little quartz, augite, hornblende, and biotite in a dense aphanitic groundmass. The longest and largest dike shown on plate 2 crops out discontinuously from near the head of Gray Copper Gulch to the south slope of Houghton Mountain, a distance of 3½ miles. A greenish-gray intrusive quartz latite occurs as irregular sills on Wood and Houghton Mountains and forms relatively thick bodies along the shaly tuff beds at the base of the Burns Formation.

Rhyolite most commonly occurs as thin discontinuous dikes along small fissures and as small irregularly shaped plugs. It is light-colored fine-grained rock with only a very few inconspicuous small phenocrysts of feldspar. The rock in the rhyolitic dikes is dense and platy or ropey. One rhyolitic dike on the southeast side of California Mountain consists of both dense and porous layers; the porous rock contains irregularly elongated vesicles, several inches long, filled with quartz and a little calcite. Rhyolite intrusive bodies occur at Denver Hill and at California Mountain. The rhyolite in both plugs is white to gray cryptocrystalline rock; at Denver Hill it is massive, whereas at California Mountain it has long thin streaks of coarser, crystallized granular material. In places, the streaky texture is somewhat wavy or wraps around a few inclusions of crystalline rock. Most of the groundmass is too fine grained for identification of its mineral components, but the coarser bands consist in part of some quartz and potassic feldspar intergrowths. A little chloritic material, grains of iron oxides, and rare flakes of mica, probably altered biotite, are visible in some grainy patches.

Intrusive clastic dikes closely related to some of the igneous intrusives but not of primary igneous origin occupy a few randomly oriented and discontinuous fissures throughout the map area. The contact of these dikes with the wallrock is sharp. The dikes range in thickness from a few inches to a few feet, though they pinch and swell along the fissures. They are composed of rounded to angular fragments of the volcanic country rock and of the underlying Precambrian basement rocks. Fragmentation is believed to have been contemporaneous with the forceful intrusion.

VOLCANIC PIPES

A few volcanic pipes containing bodies of intrusive breccia and igneous rock are exposed on the slopes of Red Mountain No. 1 in the western part of the map area. These pipes are commonly found in areas where the chimney mineral deposits occur, but the two are not always closely associated. The forms and possible origin of these vertical cylindrical bodies have been described by Burbank (1941, p. 170–178), who related their mode of formation and shapes to structural influences that also bear on the origin of the chimney deposits of the region. The most symmetrical pipes typically have slightly elliptical cross sections. Some pipes are completely filled with intrustive porphyritic quartz latite or rhyolite and have sharply defined walls that may be somewhat sheeted. The intrusive igneous rock composing many of the pipes does not differ greatly in composition from the volcanic host rocks. An analysis of the various stages of pipe growth and form indicates that the pipes are so-called tubes along which the volcanic country rocks were initially brecciated and fluxed by hot gases and solutions rising from underlying magma along nearly vertical linear channels. Subsequently, these rocks were reconstituted mineralogically by metasomatic action and eventually partly incorporated in fused material.

Some pipes doubtlessly extended to the surface and perhaps formed vents for local volcanic piles. Some pipes also contain mixed instrusive masses of porhyritic quartz latite, rhyolite, and breccia and thus indicate several stages of eruptive activity.

The texture and composition of the porphyritic quartz latite and rhyolite in the pipes appear very much like that of some dikes in areas where tensional fissuring resulted in dike forms rather than the cylindrical pipes characteristic of the west margin of the Silverton cauldron. The magmas that filled the dike channels possibly had a similar origin to the magmas that filled the pipes.

STRUCTURE

REGIONAL SETTING

The Eureka district and adjoining areas (pl. 2) occupy the northeast quarter of the Silverton cauldron (pl. 1). This cauldron and the comparable Lake City cauldron to the northeast lie within the older and larger San Juan volcanic depression (pl. 4). These major structural features are related to the vast accumulation of volcanic materials that compose the so-called western San Juan source area and are the result of successive and repetitive stages of eruption, of partial engulfment of volcanic piles, and of resurging magma that caused local uplift, radial and concentric fracturing, and subsidence of some blocks.

The western San Juan Mountains basement on which this Tertiary volcanic complex formed is composed of Precambrian, Paleozoic, and Mesozoic metamorphic, sedimentary, and igneous rocks (pl. 5*A*), and has been intermittently elevated and deformed during much of geologic time. Early Tertiary streams draining westward and northward from the Needle Mountains highland to the south eroded much of the Paleozoic and Mesozoic sedimentary cover and exposed the Precambrian core, from which these sedimentary rocks dip away to the west and northwest. Here and there, residual hills rise as much as 1,000 feet above this early Tertiary erosion surface, which is locally veneered in its lower parts by the sedimentary Telluride Conglomerate.

Major northeast, north, and northwest structural trends prominent in the western San Juan block seem to intersect in the general vicinity of the Silverton cauldron. Recurring structural activity was concentrated along these trend lines throughout much of geologic time. The northeasterly alinement of some major structural features, such as the long axis of the volcanic depression of the Tertiary volcanic complex (pl. 4), could conceivably be reflections of northeasterly tectonic trends as old as Precambrian. Tweto and Sims (1963, p. 1006 and figs. 2, 5) suggested for this region a southwesterly projection of the Precambrian tectonic features that they have found for more northerly parts of the Colorado mineral belt. The northerly lineament reflected in the volcanic cover seems to be closely alined with the strongly deformed west border of the Needle Mountains uplift to the south. Along this line the Paleozoic sedimentary rocks dip abruptly westward off the highland of Precambrian rocks. The ancestory of some well-defined northwesterly trend lines is partly reflected in and partly obscured by both sedimentary and volcanic covers, but these trend lines could be related to the northwesterly trend of the Uncompahgre-San Luis highland of Paleozoic and Mesozoic age (Burbank, 1933c, p. 277–283 and figs. 13, 14). These earlier developed tectonic trends in the basement block of the western San Juans may have had some effect in localizing Tertiary volcanism.

VOLCANIC STRUCTURAL EVOLUTION

The early eruptions of materials that form the breccias, tuffs, and flows composing the San Juan Formation came from a cluster of volcanoes extending along a northeastward-trending zone from the vicinity of the Eureka district to and beyond Lake City (pl. 4). Considerable evidence as to the original nature of these volcanoes is afforded by the Lake Fork volcano east of Lake City and by another center northwest of Lake City. The Lake Fork volcano was considered by Larsen and Cross (1956, p. 64) as older than tuffs of the San Juan Formation, but considerable intermingling of debris from this center with San Juan debris to the west indicates overlapping of eruptive sequences. As a group, the volcanoes were highly explosive and yielded a great volume of mudflows and ashy-fragmental debris that spread over hundreds of square miles (pls. 4, 5*B*). Closer to the centers, flow breccias and lava flows intermingle irregularly with brecciated debris. Locally, lava flows in the upper parts of the San Juan Formation extend radially westward, northwestward, and northward from the volcano or volcanic sources that must have been in the Eureka-Red Mountain-Engineer Mountain area.

The transition from the violent San Juan type eruptions to lava eruptions of early Silverton time appears to have taken place without an appreciable interval of volcanic quiescence and erosion. However, significant eruptive and structural changes must have taken place because the great San Juan volcanic depression covering more than 400 square miles had begun to take form (pl. 5*C*). Its origins are obscure. The conclusions of Cross, Howe, and Irving (1907, p. 15) that a great erosion interval preceded Silverton eruptions and that canyons several thousand feet deep were cut in the San Juan beds, even below the level of the Telluride erosion surface (Atwood and Mather, 1932, p. 18; Wisser, 1960, p. 30), are based upon misinterpretations of structural features. The walls of the so-called canyons referred to in early reports coincide with the walls of the faulted rim zones of the San Juan volcanic depression against which Silverton volcanic rocks were deposited during evolution of the depression.

Structural events are connected either with an initial downwarping of the site of the older volcanoes (Burbank, 1933b, p. 180) or with local doming of the basement preceding subsidence and engulfment of the volcanoes. A granitic high now remains near the center of the San Juan depression between the Silverton and Lake City cauldrons, probably representing some upthrust of the basement through mantling San Juan and Silverton rocks. But the timing and magnitude of these several more obscure events remain to be clarified by further study.

Some redistribution of volcanic debris in the San Juan Formation took place during the development of the volcanic depression. In part, this was the result of local erosion, which is to be expected in an unstable volcanic environment. Backwashing of the materials toward the depression is evident at places along both the northwest and south rims of the depression. Also, abrupt thinning of the San Juan Formation to zero at the northwest corner of the map area, from a thickness of more than 2,000 feet just to the north and west of this locality, could have been the result of basinward landsliding of debris toward voids created by subsidence. But there is no evidence that extensive erosion cut great canyons through the rim zones and removed hundreds of cubic miles of fragmental debris.

The rocks of the Silverton Volcanic Group never extended far from the confines of the San Juan depression (pl. 5*D*). Thin flows of Picayune, Eureka, and Burns that overflowed to the west and northwest of the depression rim end abruptly against the wall along the north rim. The depression must have deepened gradually or intermittently with transfer of lava and ash to the surface. This deepening may have been especially accentuated during and (or) following eruptions of the Eureka ash flows. After subsidence, and welding of the ash flows, the basin floor was arched, distended, and then collapsed to some extent; this deformation initiated the major northeast-trending graben of the Eureka district. As a result, the layered volcanic rocks tend to dip outward from the line of this graben towards the rims of the depression. This structural feature was accentuated and further faulted during later intrusive and eruptive activity.

In early Burns time, the San Juan depression was bounded at many places by faulted rims along which a number of large Burns volcanoes formed. Many of the Burns flows are characterized by great thickness, the materials coming in part from the rim volcanoes and in part from large domes scattered about on the floor of the basin. At least two such domes and possibly several others lie within the Eureka district. The formation of one of these, the Mineral Point dome in the northeastern part of the map area, evidently involved some dislocation of the basin floor and possibly accentuated the dip of the already northwest-dipping Eureka beds. The line of this dislocation is marked by strong shearing and brecciation of Eureka beds northeast of Denver Lake and by a rhyolite intrusion along the north slope of Houghton Mountain.

The Burns eruptions left the basin floor in the vicinity of the Eureka district divided by the high ridge of the Mineral Point dome; the later flows, tuffs, and breccias of the Henson Formation show some effects of this barrier. To the northwest, between the ridge and the north rim of the depression, many tuff beds and some thin interbedded lava flows were deposited. South of the ridge, a great thickness of relatively thin lava flows and breccia beds was deposited in a basin covering an area west, south, and east of the Eureka district. The floor appears to have been arched and distended again along the trend of the Eureka graben; small amounts of rhyolite extruded along some of the graben faults, particularly on Treasure Mountain. Sources of most of the Henson flows are obscured or are outside the immediate area. One small circular central vent, indicated by a local accumulation of inward-dipping tuffs and agglomerate, is exposed on the slopes of the ridge about 2,000 feet southwest of Lake Emma, and other vents may be represented by dikelike bodies on the ridge east of Hurricane Peak.

Ash-flow eruptions that began in late Henson time reached a climax in the immense ash flows of the Potosi Volcanic Group (pl. 5*E*). During repeated eruptions, great volumes of ash spread for many miles over surrounding areas. As a result, a block of crust about 10 miles in diameter—the Silverton cauldron enclosing the Eureka district—was downfaulted by reactivation and extension of the west rim faults and by localized faulting along what is now the course of the Animas River above Silverton. Renewed faulting took place along the earlier mentioned Eureka graben, and probably the main displacement on the Ross Basin fault (pl. 2) took place at about this time. For several miles around the Silverton cauldron (pl. 1) the crust was domed and broken, evidently by some final resurgence of deep magma, and systems of radial and concentric fissures, faults, and dikes were formed. Small stocks invaded the newly faulted rim zones and intruded the outlying formations west of the cauldron. This final doming and intrusive activity clearly followed emplacement of the Potosi ash flows, as indicated by radial dikes that cut these ash flows (pl. 5*F*). Further subsidence of peripheral parts of the domed cauldron, however, is shown by downfaulted Potosi beds along the west rim zone. The evolution of the cauldron in its later stages compares closely with the so-called resurgent cauldrons defined by Smith, Bailey, and Ross (1961).

The late subsidence and doming of various crustal blocks of the Silverton cauldron seem to have taken place in pulsations rather than as a single event. Some radial fissures contain multiple dike intrusions which terminated in some places with injections of clastic debris. Probably the latest igneous activity was concentrated in parts of the rim zones and concentric faults of the cauldron, where the combined action of volcanic gases and magmas formed numerous igneous and breccia pipes. A few of these lie within the Eureka district; examples are those in the vicinity of the strongly bowed fault zone on Red Mountain No. 1 along the west border of the map area. Few if any of these smaller volcanic pipes have been appreciably faulted, and they very likely represent the dying phases of igneous activity. Commonly, viscous rhyolite is the youngest intrusive rock in the pipes; it followed the intrusion of porphyritic quartz latite which is locally brecciated. These volcanic pipes may have been feeders for summit volcanoes having rather viscous lava and breccia eruptions, but erosion has destroyed any positive evidence of this eruptive phase in the Silverton area.

Intermittent pulsation of the volcanic crust seems to have continued after cessation of igneous activity because many mineralized fissures were reopened repeatedly during the formation of compound vein deposits, for example, those of the Sunnyside and other prominent fault-line veins of the district. Volcanic emanations were especially active in parts of the faulted rim belts, particularly along the western border of the district and in the adjoining Red Mountain area. These features will be discussed more fully in connection with alteration of the volcanic rocks (p. 29). The volcanic stratigraphy and related structural geology of the region around and including the Eureka district are summarized in table 3.

TABLE 3.—*Middle(?) Tertiary volcanic and structural evolution of the western San Juan Mountains*

Event	GEOGRAPHIC DISTRIBUTION OF UNITS: ← Generally west			Generally east →
		Quartz latite flows and intrusives		
		DOMING OF SILVERTON AND LAKE CITY CAULDRONS		
		Potosi Volcanic Group		
RECURRENT SUBSIDENCE OF SILVERTON AND LAKE CITY CAULDRONS	Gilpin Peak Tuff	Sheep Mountain Quartz Latite	Sunshine Peak Rhyolite	Huerto Formation
		Silverton Volcanic Group		
RECURRENT SUBSIDENCE AND DOMING OF SAN JUAN VOLCANIC DEPRESSION		Henson Formation Burns Formation Eurěka Tuff Picayune Formation		
		SUBSIDENCE OF SAN JUAN VOLCANIC DEPRESSION		
		San Juan Formation--Lake Fork Formation		

DESCRIPTIONS OF STRUCTURAL FEATURES

ATTITUDES OF THE VOLCANIC ROCKS

Original attitudes and relations of the various rocks in the Eureka district and adjoining areas sometimes were difficult to decipher despite extensive lateral and vertical searching throughout individual units. Typically in volcanic terranes, few, if any, units serve as reliable horizon markers for any great distance. Planar structures generally lie nearly parallel to the bottoms and tops of many lava flows. Some flows, particularly in the Burns Formation, possess strongly contorted layers that are apparently unrelated to the normal internal attitudes of typical lava flows. The original layering in the welded tuffs also was nearly parallel to the bottoms and tops of the ash flows, but topographic irregularities on the underlying surface probably produced significant local variations. The lake-deposited limestones and varved shales in the Burns Formation and the fluviatile sandy tuffs form the most reliable horizon markers, but these beds unfortunately are limited or lacking in a number of structurally critical areas.

In some localities, the steeply dipping to vertical flow banding is believed to represent local domes and ridges of viscous lava that rose from vents on the floor of the depression; in other places, it represents local effects of flowage. The absence of interbedded tuffs and sedimentary units at domed bodies may indicate that the bodies were emplaced above the average depositional level of the tuffs and sediments.

Dip and planar flow symbols on plate 2 commonly represent averages of many local readings. Dips of 25° to locally 50° or more in the tuffs, limestones, varved shales, and on contacts between flows, and local consistency in the attitudes of flow layering in lava flows established with reasonable assurance the true tilting and deformation in numerous fault blocks of the district.

These general features thus indicate a wide depression floor on which ridges and domelike bodies of lava were separated by areas of more nearly horizontal lava flows, tuffs, and breccias and a few lake beds. This melange contrasts strongly with the consistently layered and nearly horizontally bedded flows and tuffs outside the San Juan depression margins. The faulting and tilting of the beds and masses composing the depression floor was intermittent, and the final complex probably is the result of many episodes.

MAJOR STRUCTURAL ELEMENTS

Aside from the local deformation of the volcanic formations throughout the map area, there are four dominant structural elements and trends: (1) an incomplete but complex system of roughly concentric ring faults and fissures related to the main downfaulted central block of the Silverton cauldron, (2) the northeast fault trough or graben block lying between major faults that are part of a system of nearly parallel and interconnecting faults and fissures of northeast trend, (3) a north-trending horst and graben structure in Poughkeepsie Gulch, and (4) a large downfaulted oval-shaped block, the Red Mountain block, along the west border of the district. Superimposed upon these structures throughout the area are other minor structural features of local and often obscure nature, which will be mentioned specifically later.

CAULDRON RING-FAULT BELT

Part of the ring-fault belt of the Silverton cauldron is expressed both structurally and topographically within the map area. In the northwestern part of the area, the faults and mineralized fractures included in the ring-fault belt consist of the northeast-trending set which crosses Brown Mountain just south of Mount Abrams with but little topographic expression. The set extends southwest across the upper end of Ironton Park and then south through the Red Mountain Pass area, west of the map area. (See Burbank and Luedke, 1964.)

Within the rest of the area, at the north and east edges, an arcuate topographic depression or trough on this structural belt extends from the mouth of Poughkeepsie Gulch along Mineral Creek by Engineer and Seigal Mountains down the valley of the Animas River past the townsite of Eureka (fig. 3). The northeast- and east-trending ring-fracture sets are less strongly defined and may die out where they abut or possibly turn into the northwest-trending faults, also considered as part of the ring structure, near the San Juan Chief mill site. Farther along the south side of Engineer Mountain, only a few east- or southeast-trending mineralized fractures were observed.

FIGURE 3.—View southwestward into glacier-carved Animas River valley from Cinnamon Mountain. Valley parallels ring-fault belt of Silverton cauldron. Former Eureka townsite at head of flats, bottom center.

West of Seigal Mountain, no major southward-trending structures corresponding to the ring-fault belt were observed; a few locally sheeted zones and a few weakly mineralized fractures occur in the rocks. North of the Cinnamon fault are a few south- to southeast-trending mineralized fractures and the dogleg or offset in the north branch (Sunnyside-Wood Mountain faults) of the Sunnyside fault system (pl. 6). South of the Cinnamon fault are several known strong ring faults which can be traced down the Animas River valley to and beyond the Eureka townsite (those east of the river are not shown on pl. 2 or 6).

The faults and fractures considered to compose the ring-fault belt are vertical or nearly vertical. The movements on these faults and fractures are thought to have been vertical with little or no horizontal component, and the downthrown blocks generally are on the cauldron side. Locally, the stratigraphic section has been repeated several times within the ring-fault belt, particularly where several faults make up the belt.

EUREKA GRABEN

The principal faults of the graben block herein named the Eureka graben include the Sunnyside fault and its continuation in the Wood Mountain and Cinnamon faults, the Ross Basin fault, the Bonita fault, and the Toltec fault and its continuation in the Anaconda fault (Burbank, 1951); together these form a large boot-shaped complex outlining the graben shown on plate 6. Several of these faults or parts of them were first mapped in the Silverton folio (Cross, Howe, and Ransome, 1905). Details of the fault extensions east of the Animas River have not been mapped, but these extensions, essentially as shown in the Silverton folio, have been confirmed.

The Ross Basin fault, forming the top of the "boot's toe," trends southeastward along a curving course from east of Red Mountain No. 1 through Ross Basin to near Lake Emma in Sunnyside Basin (pls. 2, 6). The fault dips 70°–85° S., and the south block is downthrown relative to the north block. Maximum displacement of rocks on the fault occurs near the right-angle junction with the Sunnyside fault near Lake Emma and diminishes westward along its course toward the junction with the Bonita fault. Flows and tuff beds north of the fault generally are tilted 25°–35° NW. in narrow northward-trending fault blocks which are successively repeated to the east in Hurricane Peak (pls. 2 and 3, section *B–B′*). The flow and tuff beds south of the fault are tilted more moderately southward.

The main Sunnyside fault extends from the nearly right-angle junction with the Ross Basin fault in Sunnyside Basin northeastward into Placer Gulch for about 2 miles, where it splits into two major branches. The southeastern branch, called the Cinnamon fault, continues northeastward across the cauldron's ring-fault belt with little or no displacement and may be traced several miles beyond the map area. The Wood Mountain fault is considered to be the northwestern branch, although it is offset to the north (pl. 6) along the ring-fault belt; this branch fault likewise may be traced several miles northeastward beyond the map area. The Sunnyside and the Wood Mountain faults dip 70°–75° S.; the Cinnamon fault dips 65°–70° S., but steepens to vertical east of the Animas River. The blocks south of the faults are downthrown relative to those north of the faults. The Sunnyside fault at its junction with the Ross Basin fault and near the head of Placer Gulch actually consists of several major fractures and sheeted ground.

The Toltec fault forms the south edge of the graben and extends from a nearly right-angle junction with the Bonita fault at Emery Peak northeastward with little change in trend or strength across the ring-fault belt along the Animas River valley. Its continuation eastward beyond the map area is called the Anaconda fault. Dips on the Toltec and Anaconda faults are 60°–70° N., but locally flatten to 45° at slight changes of trend such as near the mouth of McCarty Basin and north of Eureka Mountain. Rocks north of the faults are downthrown relative to those south of the faults.

The boot-shaped Eureka graben block is bounded at the southwest, or the "sole of the boot" by the Bonita fault. This fault dips steeply northeast, opposite to the Ross Basin fault, and the body of rock within these bounding faults must taper downward in the same manner as the northeast-trending block forming the main part of the Eureka graben. (See pls. 3, sections *A–A′*, *B–B′*, *E–E′*, and 6.) The volcanic formations bounding the Bonita fault on the southwest are tilted down to the southwest and are broken by many small faults and sheeted zones parallel and diagonal to the Bonita fault.

As shown on plate 2, the Ross Basin fault cannot be recognized beyond the right-angle junction with the Sunnyside fault. However, beyond this junction along a projected trend east-southeastward to the townsite of Eureka in the Animas River valley, the flows and tuffs forming the steep north slopes of Eureka Gulch are monoclinally tilted and step-faulted down on minor faults southwestward (pl. 3, sections, *D–D′*, *E–E′*). The combined displacement of this mile-wide belt of monoclinal tilting and faulting possibly amounts to as much as 1,000 feet and thus represents a downthrow corresponding roughly to the displacement on the Ross Basin fault. Where this folded and faulted belt is crossed by the graben's south-bounding Toltec fault, there is no appreciable change in structural attitude of either this belt or the Toltec fault.

The many northeast-trending mineralized fractures and faults north of the Eureka graben and east of Brown Mountain (pl. 2) are in part probably related to the later deformation of the graben.

As stated previously, the bounding faults of the Eureka graben apparently follow closely fault lines established probably in late Eureka time. Thus, all the bounding faults and structural features of the Eureka graben are probably not the sole result of a younger (late or post-Potosi time) subsidence and uplift. However, the principal cause of settling of the wedge-shaped Eureka graben was the arching or doming, and distention, of the units within the Silverton cauldron. This wedge-shaped graben is well illustrated in sections *A–A′*, *B–B′*, and *E–E′* of plate 3 and section *B–B′* of plate 6. Most of the late structures are closely connected genetically and together indicate that the graben they compose could scarcely have resulted from unrelated structural events of greatly different ages and origins.

FAULT SYSTEMS OF POUGHKEEPSIE GULCH

A strong set of north-trending faults bounding long narrow blocks extends from the Ross Basin fault north along Poughkeepsie Gulch (pl. 2). This set of faults and a northeast-trending set form a system that complexly dislocates the volcanic formations. Many of the faulted blocks have a horst-and-graben relation to each other, although the dominant displacement on most of the north-trending faults is a downthrown east side.

The north-trending set, particularly, of this system of faults seems to be bounded on the south by the west- to northwest-trending Ross Basin fault and on the north by the northeast-trending fault near the mouth of the gulch and on the south flank of the Poughkeepsie Gulch volcano (Burns Formation). This latter fault belongs to the peripheral ring-fracture system of the Silverton cauldron. Very locally, a few faults of the north-trending set tend to be deflected or to turn into the southeast-trending set, particularly in the vicinity of Lake Como.

Generally along the west side of Poughkeepsie Gulch the rocks dip gently to moderately westward. Northeast, in the vicinity of Canadian Lake, the dips are gently to moderately northwestward. East of and near the head of the gulch in the vicinity of Lake Como, the beds are more steeply tilted westward and locally repeated along the north-trending faults (pl. 3, section *B–B′*). The gentle dips within the horst block in the bottom of the gulch north of Lake Como are generally more to the north.

Some late movement of the rocks is evident on the north-trending set but not south of the Ross Basin fault or north of the northeast-trending fault near the mouth of the gulch; this set was thus established almost concurrently with major cauldron depression and associated faulting. Although the relative ages of displacement on the two sets of faults in the gulch are not everywhere consistent, the north-trending set is apparently the older of the two sets; the latest movements on faults and vein fissures are confined dominantly to the northeast-trending set and possibly were in response to widespread effects of adjustments related to the Eureka graben nearer the center of the cauldron.

On the whole, the structural features of Poughkeepsie Gulch are probably more complex than shown on plate 2, but many details are obscured by lack of identifiable horizon markers and at places by strong sheeting and alteration of the rocks.

DOWNFAULTED RED MOUNTAIN BLOCK

The downfaulted Red Mountain block lies just west of the "boot" of the Eureka graben along the west border of the map area (pls. 2, 6). It consists of an irregular somewhat pear-shaped body of Henson flows and rhyolitic tuffs, 2–3 miles across, which has been downfaulted against rocks of the Burns Formation. The body includes a large part of the highly altered rocks that make up the three main Red Mountain peaks and is more completely delineated to the west in the Ironton Park quadrangle (Burbank and Luedke, 1964). Displacements on the faulted borders of this block are not accurately determined at most places, owing in large part to the extreme alteration that has obscurred reliable horizon markers. But along the south rim, just northwest of Gladstone, the Henson flows are downfaulted from 600 feet to possibly more than 1,000 feet against a large domelike body of the Burns Formation. Also, to the north across the head of Gray Copper Gulch, the base of the Henson Formation on Brown Mountain is about 1,000 feet higher than the lowest Henson beds exposed on the north slopes of Red Mountain No. 1. The downthrow on the block may, therefore, be in the neighborhood of 1,000 feet.

The boundary faults of the Red Mountain block are splayed or offset in line with the projected trend of the Ross Basin fault, and beds near the junction are broken into small irregularly tilted blocks and are intruded by bodies of porphyritic quartz latite. Any minor extensions of the Ross Basin fault within the Red Mountain block are generally too obscured by alteration to trace. It would seem, however, that much of the displacement on the Ross Basin fault was taken up by partly concealed or obscure faults at the head of Cement Creek and only to a minor degree by bounding faults of the Red Mountain block.

Most of the rock of the Red Mountain block has been pyritized, silicified, and kaolinized by gases of solfataric origin. The block as a whole probably represents a localized minor subsidence associated with late magmatic and volcanic activity of the Silverton cauldron ring zine.

CONJECTURAL STRUCTURAL FEATURES

Some of the structural features and trends in the map area are believed to be related to extrusive and intrusive activity and associated fracturing. Cone fracturing and cylindrical sheeting in areas of deformed volcanic rocks may be of some importance with regard to possible underlying vents through which the movements of both magma and later mineralizing fluids have tended to converge. Several such channels presumably underlie the Eureka district and, from the few outcropping vents observed, are believed to be mainly of the central type rather than the fissure type (Luedke and Burbank, 1961).

Characteristic structural features of the central-type vents and intrusive centers, such as ring fractures, cone fractures, radial and concentric dikes, and domelike accumulations of lava, are represented at various places throughout the cauldron area in all degrees of development. Many of these structural features, however, are much obscured because younger volcanic formations are superposed or because the features are in an incipient stage of development.

Sections *C–C′* and *F–F′* (pl. 3) across the Mineral Point dome of the Burns Formation illustrate the structural relations exposed at the surface, and it is inferred that this domal extrusion mass had its source under the Mineral Point-Seigal Mountain area. The varying gentle to steep dips in rocks of the underlying Eureka Tuff, and crushed and brecciated rocks in the northeast-striking belt northeast of Denver Lake indicate repeated adjustment and fracturing on the south side of this mass.

On Houghton and Wood Mountains, the quartz latite bodies emplaced as dikes and sills in the Eureka Tuff and Burns Formation suggest concurrent faulting and intrusion related to an underlying lava vent, possibly of a linear rather than a central type. The steeply tilted to vertical rocks of the Burns Formation between Lake Como and upper California Gulch are likewise indicative of a vent underlying this locality.

In the peripheral-fault belt of the Silverton cauldron and within the Red Mountain block, many small intrusive bodies with the form of nearly circular plugs perhaps represent central-type vents. A few plugs of this kind, chiefly porphyritic quartz latite and rhyolite, are found in the map area on Red Mountain No. 1, in Gray Copper Gulch, in Mineral Creek, and on Abrams Mountain. Detailed studies of plugs in the Red Mountains area indicate that they originated as follows. Gases escaped along fissure intersections causing leaching, fluxing, and metasomatic alteration of the rocks followed by brecciation of the vent roof by magmatic pulsations and finally by eruption of molten rock (Burbank, 1941, p. 170–179). Some of these breccia pipes and vents may have contributed to surface volcanic activity, possibly by the formation of local lava domes or explosive fragmental cones. Many of them, however, are choked with breccia and debris from the walls, or they are filled with a kind of lava found only locally at the surface. In the rocks surrounding some of the vents are peripheral structures resembling cone sheets as well as ring and radical fractures.

Ring structures of obscure origin occur north of Lake Como in Poughkeepsie Gulch, in the head of Picayune Gulch, and in the vicinity of Hanson Peak. They are tentatively interpreted as the sites of underlying intrusive plugs or of incipient volcanic vents which failed to extend to the surface.

The ring structure at the head of Poughkeepsie Gulch is about 3,000 feet in diameter, and except for a few small rhyolite and porphyritic quartz latite dikes in discontinuous ring fractures, the structure is devoid of any sign of intrusive activity that might account for its presence. The locally downfaulted beds inside the ring fractures indicate perhaps a final withdrawal of magma in an underlying plug (Luedke and Burbank, 1960).

The ring structure in the head of Picayune Gulch, including parts of Eureka and Treasure Mountains, is about a mile in diameter and is centered in the glacial basin. The bedded volcanic rocks and tuffs here are broken into small blocks by curved faults and are tilted somewhat concentrically both inward and outward with respect to the central part. The local thickening of the rhyolite flows near the base of the Henson Formation and the intrusive rhyolite along many of the fissures, probably feeders of the flows, indicate that this was possibly a minor center of eruption. Possibly complementary to this center are a series of somewhat concentric fractures on the southeast side of the basin (northeast spur of Eureka Mountain) and several curved fractures containing andesitic dikes on the northwest side of the basin (flank of Treasure Mountain).

A conjectural cone structure, centering about Hanson Peak, consists of a series of fissures and sheeted rocks that curve from north of Hanson Peak east to the Silver Queen vein at the head of Placer Gulch and then south to the Clipper vein south of Lake Emma. The diameter of the fracture set is somewhat more than a mile. The fractures, which are locally mineralized, dip 50°–65° beneath Hanson Peak and conceivably represent a cone fracture set. The north contact of the California Peak rhyolite intrusive body about 3,000 feet north of Hanson Peak may belong to the same series of conelike fractures. The attitude of the flow lines within the body suggest that it was formed by rhyolite rising along a southward-dipping cone fracture rather than vertically as a plug.

BASEMENT STRUCTURE

A discussion of the structural features of the map area would be incomplete without at least brief mention of features that may result from reactivation of old structural trends in the basement rocks not exposed in the district. These trend lines in the Precambrian basement rocks are reflected locally in features in the overlying volcanic rocks (pls. 1, 2), a relation which suggests that movement along these old lines of weakness recurred throughout geologic time until the end of volcanic activity in the late Tertiary.

A system of east-southeast-trending faults and faulted folds in the Precambrian rocks extends from Ouray south nearly to Abrams Mountain (pl. 1). The old Precambrian faults were reactivated several times, most recently after the Silverton Volcanic Group eruptions. Patterns of fissuring and faulting in the Tertiary volcanic rocks indicate that these old trend lines may extend 4–5 miles beneath the lavas, especially beneath those to the southeast along Mineral Creek (pl. 2), as denoted by the set of fissures and faults extending northwest from the vicinity of the San Juan Chief mine and mill site.

ALTERED VOLCANIC ROCKS

A variety of hydrothermal agents and volcanic emanations has altered the volcanic rocks of the Eureka district and adjoining areas. By far the most widespread of the altered rocks are the propylites, which extend throughout and in places well beyond the limits of the San Juan volcanic depression. For several miles north of the depression rim and for 8–10 miles northwest, the effects of this alteration are recognizable by changes in color and induration of the breccias and tuffs of the San Juan Formation. Alteration has changed the gray, red, or pinkish-gray colors of fresh rocks to a dull green or greenish gray and has indurated breccias so that they break across most fragments rather than around them. The surface area of propylitized rocks in and around the volcanic basin is 500–600 square miles. Within the Eureka district, virtually all rocks have been altered to some degree. Locally, later and more intense types of alteration have masked or destroyed effects of propylitization, particularly along the west edge of the district.

Less extensive but intense solfataric alteration (Burbank, 1941, p. 194–205) has taken place in local patches and longitudinal belts most commonly along the ring-faulted peripheries of the Silverton cauldron. This alteration is comparable to that at modern fumarolic and hot-spring sites where volcanic emanations containing considerable sulfur have mixed with shallow meteoric waters. These sulfurous agents have attacked the rocks along the west border of the district and more particularly in the Red Mountain area on the west. A few patches of this type of altered rock are found in the walls of some veins and locally in the northern part of the district and beyond to the depression rim. Hot acidified waters containing sulfur in various states of oxidation have leached the rock bases and converted much of the original iron to pyrite. Clay minerals, alunite, diaspore, and quartz are among the dominant products of alteration. The altering gases and solutions bleached the rocks, but more recent oxidation of pyrite has stained the mountain slopes brilliant hues of red, orange, and yellow. Solfataric activity has altered the rocks over an area of about 10 square miles along the west rim of the Silverton cauldron.

Along stretches of the ring-faulted zones, the sheared and broken rocks were more altered especially to micaceous minerals, chlorite, and clays with finely disseminated pyrite. These rocks are found generally near the bottoms of deeply incised valleys that partly encircle the Silverton cauldron. In the Eureka district, a patch of this type of alteration, in part transitional to the solfataric type, is found near the junction of Eureka Gulch with the Animas valley. Similarly altered rocks found locally beneath the solfataric zone probably indicate that rocks so altered generally underlie the solfataric layer.

Several other kinds of altered rock are coextensive with the mineral deposits and generally restricted to within a few feet or tens of feet of veins and ore bodies. Many veins were opened repeatedly during their formation, so that several suites of alteration products have become superimposed. Most vein walls have quartz-sericite-pyrite assemblages typical of many western vein deposits. Some vein walls have also been silicified or carbonatized. Rhodonite and rhodochrosite have replaced vein walls to some degree, especially along veins containing large bodies of mixed manganese silicates. These and other superimposed stages of alteration yielded disequilibrium mineral assemblages that cannot be readily systematized by chemical or mineralogical terminology.

Correlation between various products of rock alteration and the ores and gangues of mineral deposits ranges from obscure to almost obvious. Significant or useful correlations seem to be lacking between the altered walls of veins and sulfide ores in the veins, but some correlation is evident locally between the altered wallrock and dominant gangues of the veins. In general, it would seem that many of the common preore gangues had insulated or sealed the vein walls to such an extent that the effects of ore-bearing solutions were closely confined to their channels. On the other hand, obvious differences are found between the altered walls of vein deposits, mostly in propylitized rocks, and the altered walls of chimney deposits that are for the most part in or adjacent to areas of solfataric alteration. The ores in these two kinds of deposits also differ appreciably, and the possible significance of these features will be discussed in following comparisons of vein and chimney deposits.

PROPYLITIZED VOLCANIC ROCKS

MINERAL AND CHEMICAL NATURE

Virtually all volcanic rocks within the Eureka district and adjoining areas were propylitized prior to ore deposition (Burbank, 1960, p. B12). The mineral changes in the Eureka district range from weaker phases found in shallower formations and characterized by chlorite, calcite, and clays, to stronger phases found mainly in deeper formations and characterized by epidote, albite, and chlorite. Chemical changes for the most part are relatively minor and involve chiefly the addition of carbon dioxide and water (table 4), although some migration of chemical rock bases has taken place in fractured bodies of rock. Recognition of precise chemical changes is hampered by the widespread or regional nature of the alteration, but fortunately the uniformity of many flow rocks of the Burns Formation within and around the Silverton cauldron permits some significant comparisons between fresh and altered rocks.

TABLE 4.—*Estimated volatile contents of volcanic rocks before and after propylitization*

Volatiles	Before propylitization		After propylitization		Volatiles added (million tons per cubic mile)
	Range (percent)	Average (percent)	Range (percent)	Average (percent)	
H_2O[1]	0.36–2.8	1.20	1.5–3.7	2.2	125
CO_2[2]	Trace–0.89	0.08	0.1–3.5	1.6–2.0	230
S[3]	Trace–0.04	0.001–0.004(?)	Trace–0.5	0.1(?)	12(?)

[1] Fresh rocks, 57 analyses, San Juan region; altered rocks, 8 analyses from Silverton area. (Larsen and Cross, 1956.)
[2] Fresh rocks, 25 analyses (CO_2 determined) San Juan region; altered rocks, 20 analyses from Silverton area, including 12 superior analyses. (Larsen and Cross, 1956 and unpub. analyses.)
[3] Fresh rocks, 10 analyses, scattered in San Juan region; altered rocks, 6 analyses from Silverton area, excluding solfataric types with abundant pyrite. (Larsen and Cross, 1956 and unpub. analyses.)

The diagnostic weaker phases of alteration caused first the partial to complete decomposition of the ferromagnesian minerals. Even in the freshest appearing of the dense flow rocks, the pyroxenes have been changed to aggregates of quartz, chlorite, calcite, or an altered serpentine after hypersthene, iron oxides, and rutile. Calcite, clays, and micaceous minerals have replaced the feldspars to a minor degree along cleavages and cracks without changing their original characteristics.

With increased intensity of alteration the phenocrysts lose their luster and the groundmass or any glassy base is changed to fine-textured aggregates of the various secondary minerals. Pyrite does not appear as an essential product of this alteration, but in areas where the veins are closely spaced or the rocks are fractured, scattered pyrite is found locally. Possibly a trace of sulfur was introduced by the propylitizing agents, but evidence for this is generally inconclusive. The weakly altered rocks are represented especially by the dark-colored dense flow rocks of the Henson Formation capping the ridges on either side of Poughkeepsie Gulch and by equivalent flows on high ridges elsewhere.

More intensely altered rocks occur throughout the Eureka district, particularly in flows and breccias of the older and deeper Burns Formation, Eureka Tuff, and Picayune Formation. Epidote is a conspicuous product of alteration, and in large bodies of rock the feldspars were converted to albite and various micaceous minerals. Determination of the separated micaceous products by X-ray analysis shows abundant chlorite, moderate to abundant micas of the illite-muscovite group, and moderately abundant kaolinite. Montmorillonite was not identified in highly altered rocks from widely separated localities and probably is not representative of the typical propylite. The white micas are commonly of fine to medium texture and will be referred to as sericite. Chlorite seems to be represented by two varieties, as indicated by its reaction to heating and by its mineralogical characteristics. In more strongly fractured rocks, quartz and chlorite or quartz and epidote fill open fractures. In general, calcite is less prominent as an alteration product in the more highly altered rocks, but commonly, it is irregularly distributed.

The more intensely altered rocks are characteristic of thick domelike bodies of the Burns Formation and of the breccias and flows of the Picayune Formation exposed along the lower parts of Picayune Gulch and the Animas River canyon. In parts of the Picayune and Burns Formations, the rocks are converted to quartz-albite-epidote-chlorite aggregates analogous to a product of low-grade regional metamorphism.

The chemical analyses of table 5 are representative of some flow and vent rocks of the Burns Formation from the central and northern parts of the map area. The analyses of columns 1 through 4 are typical of fine-textured porphyritic rocks that have been weakly propylitized, but have not been appreciably albitized or epidotized. Analyses in columns 5 and 6 represent epidotized, albitized, and chloritized samples of flows from

TABLE 5.—*Chemical analyses of propylitized and pyritized volcanic rocks of the Burns Formation*

	1	2	3	4		5		6		7		8	
Laboratory No.	157571	157576	157672	157574		162207		162208					
Field No.	I-58-26	HP-59-54	HP-60-57	HP-59-34		61HP31		61HP32		61HP31		61HP32	
	Weight percent	Weight percent	Weight percent	Weight percent	Grams per cubic centimeter	Weight percent	Grams per cubic centimeter	Weight percent	Grams per cubic centimeter	Gains	Losses	Gains	Losses
SiO_2	59.1	57.4	56.1	57.0	1.548	59.4	1.640	57.1	1.613	0.092		0.065	
Al_2O_3	16.8	16.0	17.6	15.9	.432	16.2	.447	15.1	.427	.015			0.005
Fe_2O_3	2.4	2.5	3.4	3.2	.087	4.5	.124	5.8	.164	.037		.077	
FeO	3.2	3.9	3.3	3.6	.097	2.6	.072	.60	.017		0.025		.080
MgO	2.2	2.6	2.4	3.1	.084	1.9	.052	2.6	.073		.032		.011
CaO	3.8	4.5	6.3	5.6	.152	4.2	.115	3.9	.110		.037		.042
Na_2O	4.1	3.4	3.2	2.7	.074	3.0	.082	3.1	.088	.008		.014	
K_2O	4.0	3.5	3.2	3.4	.092	3.6	.099	3.2	.090	.007			.002
H_2O^+	1.2	2.3	2.0	1.9	.052	2.1	.058	1.2	.034	.019			.008
H_2O^-						.47	.013	.37	.010				
TiO_2	.81	.92	.84	.88	.024	.80	.022	.61	.017		.002		.007
P_2O_5	.37	.36	.40	.34	.009	.39	.011	.29	.008	.002			.001
MnO	.10	.10	.16	.13	.003	.45	.012	.16	.005	.009		.002	
CO_2	.90	1.9	1.3	1.3	.035	.12	.003	<.05			.032		.035
S								5.7	.161			.161	
Total	99	99	99	99	2.689	99.73	2.750	99.78	2.817	.189	.128	.319	.191
Net gain (g per cc)										0.061		0.128	
Specific gravity (bulk)				2.69		2.75		2.82+					
Specific gravity (powder)	2.70	2.72	2.74	2.72		2.78		2.86					

1. Rapid rock analysis. Analysts: P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe, U.S. Geol. Survey. Volcanic neck on west side and near mouth of Poughkeepsie Gulch at altitude of 11,000 ft, San Juan County.
2. Rapid rock analysis. Analysts: Same as sample 1. Probable vent of flows on ridge between California and Poughkeepsie Gulches at altitude of 12,850 ft, San Juan County.
3. Rapid rock analysis. Analysts: Same as sample 1. Dacite of the Mineral Point domal mass at junction of Henson Creek valley and Schafer Gulch, Hinsdale County.
4. Rapid rock analysis. Analysts: Same as sample 1. Specific gravity (bulk): W. S. Burbank. Propylitized flow on south side of Hurricane Peak, west of and near Sunnyside Saddle at altitude of 12,500 ft, San Juan County.
5. Rapid rock analysis. Analysts: P. L. D. Elmore, S. D. Botts, Gillison Chloe, L. Artis, and H. Smith, U.S. Geol. Survey. Specific gravity (bulk) of similar but not identical specimen at this locality: W. S. Burbank. Altered flow rock from American tunnel, approximately 9,935 ft from portal.
6. Rapid rock analysis. Analysts: Same as sample 5. Specific gravity (bulk) of similar but not identical specimen at this locality: W. S. Burbank. Altered flow rock from American tunnel, approximately 1 mile from portal.
7. Gains and losses in grams per cubic centimeter of column 5 as compared with column 4.
8. Gains and losses in grams per cubic centimeter of column 6 as compared with column 4.

the American tunnel that came from the downfaulted wedge between the Ross Basin, Bonita, and Toltec fault systems. This fractured block contains numerous small and locally mineralized fissures, accounting for the addition of sulfur to rock of column 6. Despite the considerable variations in CO_2, S, and water content, variations of the chemical rock bases and silica are relatively small. The two highly altered rocks from the tunnel (columns 5 and 6) are considered to be in roughly the same position of the Burns section as the flow represented in column 4; gains and losses of constituents in grams per cubic centimeter are given in column 7. Both rocks show a gain in silica and a loss in carbon dioxide compared with the standard, but most other gains and losses are not significant. The iron oxides computed as metallic iron indicate a slight gain in one rock and a slight loss in the other. The addition of Mn in column 5 is no doubt real, as this figure is appreciably above the average in all analyzed rocks of the area. Table 6 compares the minor elements of the rock specimens shown in table 5 and seems to indicate, as might be expected from their environment, gains in copper and lead.

TABLE 6.—*Minor elements of propylitized and pyritized volcanic rocks of the Burns Formation*

[Analyses by P. R. Barnett, U.S. Geol. Survey]

	1	2	3
Ag	0	0.0001	0.0003
Ba	.10	.1	.1
Be	0	.0002	.0002
Co	.0025	.003	.002
Cr	.0043	.003	.0015
Cu	.0057	.015	.05
Ga	.0007	.002	.002
La	.0047	0	0
Ni	.0038	.005	.003
Pb	.0015	.003	.005
Sc	.0012	.003	.001
Sr	.15	.15	.1
V	.02	.02	.01
Y	.0025	.003	.002
Yb	.00025	.0003	.0003
Zn	0	0	0
Zr	.015	.03	.03

1. Average of four semiquantitative spectrographic analyses of the rocks in columns 1–4, table 5.
2. Semiquantitative spectrographic analysis of rock in column 5, table 5.
3. Semiquantitative spectrographic analysis of rock in column 6, table 5.

A considerable increase in bulk and powder densities in the strongly epidotized rocks (2.75–2.86, table 5) and in other unanalyzed samples (bulk densities 2.75–2.8) is noted over nonepidotized or weakly epidotized propylites (2.69–2.74). The increases in density and in duration of tuffs and breccias may be attributable mainly to compaction during recrystallization, but changes in the densely textured flows must be due mainly to mineralogical factors. In epidote particularly, the resulting mineral density is appreciably greater than that of its constituents in original silicate minerals. Also, some oxides, chlorites, and micas possibly contribute to these increases. Changes in porosity could not be checked definitely because of uncertainties in correlation of individual flows, but original porosities were probably very small and near 1 percent. Nevertheless, pore spaces are undetectable microscopically in either flows or fragmental beds that have been propylitized. Cavities in breccias or amygdaloidal flows are commonly filled with the alteration products. Thus, the typical propylitic alteration increased density rather than decreased it, a result commonly considered more typical of wallrock alteration in the vicinity of veins.

The comparisons of the analyses and the computations made in table 5 are subject to many uncertainties because of the dubious correlation of beds as well as obvious variations in degree of alteration from place to place in the same rock. The computations were made for better comparison because of the marked increases in density in more highly altered rocks and not with the intention of showing precise changes in chemical constituents. To check possible additions and subtractions of substances, some propylitized rocks of the Burns Formation from different parts of the Silverton cauldron are shown in figure 4, in which some major constituents are plotted against the carbon dioxide content. Only rocks classified as dacites were used. Most variations, except silica and alumina, are very erratic. The number of samples available is obviously inadequate for definite conclusions, but MgO and total iron (as Fe) show increases with increased CO_2 content that appear significant. For comparison, the limits of variation of four samples that had little or no CO_2 are also indicated at the left of the diagram. If meaningful, the increases in total iron and MgO are indicative of migration of these constitutents in carbonatic and siliceous solutions that traversed rock pores and minute fractures, but such migration need not have been far or indicative of vertical zoning in the rock column. Rather, it is suspected that additions may have taken place along paths of migration locally favored by carbon dioxide and other fugitive emanations. Both magnesia and iron in solutions should be promptly precipitated by silica released from carbonate formation.

There is also a slight indication of silica loss with increase in fixed carbonate. This excess silica may be represented by the quartz-chlorite or quartz-epidote seams along joints in many places. Many of these seams are paperthin and noticeable only along broken joint surfaces. A very extensive sampling of the rock column would be necessary to confirm the extent of migration and its pattern. The possibility that carbonate fixation at considerable depth may have been the cause of much vein quartz will be discussed in a later section (p. 49).

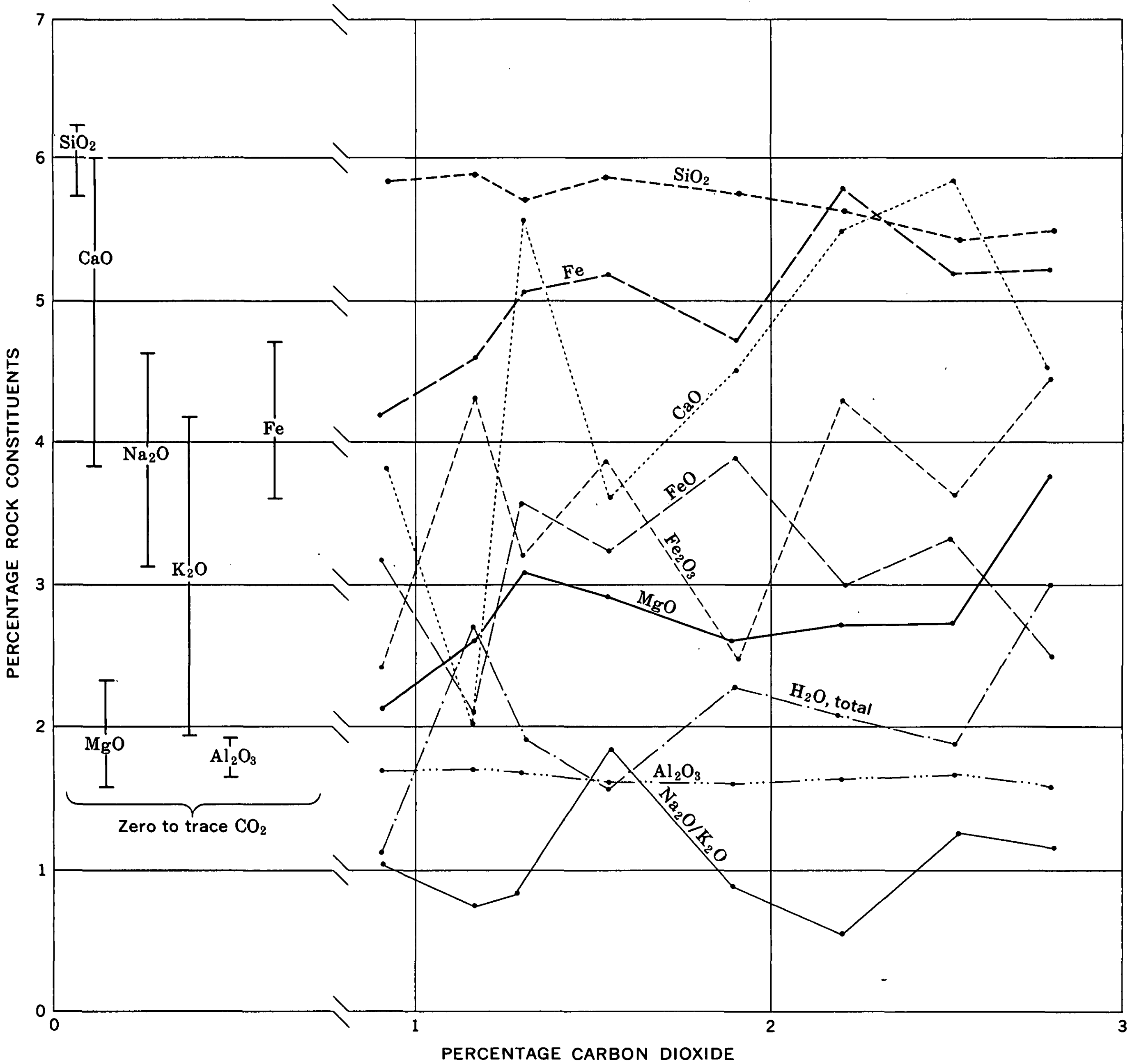

FIGURE 4.—Percentage of some major rock constituents plotted against percentage of carbon dioxide in propylitized dacites of Burns Formation. Na_2O and K_2O plotted as a ratio. At left of diagram, the range of some major constituents, silica and alumina expressed as one-tenth of contained value, in dacites with no or only traces of CO_2.

ORIGIN AND TIMING OF PROPYLITIZATION

Propylitically altered rocks have been explained in a number of ways for different mineralized districts. Most of these explanations can be categorized as (1) those related to residual gases and solutions of igneous crystallization that were active immediately following eruption of the volcanic rocks and that involved processes generally considered deuteric in nature, (2) those related to solutions that were directly associated with vein formation and ore deposition, and (3) those related to postvolcanic and preore episodes in which altering agents were connected with some deep volcanic origin.

The generally low grade of alteration in some propylites is such that rocks so classified may very well have been formed under a variety of conditions wherever hot waters and associated gases permeated the rocks. But in the Eureka district the increase in intensity of alteration with depth and the distribution of altered rocks over hundreds of square miles in and around the San Juan volcanic depression favor a postvolcanic and preore incidence of alteration and its relation to some widespread and deep source of the agents. Carbon dioxide, which could have had its source in some deep igneous bodies at an early stage was also a common constituent of later vein-forming solutions. Narrow altered selvages of some veins resemble weaker kinds of the more general propylitic effects, but the scale of alteration is insignificant in comparison.

Ransome (1901, p. 118) considered that the propylite of the Silverton quadrangle had an origin probably coincident with ore deposition. But he may have thought of this only as a broad relationship, as he qualified his statement by noting that "the metamorphism is so generally prevalent that it cannot in any case be recognized as being connected with desposition of ore in any given fissure." He also wrote,

> Close to the veins, usually within a few inches, and in small horses within the veins, metamorphism of an entirely different kind frequently occurs. Here the calcite and chlorite have diminished in amount or are wholly absent and quartz and sericite constitute the bulk of the rock. This alteration which plainly emanates from the individual fissure differs from the more general metamorphism less in kind than in the relative proportions of calcite and chlorite on the one side and of quartz and sericite on the other.

To suppose that the altering agents emanated directly from the numerous fissures exposed in some localities requires a very selective penetration of carbon dioxide, at least as compared with other constituents of the mineralizing solutions, and such pervasive action could apply equally well to agents from other and deeper sources. The regional alteration does not appear to have any detectable relation to frequency and nearness of veins or to exposed igneous bodies. These conditions are similar to those noted by Takeo Kato (1928) who described propylitization near Japanese epithermal deposits. He considered that alteration so widespread must have been of deep origin and that it must represent, therefore, the first stage of postvolcanic hydrothermal processes. Coats and Calkins (Coats, 1940, p. 6–7), who had a similar opinion about the origin of propylite in the Comstock district, considered that the deeper parts of a dioritic stock were the probable source of the altering agents.

Some reasons are suggested as to why so much carbon dioxide was released in a postvolcanic and preore interval with respect to the evolution of the Silverton cauldron. (1) The latest volcanic eruptions were violently explosive ash flows of dacitic to rhyolitic composition that may have drained much of the upper more siliceous parts of the magmatic reservoirs charged with gases. (2) Carbon dioxide tends to become more highly concentrated in intermediate or mafic silicate solutions than in siliceous differentiates. (3) The gradual cooling and differentiation of rising or static parent magmas might tend to release carbon dioxide into overlying fractured rock covers during decadent stages of volcanism. This action would apply especially if conditions around the magmatic reservoirs had been osmotic so that pressures on the magma would have been greater than pressures on its gaseous constituents. Thus carbon dioxide, water, and other fugitive constituents may have been squeezed out from partly crystallized magmas prior to the latest stages of crystallization.

Magmatic activity after the latest ash-flow eruptions was manifested by doming, fracturing, and intrusion of parts of the cauldron floor and some surrounding areas. Some plutons intruded in outlying areas at this time are rather mafic and approach diorite and gabbro in composition. With decreasing pressures and some sinking or readjustment of local crustal blocks, further injections took place in the form of clastic dikes, either alongside igneous dikes or in new fissures. Various clays, sericite, and calcite in these dikes and narrow green selvages along the dikes where they cut red beds probably indicate that gases analogous to those causing propylitic alteration were propelling agents. Hence, the incidence of propylitic alteration just following dike intrusion seems indicated. As many dikes contain fragments of Precambrian basement rocks, they must have originated by explosive disintegration of rocks at depths locally exceeding a mile. These clastic injections tended to seal or choke fissures; thus high pressures were retained at depth and perhaps promoted the penetration of the gases throughout the volcanic rocks.

As represented by table 7, the better sources of carbon dioxide are likely to have magmas of intermediate to mafic composition, rather than more siliceous differentiates such as the dacitic domes of Japan. The experimental work of Morey and Fleischer (1940) on the system CO_2–H_2O–K_2O–SiO_2 shows that solubility of CO_2 in alkali silicate solutions decreases much more rapidly than that of HO_2 as the silica content of the solutions increases. They concluded (p. 1056) that this relation would also apply to more complex silicate mixtures.

Had the ratio of CO_2 to H_2O been relatively low, about 1 : 30 or 1 : 100 as in dacitic fumaroles, presumably all CO_2 would have been contained in more or less saturated solutions of various bases. Such solutions seem incompatible with the pervasive nature of alteration in compact rocks of low porosity. With high ratios of CO_2 to H_2O, however, greater penetrating action might have

TABLE 7.—*Composition, in weight percent, of gases from volcanic fumaroles, igneous rocks, steam wells, and geysers*

[Data from Rubey (1951, p. 1137) and White and Waring (1961, p. C311). Data in parentheses added for comparative purposes. Small quantities of CH_4 and CO ignored in figures for total C as CO_2. n.d., not determined]

	Kilauea and Mauna Loa	Basalt and diabase	Obsidian, andesite, and granite	Fumaroles, steam wells, and geysers	Fumaroles of dacitic lava domes, Usu volcano, Showa Shinzan, Japan		
					760°C	525°C	200°C
H_2O	57.8	69.1	85.6	99.4	96.7	97.1	98.4
Total C as CO_2	23.5	16.8	5.7	.33	2.92	2.58	1.30
Total S as S_2	12.6	3.3	.7	.03	(.078)	(.040)	(.138)
H_2S					.0008	.0042	.1080
S					.0004	.0002	
SO_2					.1490	.0716	.0716
SO_3					.0021	.0011	.0003
N_2	5.7	2.6	1.7	.05	.0567	.0676	.1250
A	.3	Trace	Trace	Trace			
Cl	.1	1.5	1.9	.12	.0728	.0420	.0433
F	n.d.	6.6	4.4	.03	.0238	.0169	.0035
H_2	.04	.1	.04	.05	.0685	.0381	.0020
SiO_2	n.d.	n.d.	n.d.	n.d.	.0253	.0289	.0048
Metals	n.d.	n.d.	n.d.	n.d.	.00014	.00007	.000004

prevailed because of the low mutual solubilities of these substances. Garrels and Richter (1955, p. 449) have shown that under lithostatic loads to depths of more than 10,000 feet and near 150°C, only 3–4 mol percent CO_2 is soluble in H_2O. Although the density of gaseous CO_2 at such depths is near that of water, it seems likely that water would condense first in minute pores and cracks of the rocks and thus promote conditions favorable for reaction between CO_2 and rock minerals. At shallow depths, CO_2 would expand very rapidly and tend to saturate rock pores. That pressure gradients may have been maintained in a pervasive gas phase relatively rich in CO_2 may account for the very great differences in penetrating actions of propylitic agents and solutions of the vein systems.

Temperatures involved in propylitic alteration may be gauged roughly by experimental work on hydrolysis of feldspars (Hemley, 1959; Hemley and others, 1961), but the systems studied are much less complex than actual rock environments. The effects of magnesia, iron, and lime and the coexistence of chloritic products in the system are yet to be evaluated. White and Sigvaldeson (1962) noted that the chlorite-epidote-albite suite of metamorphic minerals was generally considered to form at depths of 25,000–30,000 feet at temperatures near 250°C. Recent core drilling in the Salton Sea region, however, has disclosed a similar suite of minerals in young sedimentary rocks at a mile depth and at temperatures believed between 270° and 370°C (White and others, 1963). The occurrence of kaolinite rather than montmorillonite in alteration of plagioclase in the Eureka district agrees with the conclusion of Hemley, Meyer, and Richter (1961, p. D340) that at low Na^+ to H^+ ratios, representing moderate acidity, kaolinite is the stable product. As most of the reactions are exothermic and because the local environment is volcanic, the lower ranges in temperature previously noted do not appear excessive for depths of about 1 mile. The effects of possible osmotic conditions and the presence of considerable CO_2 on the partial pressure of H_2O cannot be evaluated at present.

ALTERED ROCKS OF THE SOLFATARIC ENVIRONMENT

The solfataric environment as recognized locally (Burbank, 1941, p. 194–205; 1950, p. 291) is characterized by a variety of altered rocks, most of which have been attacked by gases and solutions containing sulfur in states of oxidation ranging from native sulfur to sulfuric acid. This chemical environment is estimated to have extended several thousand feet beneath the original volcanic surface, a distance which is much greater than that known in modern environments designated as solfataras. All the volcanic and late intrusive rocks have been leached and altered to some degree so that conditions clearly represented those of decadent stages of the volcanism. The large quantity of sulfur in various mineral combinations introduced into altered rocks sharply distinguishes the alteration from that of the propylitic type.

The main parts of the Eureka district, as properly restricted to the central and southern parts of the map area, do not contain appreciable bodies of rock altered by solfataric processes. The Red Mountain ridges along the west border of the map area, extending from Gray Copper Gulch south to the head of Dry Gulch, form the east edge of a large area of extensively altered rocks that includes the Red Mountain district to the west. The east limit of the most strongly altered rocks is defined roughly by a series of curved faults outlining a large block of the Henson Formation called the Red Moun-

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tain block that is downfaulted against rocks of the Burns Formation. The downfaulted block, several miles in diameter, includes all the highly altered Red Mountain peaks and ridges (pl. 1) and is intruded by numerous plugs of rhyolite and quartz latite. The block subsided after propylitic alteration was well advanced and before solfataric alteration began, as indicated by the strongly epidotized Burns rocks along the fault line in contrast to the weakly chloritized Henson rocks within the sunken block.

There are local patches of rocks altered by solfataric emanations in the extreme northern part of the map area on the higher slopes of Engineer Mountain and on the ridges extending from it. These patches are generally centered about intrusive or breccia pipes, but selvages of this type of altered rock border some veins.

The restriction of solfataric alteration to the peripheries of the cauldrons and to local faulted blocks and pipelike bodies of breccia and intrusive rocks is indicative of the control by late ring intrusions and dislocations caused by them. In general, the most strongly altered rocks are the interbedded breccias, flows, and tuffs of the Henson Formation, as shown in the rocks of the Red Mountain ridges. Nevertheless, near channels of the altering solutions, even the most compact flows and intrusive rocks have been strongly leached or silicified and kaolinized with introduction of sulfur to form sulfides and sulfates. Bleaching of the rocks and their subsequent staining by surficial oxidation of pyrite is generally an indication of solfataric emanations.

MINERAL AND CHEMICAL EFFECTS OF SOLFATARIC ACTIVITY

The strongest effects of solfataric activity, especially in porous ground or at centers of pipelike bodies, is a complete leaching of the rock substance, leaving only irregular open channels or cavernous and porous ground. Some of these leached openings remain barren, but others are partly lined or filled with products of rock decomposition and sulfide ores. Some bodies of sulfides that filled cavities and replaced their walls formed exceedingly rich but small ore bodies in the Red Mountain district. In some bodies of rock, the sulfides are widely disseminated in porous leached ground but in insufficient concentration to form ore.

In some channels, especially vertical pipelike forms, there is a definite zoning of alteration products from silicified casings around the channels, to argillized walls, and locally to surrounding bodies of propylitized rock. The immediate walls were converted to fine-textured and dense aggregates of quartz, or quartz and clays and minor accessory minerals. The outer walls were altered to quartz and various clay minerals, such as dickite, pyrophyllite, montmorillonite, and kaolinite. Locally, the minerals alunite, zunyite, and diaspore are mixed with clays in pockets or are disseminated in strongly altered rocks. Near sulfides, micaceous minerals allied to sericite or illite are generally intergrown with or replace clays and quartz. Any remaining iron in the leached and altered rocks has been converted to pyrite. Oxidation of pyrite disseminated in altered rock in the Red Mountain area results in surficial staining of the bleached rocks.

The chemical results of solfataric alteration are well illustrated by the walls of the Polar Star vein on the higher slopes of Engineer Mountain. Analyses of the altered wallrock and of the equivalent nearby propylitized country rock (flow in the Henson Formation), as given by Ransome (1901, p. 122), have been recalculated to changes in grams per cubic centimeter in table 8. This example is especially significant in showing changes brought about by the alteration in rock previously propylitized, and it also avoids the widely variant results obtained in anlyzing strongly leached and porous bodies of altered rock. The chemical changes show a typical gain in silica and loss in carbon dioxide, alumina, and chemical rock bases. Most, but not all, of the iron is converted to pyrite. The recalculated mineral compositions of the propylite and its altered products are also shown in table 8. A moderate increase in porosity of the rock is probably the result of unfilled spaces that were leached in early stages of alteration.

The sequence of alteration processes and their changes in depth are perhaps best shown in the mineralized chimney deposits. In upper parts of the chimneys, large cavernlike spaces or irregular tubes were leached in the rocks, and these spaces were later partly or completely filled with products of rock decomposition or with ore minerals and gangues. The margins of some of these chimney deposits have many small or even large unfilled spaces, illustrating that in some places leaching considerably exceeded filling except along certain preferred channels of continued solution migration. In deeper parts of channels, the excess leaching tends to diminish both in relative volumes left unfilled and in size of the spaces leached. The leaching and filling effects gradually become indistinguishable from conditions generally considered indicative of metasomatic replacement. The processes thus represented from the top to the deeper parts of the chimneys are considered to represent coupled processes, which merely become more closely balanced at depth. Replacement by many of the secondary minerals and sulfides does not constitute lattice substitution of one molecule for another, but rather

TABLE 8.—*Chemical analyses of altered wallrocks at the Polar Star mine, Engineer Mountain*

[Source: Ransome (1901, p. 122–123)]

	Propylitized wallrock		Solfatarically altered wallrock		Gains	Losses
	Weight percent	Grams per cubic centimeter	Weight percent	Grams per cubic centimeter	Grams per cubic centimeter	
SiO_2	55.61	1.533	64.79	1.773	0.240	
Al_2O_3	16.40	.455	18.93	.518	.063	
Fe_2O_3	5.44	.150	None			0.150
FeO	2.37	.066	None			.066
MgO	3.25	.090	None			.090
CaO	5.85	.162	.43	.012		.150
Na_2O	2.61	.072	.15	.004		.068
K_2O	3.77	.104	.24	.007		.097
H_2O+	1.51	.042	5.39	.147	.105	
H_2O-	.46	.013	.50	.014	.001	
TiO_2	1.10	.030	1.21	.033	.003	
CO_2	1.33	.037	None			.037
P_2O_5	.45	.012	.51	.014	.002	
MnO	.09	.003	None			.003
BaO	.03	.001	.06	.002	.001	
SrO	.05	.001	Trace			.001
FeS_2	0		7.19	.197	.197	
Total	100.32		99.40		0.612	0.662
Specific gravity (bulk)	2.764		2.734			
Specific gravity (powder) (calculated)	2.8±		2.86±			
Porosity (percent)	1.3±		4–5			
Net loss (g per cc)						0.050

Calculated approximate compositions			
Propylitized rock		Solfatarically altered rock	
Mineral	Weight percent	Mineral	Weight percent
Labradorite (Ab, An)	33.9	Quartz	48.8
Orthoclase [1]	22.4	Kaolinite	30.3
Quartz	14.0	Diaspore	6.6
Diopside [$CaMg(SiO_3)_2$]	4.7	Pyrite	7.2
Chlorite [$H_{40}(FeMg)_{23}Al_{14}Si_{13}O_{90}$]	7.0	Sericite	3.9
Calcite	3.0	Rutile	1.2
Serpentine	2.8	Apatite	.7
Kaolinite	2.6		
Magnetite	2.3		
Hematite	3.8		
Apatite	1.0		
Rutile, etc	1.4		
Total	98.9	Total	98.7

[1] Includes some micaceous minerals (sericite and similar minerals) normally found in propylites of area.

the complete destruction of one mineral lattice and substitution of another. Probably both forms of substitution take place where leaching and filling are closely balanced and where ionic diffusion is more important.

CHEMICAL AND PHYSICAL PROBLEMS OF SOLFATARIC ALTERATION

The chemical problems of a solfataric environment appear to be more complex than the physical problems. As yet, there does not seem to be any unique answer to the origin of sulfates in shallow volcanic environments, and very likely the sulfates originate in more ways than one. Ransome (1909, p. 193–197), in reference to occurrences of alunite at Goldfield, proposed that hypogene sulfide solutions had become oxidized by atmospheric oxygen in the surface waters and that these acidified solutions upon descending in the fissures by convection reacted with the rocks to form alunite. This mode of origin of sulfates cannot be dismissed altogether, as some modern cold waters of the Red Mountains area contain free sulfuric acid generated by shallow oxidation of pyrite. These acidified waters circulate to depths of a few hundred to perhaps 1,000 feet in open fissures and mine workings, but such conditions are hardly applicable to deep hydrothermal environments where temperatures and pressures of emanations would tend to limit downward circulation of surface waters. On the other hand, convection to moderate depths under fumarolic and hot-spring conditions cannot be eliminated as a factor of solfataric alteration.

A number of oxidation reactions have been suggested (White, 1957, p. 1648–1651; Graton and Bowditch, 1936, p. 687–691) as applying to waters that may in part be magmatic. Aside from surface oxidation, suggested origins include direct emission of oxidized sulfur gases from magmas, decomposition of polybisulfides to form sulfide and sulfate plus free acid, and cataytlic effects of halogen acids in oxidizing sulfur in acidified solutions (Burbank, 1932, p. 84). That the gases and water contained both chlorine and fluorine is indicated in Red Mountains area by minerals such as zunyite and fluorite. None of the suggested reactions has been definitely established to the exclusion of possible surficial reactions. The fact that sulfates do form under hydrothermal conditions at depths generally considered below the limits of surface reactions seems well established however. Even in some modern hot-spring areas, such as at Frying Pan Lake in New Zealand (White, 1957, p. 1648), the discharge of free sulfuric acid at the surface appears much beyond the quantitative capacity of oxidation by surficial agents.

The reconstructed physical conditions that seem to have prevailed in solfataric ground at Red Mountains (Burbank, 1941, p. 194–199; 1950, p. 288–300) have some bearing on the relations between rock alteration and the occurrence of associated ore deposits. The rocks now exposed by deep erosion in the western part of the Eureka district and the adjoining Red Mountains area probably ranged from nearly 1,000 feet to more than 3,000 feet beneath the reconstructed surface at the time of solfataric alteration. The base of solfatarically altered rocks is not exposed everywhere, but the walls of some deeper explored ore deposits consist of propylitized rocks that have been only partially decomposed by the acidic emanations. The positions of these partially decomposed rocks are considered to be near the base of an irregular zone from which hypogene solutions or gases passed from narrow constricted channels to more open breccias and fractured shallow rocks that form the bulk of highly altered ground. These observed conditions appear compatible with a near-surface environment and with the strong telescoping of alteration and ore deposition brought about by abrupt release of pressure on various emanations. The numerous intrusive plugs in this ground indicate also that temperatures were probably fairly high during initial stages of alteration.

Parts of altered ground and the tops of some ore chimneys have been converted to fine-grained semipervious siliceous rocks. Those parts associated with ore chimneys tend to have the form of inverted cuplike bodies that encase or overlie the main ore zones. Commonly these caps or envelopes diminish in size and prominence with depth (fig. 5). These siliceous bodies, consisting in places of 85 percent or more silica with minor clays and accessory minerals, are considered to represent the redeposition of silica that has been leached from underlying channelways by the acidified emanations. The silica and clays have filled cracks, fissures, and pores of the altered rocks to form envelopes that must have resisted the passage of condensed solutions but very likely were more or less pervious to gaseous emanations. Wherever appreciable ore bodies are present beneath such caps, the siliceous caps and the altered ground above contain only minor seams or disseminations of ore minerals.

These various conditions seem related to two kinds of physical effects (Burbank, 1950, p. 289, 309): (1) a throttling action as emanations from depth at relatively high temperature and pressure passed through constricted openings to lower pressures and (2) a sealing or plugging effect in higher ground where expanding gases and solutions redeposited the least soluble substances in spaces already leached or in any fractures that had formed. These two effects in conjunction would exert a certain control on pressures prevailing in any body of ground. As sealing became more effective, the pressures in leached ground and channels beneath would tend to rise and thus permit the entrance of solutions from below at pressures sufficiently high that vaporization and explosive expansion of gases would be greatly restrained. A continued passage of gases through the capping envelopes or walls might then result in cooling

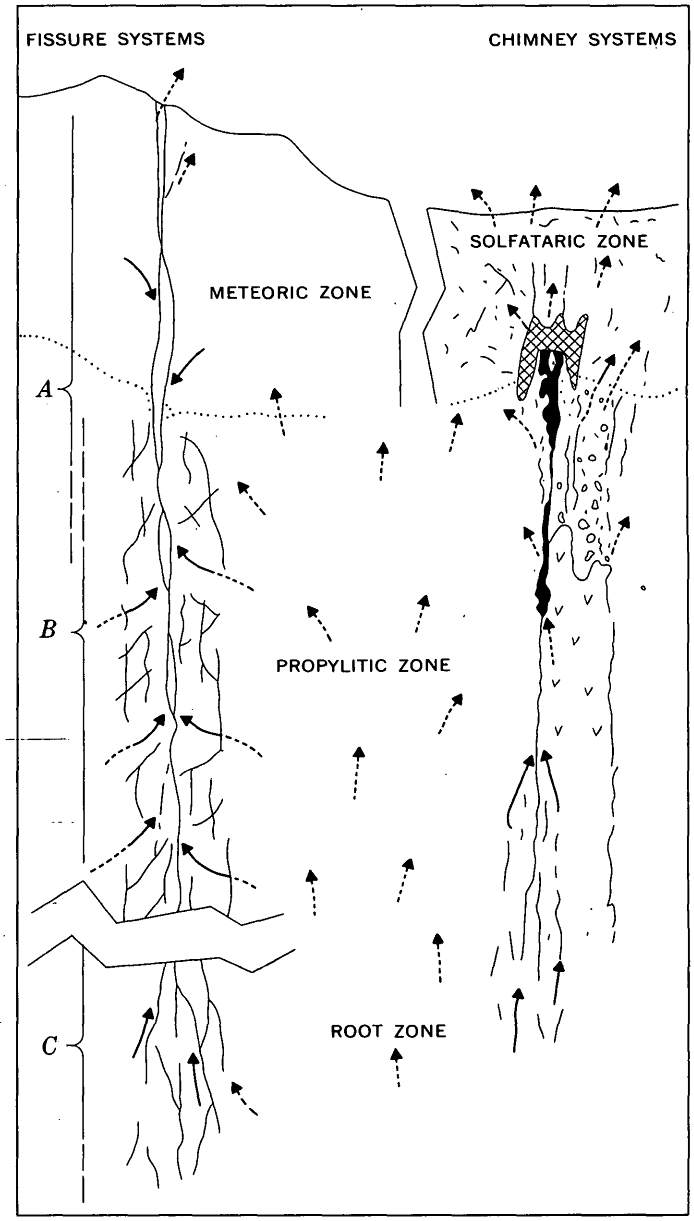


FIGURE 5.—Environment and depth zones in fissure and chimney systems of the Silverton cauldron mineralized belts. *A*. Zone of mixing of mineralizing solutions with partly oxygenated meteoric waters (locally 3,000–4,000 ft deep). *B*. Zone of influx of fractionated end-products of rock alteration that mix with meteoric waters from above and sulfide solutions from below. *C*. Zone of influx of primitive ore solutions and products of deep rock alteration. Chimney deposits are in rocks locally preheated by volcanic pipes and have only minor influx of solutions from zone *B*. Chimney feeders are not reopened as frequently as feeders of fissure systems. Crosshatching indicates siliceous envelope of altered and mineralized ground; black areas indicate sulfide deposits. Propylitic zone represents rocks charged with carbon dioxide and other gases, coming from deep-seated sources of cauldron core. Dashed arrows indicate general movements of gases, solid arrows movement of solutions.

of solutions and in more gradual precipitation of entrained substances, whether those substances were ore minerals or products of rock decomposition.

The overall results of alteration in solfataric ground thus represent a coupling of physical and chemical actions that permitted the local passage of solutions from depth into relatively shallow positions to form ore bodies. For the most part, the ores deposited in open spaces contain very little intergrown quartz gangue, although some ore has been deposited in and around quartz crystals and porous siliceous aggregates formed by rock decomposition. In general, the conditions of rock alteration and ore deposition are believed to differ markedly from those in the extensive open fissures characteristic of the greater part of the Eureka district. In the open fissures it is thought that the ore solutions from below mixed with meteoric waters, and became greatly diluted, and then passed to the surface under pressures more nearly approaching hydrostatic gradients than did solutions in the chimney environment. In general, the steeper gradients prevalent in chimney ground resulted in telescoping of the ore bodies.

The thermodynamics of throttling processes has been discussed at some length in various texts and recently in connection with deposition of ores (Keenan, 1941; Barton and Toulmin, 1961). Irreversible throttling processes are those thought most likely to prevail in an environment such as that under consideration. In general, irreversible throttling (Keenan, 1941, p. 138, 314–336) results in the cooling of the throttled fluids. If pressures fall sufficiently below the throttling point, an original dense gaseous fluid may change from a single-phase condition to a two-phase condition where both condensed fluid and gas coexist. Accordingly, both gases and solutions could have coexisted in some leached spaces in solfataric ground. An exception to the cooling of fluids may take place when the velocity of gases escaping through a throttling position exceeds the velocity of sound in the fluid. In such a case, shock waves form and the heat content and the pressure of the fluid increase, but this condition would be likely to prevail only, if at all, in the throats of exceptionally violent fumaroles. Whatever other conditions prevail, the entropy of irreversibly throttled fluids always increases. These various changes in the thermodynamic properties of throttled fluids may have important bearing on the chemistry of precipitation and on the formation of mineral substances. Barton and Toulmin (1961), in applying throttling processes to precipitation of ores and vein material, considered the processes as ideally taking place at constant heat content (isenthalpic). It may be argued that work must generally be performed by the expanding fluids in displacing substances in the path of the fluids, such as pockets of condensed solutions or ground waters that may have seeped into openings, and in raising substances in a gravitational field. As such work is performed, the heat content will decrease rather than remain constant. However, owing to various chemical reactions that may be induced in complex chemical solutions, such as oxidation of sulfur compounds, the net changes in heat content of throttled fluids cannot be estimated with any degree of assurance. Speculations on the thermodynamic properties of pure substances, such as water, acocrdingly seem of minor value in solving the chemical problems of solfataric alteration. However, it may be concluded that throttling probably had an important effect on the processes involved in solfataric alteration.

The formation of new mineral substances in the altered rocks and ores and the modes of their precipitation probably included, in part, some of the following processes: (1) abrupt cooling as a result of throttling, resulting in telescoped deposition, (2) loss of some vapors by osmosis through sealing envelopes and rock walls or by simple boiling, (3) mixing reactions in solutions of diverse origin, (4) decomposition of various solution complexes of the mineral anions, such as sulfide complexes to yield sulfides and sulfates, and (5) dilution and mixing of rising solutions or gases with ground waters, probably including shallow oxidation. Most of these processes need no explanation and have been commonly recognized, but some comment regarding mixing reactions may be necessary.

Wherever acidic gases escape from hypogene fluids, by either osmosis or vaporization, they will tend to recondense in cracks and pores of colder rocks or in any dilute or connate waters in porous rocks. The secondary acidified solutions, then being unsaturated with rock substances, will tend to attack and partly dissolve minerals. Part of the solutions containing dissolved minerals will be forced away by pressure of expanding gases, but some will remain in pores and cracks. If sealing causes pressures to build up again in this partly leached body of rock, primary or modified solutions from below, under higher pressures, may advance into the spaces, mix with remnants of the secondary solutions, and react with them to form new mineral substances. Loss of pressure and heat are not of course the sole causes of precipitation of these new substances, since the mixing may take place with rising temperature and pressure. If reactions are exothermic, they may even cause a further rise of temperature.

ALTERED WALLROCKS OF VEIN DEPOSITS

The wallrocks of the common types of veins in the Eureka district have been subjected generally to several periods of alteration and to successive changes in chemical and mineral composition. Many veins are compound and indicative of repeated openings, along which solutions of obviously different composition circulated. Quartz, sericite, and pyrite are common products of alteration in many of the siliceous sulfide veins. Chlorite and calcite in weakly altered walls may represent at places an intensification of processes allied to propylitization. The introduction of sulfur and traces of metals into altered walls is illustrated in analyses of rocks from the American tunnel under the discussion of propylites (p. 26). Locally, a particular stage of rock alteration is characterized by some unique mineral assemblage or compositional change, such as the high content of manganese in rocks adjacent to veins of manganese silicate and carbonate. Manganese minerals are common constituents in veins of the central part of the Eureka district, and enrichment of vein walls in manganese gives an indication of the degree to which vein solutions have penetrated their walls. This penetration may be estimated at places on the surface by characteristic stains from oxidation of manganiferous carbonates in the rock.

Table 9 illustrates gross changes in the composition of propylitized dacite of the Burns Formation as a result of mineralizing solutions that penetrated the footwall of the mineralized Ross Basin fault. Two samples were selected about 20–25 feet within the slightly shattered footwall of the vein zone, one showing obvious stains of manganese oxides and the other showing none. Fractures in the analyzed rocks were noticeable only on a microscopic scale, and no veinlets were visible to the naked eye. The two altered and mineralized rocks (columns 2, 3) are compared with rock (column 1) from a nearby ledge of propylite of similar texture though not certainly from the identical horizon. All rocks show the common products of propylitic alteration with only minor epidote. The two mineralized rocks show an obvious introduction of quartz and pyrite with intensification of sericitic alteration in plagioclase and groundmass. The gains in S and SiO_2 and losses in Al_2O_3 probably took place when solutions of the early quartz-pyrite stage of mineralization were introduced into the fractured walls.

Semiquantitative spectrographic analyses (table 10) suggest that there is a slight gain in Pb and possibly a loss of Ba and Sr. The gain in Pb doubtlessly took place during the main sulfide stage of vein genesis, but the losses in total iron as Fe, in Na_2O and K_2O, and in Ba and Sr cannot be as definitely correlated with vein stages. The changes in CO_2 and MnO are more defi-

TABLE 9.—*Chemical analyses of altered rocks near Sunnyside Saddle*

	1		2		3		4		5	
	Weight percent	Grams per cubic centimeter	Weight percent	Grams per cubic centimeter	Weight percent	Grams per cubic centimeter	Gains	Losses	Gains	Losses
SiO_2	57.0	1.548	63.68	1.714	65.61	1.758	0.166		0.210	
Al_2O_3	15.9	.432	11.74	.316	13.16	.353		0.126		0.079
Fe_2O_3	3.2	.087	.70	.019	.41	.011		.068		.076
FeO	3.6	.097	3.78	.101	4.44	.119	.004		.022	
MgO	3.1	.084	2.39	.064	1.89	.051		.020		.033
CaO	5.6	.152	4.96	.134	2.19	.059		.018		.093
Na_2O	2.7	.074	1.47	.038	3.13	.084		.036	.010	
K_2O	3.4	.092	2.32	.062	2.61	.070		.030		.022
H_2O	1.9	.052	2.24	.060	2.00	.054	.008		.002	
TiO_2	.88	.024	.58	.016	.68	.018		.008		.006
P_2O_5	.34	.009	.23	.006	.28	.008		.003		.001
MnO	.13	.003	1.09	.029	.19	.005	.026		.002	
CO_2	1.3	.035	2.89	.075	1.07	.029	.040			.006
SO_3			.02	.001	.06	.002	.001		.002	
S			1.63	.044	2.52	.068	.044		.068	
Total	99	2.689	99.72	2.679	100.24	2.689	.289	.309	.316	.316
Less O			.41		.63					
			99.31		99.61					
Specific gravity (bulk)	2.69		2.68		2.68					
Specific gravity (powder)	2.72		2.75		2.73					
Porosity (percent)	1.1		2.4		1.8					

1. Field No. HP-59-34; lab. No. 157574. Rapid rock analysis. Analysts: P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe, U.S. Geol. Survey. Specific gravity (bulk): W. S. Burbank. Propylitized flow of Burns Formation from south side of Hurricane Peak, west of and near Sunnyside Saddle.
2. Field No. 59-B-10; lab. No. G3152. Standard rock analysis. Analyst: Paula M. Buschman. Specific gravity (powder): V. C. Smith, U.S. Geol. Survey. Specific gravity (bulk): W. S. Burbank. Altered flow of Burns Formation in footwall of Ross Basin mineralized fault, west of and near Sunnyside Saddle.
3. Field No. 59-B-12; lab. No. G3153. Standard rock analysis. Analyst: Paula M. Buschman. Specific gravity (powder): V. C. Smith, U.S. Geol. Survey. Specific gravity (bulk): W. S. Burbank. Specimen from same location as specimen in column 2.
4. Gains and losses in grams per cubic centimeter of specimen in column 2 as compared with specimen in column 1.
5. Gains and losses in grams per cubic centimeter of specimen in column 3 as compared with specimen in column 1.

TABLE 10.—*Minor elements of altered rocks near Sunnyside Saddle*

	Propylitized	Mineralized	
	1	2	3
Ag	0	0	Trace
Ba	.10	.03	0.03
Be	0	.00015	.00015
Co	.0025	.0015	.0007
Cr	.0043	.0015	.0015
Cu	.0057	.003	.003
Ga	.0007	.0007	.0007
La	.0047	.003	.003
Ni	.0038	.0007	.0015
Pb	.0015	.0007	.03
Sc	.0012	.0015	.0015
Sr	.15	.03	.03
V	.02	.015	.015
Y	.0025	.0015	.0015
Yb	.00025	.00015	.00015
Zn	0	0	0
Zr	.015	.015	.007

1. Semiquantitative spectrographic analyses of average propylite. From column 1 of table 6.
2. Semiquantitative spectrographic analysis of rock in column 2 of table 9. Analyst: P. R. Barnett, U.S. Geol. Survey.
3. Semiquantitative spectrographic analysis of rock in column 3 of table 9. Analyst: P. R. Barnett, U.S. Geol. Survey.

nitely correlated with the manganese silicate and carbonate stage of vein formation that followed the main sulfide introduction. Microscopic examination of the altered rocks shows that some rhodonite was first formed by reaction of the manganese-bearing solutions with rock silicates and that the rhodonite later became converted in part to manganiferous carbonate by continued or later introduction of carbon dioxide. Possibly some of the losses in chemical rock bases took place during the later carbonate stage of alteration. There are slight gains in powder density and porosity as compared with the propylite used as a standard. It is likely that leached rock constituents were carried outward into fractures of the wall rather than diffused back into the vein, both because of the distances to which alteration extends from vein walls and probable negative gradients of carbon dioxide pressures outward from the wall.

These samples confirm other evidence that carbonatic alteration in walls adjacent to carbonate stages of vein formation took place subsequent to propylitization. As the Ross Basin fault zone has considerable displacement and has fractured the rocks over widths measurable in tens of feet, the penetration of altering solutions into walls here was probably near its maximum. The significance of this alteration will be considered further in discussion of vein formation.

MINERAL DEPOSITS

The mineral deposits centered about the Silverton cauldron have been described in a number of geologic and engineering articles, but Ransome's (1901) bulletin on the economic geology of the Silverton quadrangle is the only comprehensive review of the Silverton area as a whole. Some aspects of the geology and general mining development to the mid-1940's were published by the Mineral Resources Board of Colorado (Vanderwilt and others, 1947). Local details of the geology, mines, and veins in various parts of the area have been described by Varnes (1948; 1963), Kelley (1946), Burbank (1933a, b; 1935; 1951), Burbank, Eckel, and Varnes (1947), Collins (1931), Hulin (1929), Bastin (1923), Prosser (1910), Purington (1898, 1905, 1908), Hazen (1949), and King and Allsman (1950). The several papers published since 1933 on the geology and ore deposits of the area have dealt mainly with structural aspects of the volcanism and ore deposits.

The ore deposits centering about the Lake City cauldron have much in common with those of the Silverton area, and mineralized country rock is virtually continuous between the two areas. Selected articles on the geology and ores of the Lake City area include those of Irving and Bancroft (1911), Brown (1926), Woolsey (1907), and Cross and Larsen (1935).

There have been some important mining developments in the Eureka district since Ransome's work, but except for brief local or general articles, much of the history and many of the underground geologic details of larger mining enterprises have never been published. A general historical summary to 1926 was made by Henderson (1926). It is not, however, the purpose of this paper to detail the gap in this record, much of which is not readily available, nor is it the purpose to discuss in detail the individual mines, most of which were not fully accessible to examination during the course of this investigation. The purpose of this paper is to discuss more the theoretical aspects of ore deposition based on available information. Vein structures discussed are based upon study of shallow and deep levels of a few larger mines and numerous small mine openings. Lack of full access to the older very extensive mine workings is partly compensated for by the vertical and lateral extent of surface exposures.

The two principal types of mineral deposits represented in the map area are vein systems and chimney deposits. Vein systems are by far the more important type. A few chimney deposits and some disseminations of ore minerals are found along the west margin of the map area, but for the most part these deposits are confined to the solfataric zones of the cauldron margins.

Veins of the Eureka district formed in extensive systems of open fissures of small displacement or along major faults and their subsidiary fissures. The shoots of ore are commonly tabular, although of limited lateral extent compared with the more productive veins of the northwest sector of the Silverton cauldron in the Telluride and Sneffels districts.

The vein systems are described first, followed by a brief resumé of the main characteristics of chimney deposits. The two types are contrasted with emphasis on the origin and nature of the mineralizing solutions in the different environments. The principal contrasts, aside from form of the ore bodies, lie in the extent to which ore-forming solutions mixed with shallow meteoric waters. Extensive mixing is believed to have taken place in open fissures of the vein systems under conditions approaching hydrostatic pressures, whereas mixing in chimneylike channels was greatly restricted except in shallowest ground, which was for the most part above the ore bodies, where prevailing pressures were probably much above those of hydrostatic levels.

VEIN SYSTEMS

The major radial and concentric fault and fissure systems of the Silverton cauldron are not evenly distributed about the cauldron margins but tend to be clustered into several dominant groups (pl. 1). Plate 1 does not give a complete picture, as some areas have not been mapped in equivalent detail, but the north margin from the northeastern to western sectors has been mapped in sufficient detail to be adequately represented. Sectors with strong radial systems alternate with those having relatively weak radial systems. The central Eureka district spans the area covered by a strong northeasterly system and parts of a weaker north-south system in Poughkeepsie Gulch. A curved set of northeasterly to easterly trend belonging to a concentric ring-fault system is prominent in the northwestern part of the Eureka map area and forms some of the principal veins of the Poughkeepsie Gulch area, where the north-trending radial fissures were but weakly opened and contain few veins. Moderate subsidence toward the central part of the cauldron sympathetic to the Ross Basin fault is believed responsible for opening of the northeasterly and easterly sets of Poughkeepsie Gulch. The central and northeastern parts of the Eureka area are dominated by the strong northeasterly radial system. Here the concentric fissures are but weakly opened and mineralized, whereas the northeasterly system contains the more persistent veins. Opening of the northeasterly system of fractures is believed to have resulted from subsidence related to the northeast-trending graben defined by the Sunnyside and Toltec fault systems (pl. 6).

Some individual veins and dikes show changes in direction as they pass from the northeastern sector into the area between the head of Poughkeepsie Gulch and the Ross Basin fault. Thus, some veins along the north slope of California Gulch swing from a northeasterly to an easterly trend near the head of Poughkeepsie Gulch. A dike of porphyritic quartz latite along California Gulch also changes from a northeasterly to an easterly trend where it crosses Poughkeepsie Gulch.

Faults and fissures commonly curve and splay at intersections of major trends (fig. 6). This type of intersection is illustrated where the Ross Basin and Sunnyside fault systems join just north of Lake Emma (pl. 6; fig. 6*A*). Both represent major faults of the cauldron that have undergone displacements of 800–1,000 feet. Numerous sets of curved fissures lie across the interior angle of the fault junctions, and near the main junction where the curved fissures are closely spaced, the rocks forming the common footwall are strongly sheeted and brecciated.

Some major faults and fissures are deflected in their trends where they cross intersecting fissure and sheeting systems, as illustrated by stretches of the main Toltec fault. This fault swings westward in a series of deflections on the south slope of Eureka Mountain, where it is deflected by east-west to N. 80° W. fissure systems. It continues across this belt and again swings back to its more normal approximately N. 50° E. trend in McCarty Basin south of Eureka Gulch. This deflecting belt of east-west sheeting and fissuring seems to represent the extension of the Ross Basin fault zone, which widens into a broad band of sheeted rock step-faulted and tilted down to the south.

CONTROLS OF ORE SHOOTS

Many mineralized faults and fissures can be traced for distances ranging from hundreds of feet to several miles, but ore shoots are much more restricted in their lateral extent. Intersections, deflections in direction, and variations in dips, as well as more obscure factors, have influenced the location of ore shoots. Some major faults and fissures have nearly continuous fillings of vein matter which vary in width and in proportion of barren gangues and ores. In part, this distribution is the result of numerous reopenings of the fissured ground and of variations in the mineral content of solutions at different stages of vein formation. Conditions either favorable or unfavorable to precipitation of ore minerals from solutions may have been a factor in some places, but such factors are of a chemical or thermodynamic nature and will be considered in connection with the nature and origin of the vein-forming solutions. Some controls of ore shoots are obviously structural, however, and the influence of structural patterns on distribution of ore and vein widths is summarized in this section.

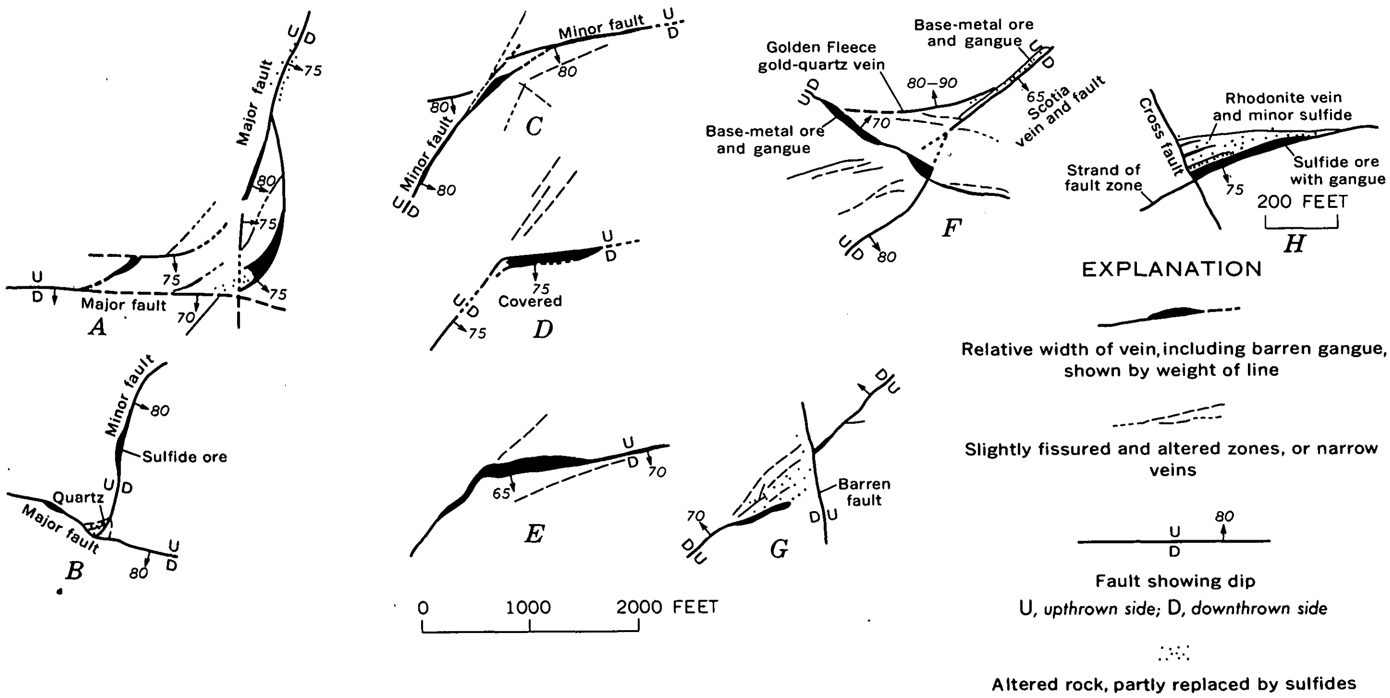


FIGURE 6.—Types of fault intersections in plan view; ore shoots and deflections in fault trend related to fault intersections. *A*. Junction of two major faults with weak extensions beyond junction. The faults appear to horsetail into each other, forming faulted and fractured ground chiefly in footwall at junction. Detail of ore shoot in this ground shown in *H*. *B*. Minor fault ending at intersection with major fault. Wedge of rock near junction is fractured, altered, and replaced by quartz. *C*, *D*, and *E*. Minor faults intersecting to form acute angle. Fracturing and veining chiefly in common hanging wall of obtuse angle. *F*. The fault intersections are somewhat like *B*, but the faults continue through each other. Later fracturing between the hanging wall of one fault and the footwall of the other has produced steep fissures that are filled with narrow veins of a late stage of gold-bearing quartz. The main intersections have a steep pitch, and the narrow veins probably are continuous individually in depth; others may occur at similar positions in depth. *G*. Major mineralized fault intersects a barren fault of the cauldron peripheral belt. Indications are that fractures were deflected into the hanging wall of the mineralized fault on one side of the barren fault. *H*. Detail of ore shoot in ground of *A*, showing wedgelike growth of fissured and mineralized ground into footwall of mineralized fissure. The rhodonite is later than base-metal ore. Modified from Hulin (1929).

Several of the major ore shoots of the district are either in major fault systems or in subsidiary fissures related to the faults. Shoots of intermediate to minor productivity are widely scattered in veins of the northeasterly system where fault displacements are relatively minor. These are represented by the veins of Mineral Point and Poughkeepsie Gulch.

The major ore shoots of the district are clustered near the intersection of the Sunnyside and Ross Basin faults (pl. 6) and account for the greater part of the district production. Shoots of the Sunnyside vein systems have been mined to depths of about 2,500 feet beneath the outcrop, and some are known to extend 500 feet deeper. Near the surface, the lateral extent of the known productive shoots is about 1,000–1,500 feet on the Sunnyside fault system and less on the Ross Basin fault. The wider veins and bodies of veined and altered rock span as much as 100 feet, and stopes on ore in the Sunnyside mine are reported to have been 50 feet wide in places. Hulin has figured (1929, p. 42, fig. 12) a large wedge-shaped shoot in plan and argued from the distribution of different stages of vein matter that the widening took place by successive reopening and growth of the vein by accretion. (See fig. 6*H*.) He also noted that shoot widths are greater along stretches of steeper dips, as illustrated by the Washington vein. Some roughly parallel and curving branches of the Sunnyside vein system were formed in the footwalls of the Sunnyside and Ross Basin faults; these branches are illustrated by the No Name vein and the hanging wall and footwall branches of the eastward-trending veins related to the Ross Basin fault (fig. 6*A*). Inasmuch as there is considerable vertical displacement on some of the branch veins and fissures, the widths of openings may have been controlled to some degree by juxtaposition of irregular walls and by the tilting of some segmented blocks in the common footwall. Under such conditions the localization of wide openings might be erratic and thus difficult to predict from local strikes and dips.

Shoots of ore were formed locally along intersections of the northeast-trending fissures and east-west fissures in the Ross Basin area and adjoining parts of Poughkeepsie and California Gulches. These ore bodies form dogleg shoots where the veins switch locally from a northerly or northeasterly trend to an easterly trend (figs. 6*C*, *D*, *E*). Shoots of this type are at the Mountain Queen at the head of California Gulch, at an undeveloped body about 1,500 feet to the southwest, and in several veins about 1,500–2,000 feet southwest of Lake Como in the high north branch of Ross Basin. Few shoots of this kind are longer than about 1,000 feet along the outcrop, but small patches of ore or quartz appear elsewhere along straight stretches of the veins.

Deflections in trend of numerous faults and fissures control the location of some wider shoots of vein matter, whether they are of barren gangues or of ore. This control is evident from many surface outcrops, for example, the mineralized Toltec fault where it crosses the south slope of Eureka Mountain. The several wider mineralized stretches of the fault system were formed near deflections in its trend, such as near the crossing of Eureka Gulch, near the crossing of Parson Gulch, and just east and west of the crest of Eureka Mountain. A branching and deflection of the Sunnyside fault resulted in a wide band of quartz veins where the fault crosses the north end of Treasure Mountain (pls. 2, 6) and passes through the Lost Treasury vein to join the Cinnamon fault east of the Animas River. Not all these widenings were favorable to shoots of sulfide ore, however; some consist mainly of barren gangues, and others are part gangue and part ore. A wide band of relatively barren quartz was formed where the Bonanza vein crosses Lake Como near the head of Poughkeepsie Gulch. A number of major and minor features of this type are illustrated in figure 6.

The structural control of shoots that yielded 15–20 percent of production from the central part of the district is represented by veins, of which two of the most productive were the Gold King and the Lead Carbonate (pl. 6, Nos. 2, 3) near the footwall of the Bonita fault (Burbank, 1951, p. 296). As shown on plate 3 (sections *A–A′*, *B–B′*) and plate 6 (section *B–B′*), the volcanic formations are tilted away from the downfaulted graben block. Opening of the faults during distension of the crust permitted the block between the Toltec and Sunnyside faults and the Bonita Peak block east of the Bonita fault to subside. The downward wedging of these blocks, perhaps during alternating tensional and compressional stresses resulting in part from resurgent doming caused by magma pressure tended to accentuate outward tilting of the bounding volcanic beds. The sinking of the keystone blocks would produce some wedging action on surrounding bodies of fissured rock, and this action would tend to dilate fissures trending at high angles to the fault faces. This kind of action seems most pronounced in the footwall of the Bonita fault where a few fissures of northeastward trend, as represented by the Gold King and Lead Carbonate, intersect the northwestward-trending fault. Similar action on a minor scale is noticeable on northeasterly fissures in the footwall of the Ross Basin fault (fig. 6*B*).

Antithetic fissures in the hanging walls of some major faults are fairly common loci of ore deposition. Several of the more prominent examples are the Hidden Treasure, Sound Democrat, and Silver Queen veins in the hanging wall of the Sunnyside fault near the head of Placer Gulch east of Hanson Peak (pls. 2, 6). These are shown somewhat diagrammatically in sections *A–A′* and *B–B′* of plate 3. They diverge in strike from the main fault zone and apparently converge with the fault somewhere beneath the alluvium at the bottom of the Gulch. Possibly some mineralized fissures in the hanging wall of the Ross Basin fault near the head of Cement Creek are of similar origin. These dip in reverse direction and diverge westward from the main fault zone (pl. 2).

More complex fissuring in hanging walls and footwalls of minor faults is illustrated by the Golden Fleece and other veins near the junction of the Scotia and Great Eastern mineralized faults (pl. 2; fig. 6 *F*). The Golden Fleece is a narrow, steep vein composed largely of quartz and free gold, occurring in the angle between the two mineralized faults. Possibly late tension fracturing in the block between the two faults permitted access of late-stage gold-bearing solutions to the Golden Fleece vein. From the known stopes, it would appear to have been fed from the footwall of the Scotia. Several other small veins in the footwall of the Scotia just to the north have also been mineralized. Veins such as the Golden Fleece probably do not have much vertical continuity.

Examples of relatively minor vein patterns and their control of small ore shoots are illustrated in figure 7. The rather common angular forms of vein structure reflect control by preexisting joint and fissure systems. Probably at moderate depths many of these minor and more complex patterns change shape or assume simpler forms.

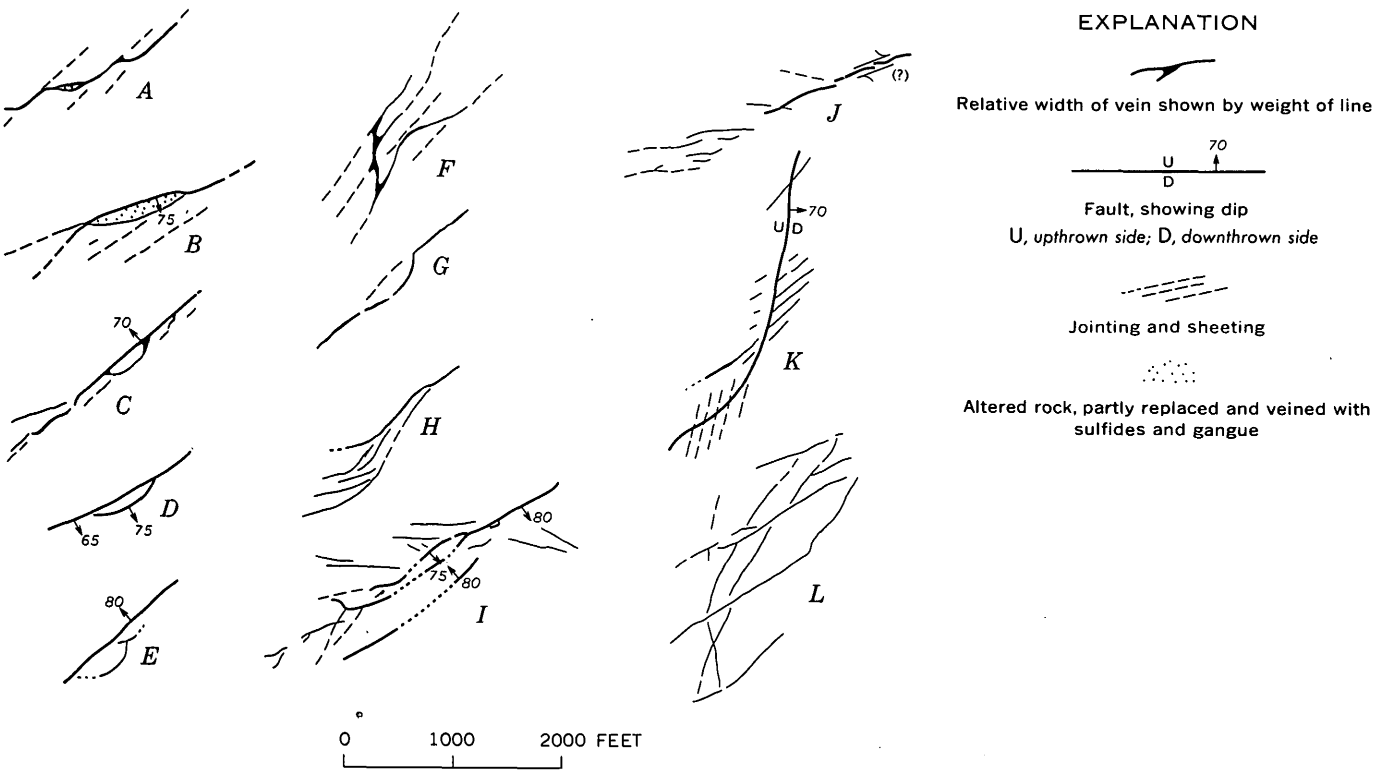


FIGURE 7.—Plan view of types of vein patterns as illustrated on plate 2. *A*. Main vein deflected from one major joint to another by diagonal links. *B–G*. Loop structures along veins formed in part by double linking structure and possibly in part by saucerlike fractures produced by percussion in one of the walls. Many of the fractures rejoin the main break both vertically and horizontally and thus enclose a horse of altered or partly replaced rock as in *B*. In structures like *C* and *F*, which are comparable in origin to *A*, the junctions may have moderate vertical continuity; small thickened Y-shaped shoots of ore form at the forks. In *F* the double curvature of the linking structures has produced a series of small steep shoots (somewhat enlarged in true proportion so as to show their shape in plan). *H*, *I*. Horsetail structures where movements on faults and fissures are dispersed along numerous smaller fissures. *J*. En echelon and shingle fissures that have the general pattern of horsetail structure. *K*, *L*. Vein systems produced by primary acute angular patterns of fracturing. The fault in *K* is the main feeding channel for small veins and sets of altered and weakly mineralized joint fissures (herringbone pattern).

VEIN STRUCTURE

Ideas concerning the origin of veins in the Eureka district and adjoining areas of the Silverton cauldron evolved from the work of Purington (1898) on mines in the Telluride area. He postulated that vein material in the outer mineralized zones 8–10 miles northwest of the Eureka district filled open fissures and that the included rock fragments and vein walls were little corroded or replaced in the process. Moreover, he noted that individual vein zones commonly show alternating ore and country rock, as illustrated in figure 8A, and that the succession of minerals deposited in the different layers of vein matter may be repeated several times across the full face of the vein. He (1898, p. 799) also recognized that in addition to a repetition in kind of filling, the succession of bands differed in composition and in proportion of ore minerals and gangue. Thus Purington recognized early that veins of the region were compound and were formed by successive depositions of ore and gangue minerals. Purington also favored in some degree the ideas that fillings of some gangues might have been in part derived by dissolution and redeposition of materials already present in deeper parts of the fissures or in part derived from interaction with the wallrock.

Hulin (1929), with reference to the Eureka district and in particular to the Sunnyside veins, expressed views generally in accord with those of Purington. He stressed repeated opening of fissures as a cause of accretional growth of veins and the importance of these factors in the localization of ore shoots. Also, he (p. 32) recognized three successive major periods of vein formation: barren pyrite-quartz veins, base-metal veins, and barren rhodonite veins and ribs. Examinations that we were able to make both in the upper near-surface positions and near the deeper levels off the American

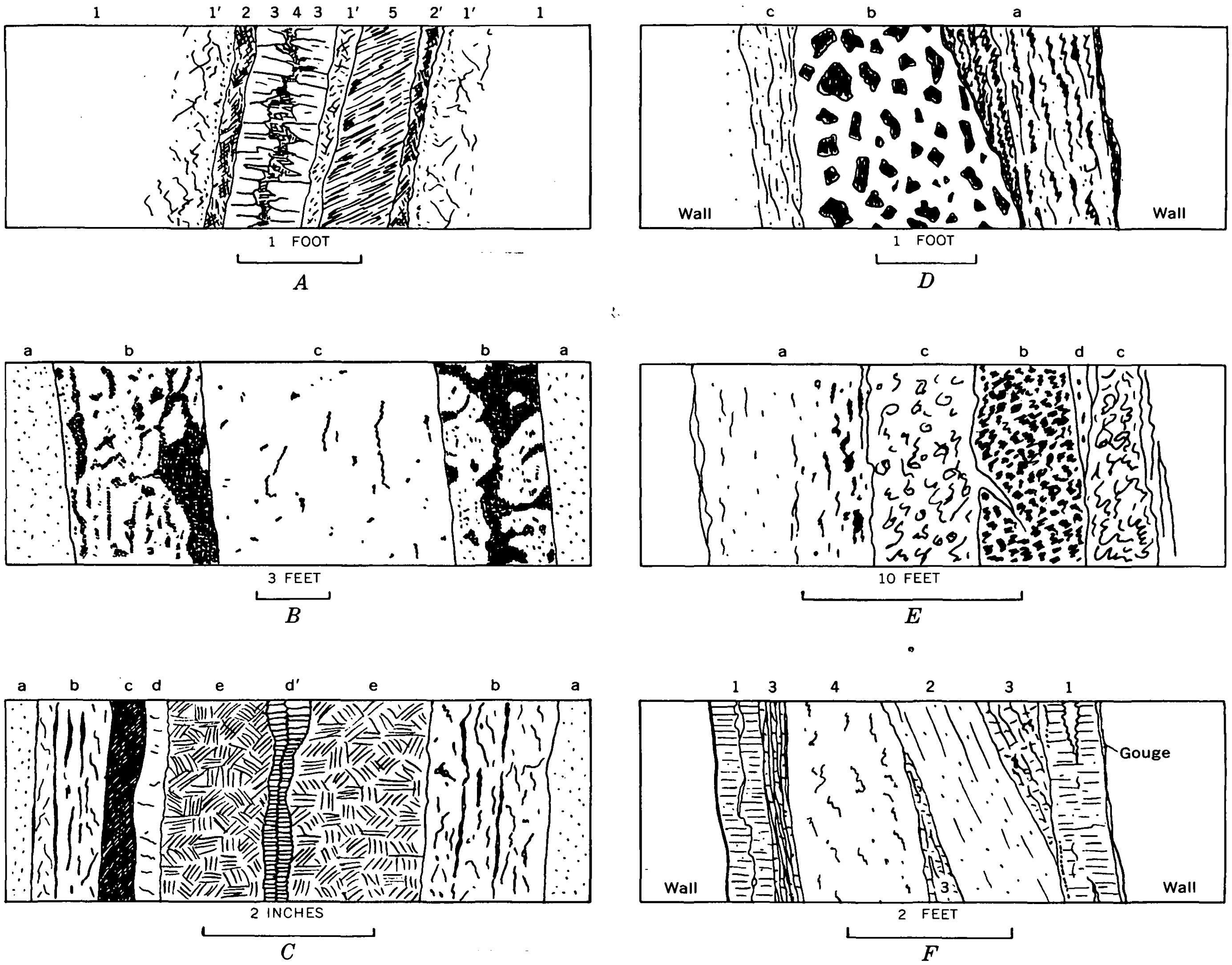


FIGURE 8.—Structural features of compound veins within and northwest of the Eureka district. *A*. Vein in Mendota workings, Smuggler vein, Telluride district (modified from Purington, 1898). 1, country rock; 1′, sericitized and impregnated country rock; 2, sphalerite with calcite; 2′, sphalerite and galena; 3, white quartz; 4, rhodochrosite; 5, blue quartz with finely disseminated sulfides and sulfosalts. *B*. No Name vein, Eureka Gulch (modified from Ransome, 1901). a, country rock; b, ore, chiefly galena with quartz gangue; c, rhodonite. *C*. Banded vein near the London shaft, Mineral Point (modified from Ransome, 1901). a, country rock; b, quartz and chalcopyrite; c, tetrahedrite; d, d′, quartz; e, galena. *D*. Washington vein, raise from American tunnel, Sunnyside mine. a, quartz-pyrite and sheared base-metal sulfide vein replaced locally by rhodonite and rhodochrosite; b, rhodonite vein with angular inclusions of base-metal ore; c, altered wall. *E*. No Name vein, Sunnyside vein system, Eureka Gulch (from Burbank and Luedke, 1961). a, quartz with pyrite and minor sphalerite and galena; b, mainly sphalerite, galena, and chalcopyrite, intergrown with quartz and some pyrite; c, rhodonite ribs with patches of tephroite, friedelite, carbonates, and quartz; d, quartz. *F*. Vein in Placer Gulch, Eureka district. 1, quartz, barren or with minor sulfides; 2, silicified and sheared country rock; 3, altered and sheared country rock; 4, quartz, rhodonite, galena, chalcopyrite, sphalerite, and pyrite. The barren quartz veins represent a late stage of filling.

tunnel confirm Hulin's generalized sequence for the Sunnyside veins, but in addition, we find that the late rhodonite stage is complex and possibly divisible into a number of prerhodonite and postrhodonite stages of evolution.

Ransome (1901, p. 87–92) classified the vein structures as massive, banded by deposition (figs. 8*B*, *C*), brecciated, cellular, and spherulitic. He did not subscribe to the view that successive deposition could account for all the vein structures. He stated (p. 136):

> The fissures are filled by coarsely crystalline allotriomorphic aggregates of ore and gangue (massive structure) and there is no evidence to show that such a structure could result from successive deposition upon the walls of the fissure until the

whole was finally filled. On the contrary, crystallization has proceeded simultaneously from many points within the solution. Quartz, galena, pyrite, sphalerite, chalcopyrite, and other minerals have formed practically contemporaneously about local centers of crystallization scattered irregularly through the solidifying mass.

In this statement he presumably refers to ore such as represented in bands marked "b" in figure 8*B*.

Figures 8*D*, *E*, and *F* illustrate structural variations in veins of the Sunnyside system and of a siliceous vein in the footwall of the Sunnyside fault on the northeast slope of Hanson Peak. All show the same general sequence of early quartz-pyrite, quartz and base-metal sulfides, rhodonite-rhodochrosite veins, and late comb quartz. The breccia and sheared quartz-sulfide ore of sketch *D* are described and figured later in connection with microscopic features of the ores. In parts of the Sunnyside workings and in other mines of the district, these clearly defined sequences are much obscured by repeated crushing and veining and by replacement of one gangue by another.

Moehlman (1936) stated that the role of metasomatic replacement in vein-forming processes had been greatly underestimated, especially with reference to veins of the northwestern sector of the Mount Sneffels area (pl. 3). For example, he found that barite in some veins had been more or less replaced by quartz. This sort of replacement of one gangue by another is not uncommon, but it affords no clue to the space originally available for deposition of the barite. On the whole, evidence favors a considerable amount of open space available for filling during the different stages of vein formation even though leaching and redeposition or replacement took place in all stages.

The proportion of space provided by openings as compared with that provided by chemical leaching or by replacement of preexisting material is very difficult to estimate in the more complex veins of a compound origin. Successive depositions and resolution or replacement of vein matter seem typical of most veins, whether massive, banded, brecciated, or compounded of these various structures. The compound banded veins permit in many instances the unraveling of complex relationships that are otherwise obscure. Studies of the minutia of ore and gangue aggregates in randomly collected samples of vein matter may lead to contradictory and confusing mineral succession unless these samples are correlated with the grosser features of vein structure. Some of the common sulfides may be found in most or all of the major stages of vein formation.

STRUCTURAL CONTROL OF CHIMNEYS AND BRECCIA BODIES

Certain physical and chemical factors controlling deposition of alteration products and ores in solfataric ground have been reviewed (p. 31). These factors are, however, mainly secondary effects of the altering agents and are not related to any structural controls that may have influenced the position and form of chimneylike ore bodies. Detailed description of the many complex forms of ore bodies in chimneys, breccia bodies, and disseminations in solfatarically altered rocks is beyond the scope of this report. But a brief mention of some controls affecting the various types of ore bodies and their localization is desirable in view of these marginal areas of the map area (pl. 2) that lie within the east border of highly altered ground.

Because of the general north-south alinement of some larger chimney ore bodies of the Red Mountain district, the control of north-striking fissures or faults, called breaks by the miners, has been recognized since the early mining operations. Exposures at depth in some of the chimneys reveal fissurelike bodies of ore trending in the direction of elongation of the ore zones. In the Guston mine at Red Mountain No. 2, for example, a tabular body of sphalerite and galena that seems clearly to have been a fissure filling lay along the east edge of stoped chimney ground. There are also reliable reports (G. E. Collins, oral commun.; see also Collins, 1931, p. 419–422) that at the bottom levels of at least one mine (now inaccessible) the ore was mainly confined to fissures. At other places, the ore is found mainly in fissures without associated chimney bodies or in bunches along gougy fault zones.

Cross fissuring that aided in guiding the altering and mineralizing agents at certain places along the feeding fissures probably was a factor in controlling the position of some chimney bodies. Collins (1931, p. 418), in connection with ore bodies at Rico, Colo., distinguished so-called "pay" fissures and "cross" fissures, the pay fissures being those opened during favorable stages of mineralizing solutions. This condition may hold for some fissure intersections in solfatarically altered ground. Such conditions might also result from purely structural factors, fissures of certain trends being more generally subjected to tensional stresses. Insufficient data and usually poor exposures in the altered and fractured ground do not permit complete judgment regarding the major factors that controlled many small ore bodies in the solfataric environment. There are three main types of ore bodies, pyrite-enargite ores, copper-silver ores, and sphalerite-galena ores, but whether or not these were sharply separated in time of emplacement and represent several major openings of the feeding channels is not well established as a general rule. Some of the chimneys contain complex mixtures of all types.

Both coarse structural and microscopic evidence establishes an indefinite number of stages of fissuring in chimneys, as in vein deposits, but because of leaching origin of many spaces filled with ore, banded sequences are more likely to be found along the walls of partly filled caves than in fissures. Fissuring of the siliceous envelopes that permitted solutions under pressure to advance into shallow ground tended naturally to relieve pressures until the new openings became repaired by further sealing action. Locally, release of pressure furthered activity of acidic vapors or solutions, so that minerals typical of acidic environments alternate with those of more alkaline or neutral conditions. In the same manner, leaching may have alternated with filling. The complete history of such stages in chimney ground is not likely to be found at any one place as it is for vein deposits. Thus, the lack of any thorough study of a single chimney ore body during its development and mining results in gaps in the knowledge of the history of chimney formation.

Some mineralized bodies of breccia represent mineralized and altered pipe breccias of volcanic origin, as these contain fragments of several intrusive rocks and are locally exposed in their unaltered condition. Other breccias evidently represent fragmentation of the rocks by infiltration of altering and mineralizing solutions; in these, leaching and possibly slumping have contributed to breccia formation. Still other mineralized layered breccias represent extreme alteration, leaching, and mineralization of layers that are considered to have been original volcanic breccia beds. In some places, these beds are so highly altered and silicified that ghostly outlines of fragments are the only clue to their origin.

A mineralized breccia body of uncertain outline in the propylitized Burns rocks north of Gladstone is marked by a wide apron of iron oxide along the east side of Cement Creek. Its origin and nature is obscured by poor exposures, but one tunnel exposed altered and brecciated country rock containing chiefly pyrite; oxidation of this pyrite by ground waters has formed a blanket of iron oxide on the hillside.

MINERALOGY AND MINERAL PARAGENESIS

The most common sulfide minerals of the veins are pyrite, chalcopyrite, sphalerite, galena, and tetrahedrite or tennantite. Native gold is widely distributed, but in scattered shoots in siliceous gangues and in minor association with sulfides of the base-metal ores. Silver is found mainly in argentiferous tetrahedrite, locally associated with various sulfobismuthites, and less commonly with silver sulfosalts. The common gangues of the veins include quartz, rhodonite, rhodochrosite, calcite, fluorite, and barite. Adularia is associated with some late quartz veins. In the vein systems of Sunnyside Basin and at the head of Placer Gulch, some less common manganese minerals are associated with the predominant rhodonite and rhodochrosite gangues (Burbank, 1933a). These include friedelite (H_7 (MnCl) $Mn_4Si_4O_{16}$), alleghanyite ($5MnO \cdot 2SiO_2$), tephroite ($2MnO \cdot SiO_2$) helvite (3 (Mn,Fe) $BeSiO_4 \cdot MnS$), and alabandite (MnS).

The veins of Poughkeepsie Gulch and Mineral Point in the northern part of the map area contain many of the common gangues and sufides, but are notable especially for pockets of soft lead-gray minerals rich in silver and identified generally as sulfobismuthites (Kelley, 1946; Ransome, 1901, p. 83).

Some of these minerals have been shown to be mixtures. A notable example is alaskaite, a mixture of matildite, aikinite, and other minerals (Thompson, 1950). Beegerite, reported from the Old Lout mine in Poughkeepsie Gulch, may be all or in part mixtures of schirmerite and matildite (Eckel, 1961, p. 67). A mineral generally identified as cosalite occurs fairly commonly in bismuth-bearing ores, some of it being argentiferous and locally associated with bismuthinite (Eckel, 1961, p. 117).

A number of quartz-pyrite veins of Cement Creek contain hübnerite, locally in sufficient quantity to constitute marginal ore of tungsten. Adularia, hübnerite, and molybdenite have also been identified as rare constituents in late quartz veins, such as the gold-bearing quartz of the Sunnyside vein.

Common minerals of the chimney ores include enargite, pyrite, sphalerite, galena, bournonite, chalcopyrite, proustite, pyrargyrite, stromeyerite, covellite and chalcocite. Specks of a mineral identified as colusite (Burbank, Eckel, and Varnes 1947, p. 430) were found in enargite-tennantite-galena ore. Spectroscopic examination revealed traces of tin and larger amounts of gallium and indium. The mineral associations of the latter metals have not been completely identified. Other bulk samples of sulfides from several deposits contained from 0.01 to 0.1 percent tin and as much as 1 percent indium. Barite, calcite, fluorite, and sericite occur as gangue minerals in addition to secondary products of rock decomposition.

PHYSICAL AND CHEMICAL PROPERTIES

Wide variations in the colors of sphalerite, both in vein and chimney ores, led to the belief that this mineral might prove useful in geologic thermometry. In general, the younger sphalerites tend to be light or rosin colored in contrast to the dark-colored variety of the older base-metal ores. Weinig and Palmer (1929, p. 54) reported that some sphalerite of the Sunnyside vein was high-iron marmatite; however, quantitative spectrographic analyses of 12 sphalerites from vein and chimney deposits revealed only one sample that contained as much as 1 percent iron (table 11). Several samples of low iron content were checked by wet-chemical methods by J. J. Fahey of the U.S. Geological Survey, and these results confirmed an iron content of less than 1 percent. Very possibly sphalerite higher in iron might be found in deep Sunnyside ores. Some black sphalerite with associated pyrite was found at the American tunnel level after these iron analyses were made. The reason for the dark colors of several vein sphalerites, including some from the Sunnyside mine, is not known. Although the results did not prove useful in geologic thermometry, certain contrasts in minor elements between sphalerites of the ore chimneys and those of the veins are of interest. Manganese and iron are generally higher in the vein sphalerites, whereas germanium, thallium, and indium are generally higher in the chimney sphalerites.

TABLE 11.—*Selected minor elements in sphalerites from vein and chimney deposits*

[Quantitative spectrographic analyses. Analyst: Sol Berman, U.S. Geol. Survey. Zero in unit column means element not detected]

Location	Field No.	Laboratory No.	Elements analyzed, in weight percent											
			Fe	Mn	Cu	Ge	Sn	Pb	As	Cd	Tl	In	Ga	Ag
Chimney deposits														
National Bell	SJ-56-1	150149	0.009	0.02	0.3	0.003	0	0.05	0.3	0.1	0.07	0.01	0.007	0.0X
Do	SJ-56-2	150150	.004	.004	.1	.02	0	.01	0	.2	.03	.008	.005	.0X
Carbon Lake	SJ-56-4	150152	.006	.03	.3	.002	0	.08	.2	.7	.05	.08	.03	.X
Robinson	SJ-56-7	150154	.08	.03	.3	.003	0	.1	0	.3	.05	.06	.03	.X
Guston	SJ-56-8A	150155	.3	.02	.2	0	0	.08	0	.3	.05	.1	.03	.X
Do	SJ-56-8B	150156	.08	.01	.2	0	0	.07	0	.4	.04	.09	.03	.X
Vein deposits														
Sunnyside	SJ-56-13A	150160	0.3	0.3	0.02	0	0	0.005	0	0.6	0	0	0.009	0.00X
Do	SJ-56-13B	150161	.8	1.	1.	0	0	.03	0	.7	0	0	.02	.0X
Barstow	SJ-56-14	150162	.7	.07	.1	0	0	.02	0	.5	0	0	.004	.0X
Old Lout	SJ-56-12	150159	1.	.2	.3	0	.003	.06	0	.7	0	0	.003	.00X
Terrible	SJ-56-11	150158	.7	.5	.1	0	0	.04	0	.6	0	0	.002	.X
Altoona	SJ-56-9	150157	.6	.6	.1	0	0	.07	0	.7	0	0	.002	.X

Microscopic examination of the abundant rhodonitic gangue of the Sunnyside vein systems (Burbank, 1933a) reveals that thick bodies are locally complex mixtures of a number of manganese silicates containing different proportions of manganese and silica. The optical properties of these minerals are given in table 12. The most conspicuous, but not the most abundant, of these silicates is orange to rose-red friedelite, which occurs in scattered patches throughout some bodies of massive mixed silicate gangue. As seen in thin section, these masses of friedelite are composed of fine compact micaceous-appearing plates 0.01–0.02 mm in diameter. Near some vuggy areas the friedelite forms tabular crystals 0.06–0.13 mm in diameter. Qualitative chemical tests of the mineral made by Waldemar Schaller of the U.S. Geological Survey showed the presence of both chlorine and arsenic. An analysis of a sample of the mixed silicates (table 13), which contained roughly 5–10 percent friedelite, indicated that chlorine is in excess of arsenic and thus confirmed the optical identification as friedelite rather than the arsenic variety, schallerite.

TABLE 12.—*Optical properties of some manganese silicate minerals from the Sunnyside veins, Eureka Gulch, San Juan County*

[Source: Burbank, 1933a, p. 513–527]

	Friedelite	Alleghanyite	Tephroite	Rhodonite
Indices of refraction	$\omega=1.657$ $\epsilon=1.625$	$\alpha=1.756$ $\beta=1.776$ $\gamma=1.790$	$\alpha=1.771$ $\beta=1.800$ $\gamma=1.815$	$\alpha=1.733$ $\beta=1.736$ $\gamma=1.747$
Birefringence	0.032	0.034	0.044	0.014
Optical character	Negative	Negative	Negative	Positive
2V	0° or small	75°–80°	70°±	55°–60°

TABLE 13.—*Partial chemical analysis of mixed manganese silicate gangue, Sunnyside mine, Eureka Gulch, San Juan County*

[Field No. 60–B–1, serial No. 287139; As (sample in duplicate) determined colorimetrically by E. J. Fennelly, U.S. Geol. Survey; CO_2 determined gasometrically, total S and sulfide S determined gravimetrically by I. C. Frost, U.S. Geol. Survey; Mn determined colorimetrically by D. L. Skinner, U.S. Geol. Survey; H_2O^+, H_2O^-, P_2O_5, Cl, and F determined by Elaine L. Munson, U.S. Geol. Survey; calcium content not determined in this sample. See also table 15]

Constituent	*Percent*	*Constituent*	*Percent*
Mn	40.4	F	.21
As	.043	CO_2	.30
Cl	.64	P_2O_5	.01
H_2O^+	3.94	Sulfide S	.04
H_2O^-	.05	Total S	.18

Patches of mixed tephroite and alleghanyite can generally be recognized in hand specimens by the gray to grayish-green color in contrast to the bright pink of pure rhodonite. These patches also weather more readily than does the rhodonite to a dark stain of manganese oxide. The alleghanyite in thin section is characterized by conspicuous twinning normal to elongation of crystals.

Judged from its optical properties, the rhodonite is low in the $CaSiO_3$ molecule. A bulk spectrographic analysis of the rhodonite gangue from the No Name lode indicated only 0.7 percent Ca, equivalent roughly to 2 percent $CaSiO_3$. (See table 15.)

The helvite, first identified in mixed silicates from the Sunnyside veins, occurs in very small but brilliant honey-yellow crystals in vuggy patches of the gangue. Microscopic examination of rhodonitic gangues from other veins, notably the Ben Franklin vein of Sunnyside Basin, showed the presence of strongly zoned crystals probably indicative of different proportions of the zinc and iron-bearing molecules. Spectrographic analyses of bulk rhodonitic gangues of the Sunnyside veins and others in the area (Warner and others, 1959, p. 177, table 76) showed from less than 0.0001 (detectable limit) to 0.0021 percent BeO. Of 10 samples from the Mineral Point and Poughkeepsie areas, only one contained detectable quantities of BeO.

PARAGENETIC AND TEXTURAL RELATIONS

The gross paragenetic relations of vein structure have been summarized (p. 39) and shown in figures 8*B–F*. As the original vein matter of the shallower late-stage gold-bearing parts of the Sunnyside vein systems is no longer exposed for study, the observations of Ransome (1901, p. 177) on these earlier exposures are worth quoting in full:

> The Sunnyside vein is frozen to the walls, and gouge is usually absent. The ore minerals of the vein are galena, sphalerite, chalcopyrite, pyrite, tetrahedrite, and free gold, in a gangue of quartz and rhodonite. The ore streaks occur irregularly in the vein between partitions of rhodonite. As a rule the ore occurs near the walls, and when an ore shoot pinches on one wall it usually thickens on the other. The best ore, carrying free gold, occurs in irregular lenses parallel with the plane of the lode and sometimes 30 or 40 feet in diameter. It is usually associated with rosin-colored sphalerite and small amounts of lilac fluorite. These are regarded as useful indications, but are not invariably accompanied by free gold. The ore has been brecciated to some extent since its original deposition and is sometimes traversed by a network of veinlets. These are usually filled with quartz carrying a little chalcopyrite. But where the veinlets traverse rhodonite they are often filled with that mineral instead of quartz. The exact relations of the rhodonite 'partitions' to the ore is not always clear. In some cases the rhodonite appears to form the mass of the vein, in which the ore occurs as lenticular bodies, and sometimes lenses of rhodonite are surrounded by ore. The large masses of rhodonite, or 'pink', as the miners term it, are never regarded as ore, although they are not destitute of ore minerals. The material is rose-pink in color on fresh fracture, very compact, and exceedingly hard to work. It always contains a little quartz, calcite, and rhodochrosite. The rhodonite sometimes occurs as distinct stringers cutting the quartz and ore, while in other places it may be seen intimately and irregularly intercrystallized with them. As far as observed, neither the rhodonite nor the ore shows any regular megascopic structure, such as banding, crustification, or comb structure, other than the general relationship already indicated.

For the most part Ransome's descriptions of the general relationships of the various types of ore and gangue do not conflict with the recognized major stages of vein development, namely, an early quartz or quartz-pyrite stage preceding a base-metal stage, an intermediate rhodonitic stage, and final stages of quartz, sphalerite (rosin jack), galena, chalcopyrite, tetrahedrite, and fluorite locally containing free gold. But in part his comments on the relations between rhodonite and ore seem contradictory, perhaps because it is not always clear whether his "ore" refers to early base-metal or to later sulfides and gold-bearing ore or to both intermixed. Also, the comments regarding late quartz cutting rhodonite and the change from quartz filling to rhodonite filling where the veins traverse rhodonite give rise to questions of paragenetic relations. Many of these points are clarified by microscopic examination of ore and gangue from the several vein stages. The development of rhodonite by replacement of country rock in the vein walls has already been described (on page 33). The manganese-bearing solutions reacting with siliceous minerals tended to yield rhodonite, which is the manganese silicate having the highest ratio of silica to manganese. On the other hand, when solutions saturated with silica traversed a rhodonitic mass containing the low-silica manganese silicates, such as tephroite or alleghanyite, these minerals were presumably unstable and reacted with excess silica in solution to form rhodonite. This kind of reaction relation between preexisting minerals and later stages of vein-forming solutions is confirmed by microscopic studies of the gangues. The following descriptions of some microscopic features of sulfides and associated gangues will illustrate these relations in more detail.

The earliest quartz of the veins is practically barren of valuable metals, although locally it grades inward from the vein walls to sulfide ore. The quartz is fairly commonly frozen against partly silicified walls, but repeated movement of vein walls tended to disrupt original quartz and caused repeated veining and recrystallization. Early milky-white quartz from deep levels of the Washington vein of the Sunnyside mine shows a rather crude ribbon structure adjacent to the wall (fig. 9*A*). The grain size ranges from about 0.1 to 2 mm where quartz has replaced included rock fragments. The partings in places consist partly of chloritized and silicified material containing finely divided pyrite and partly of

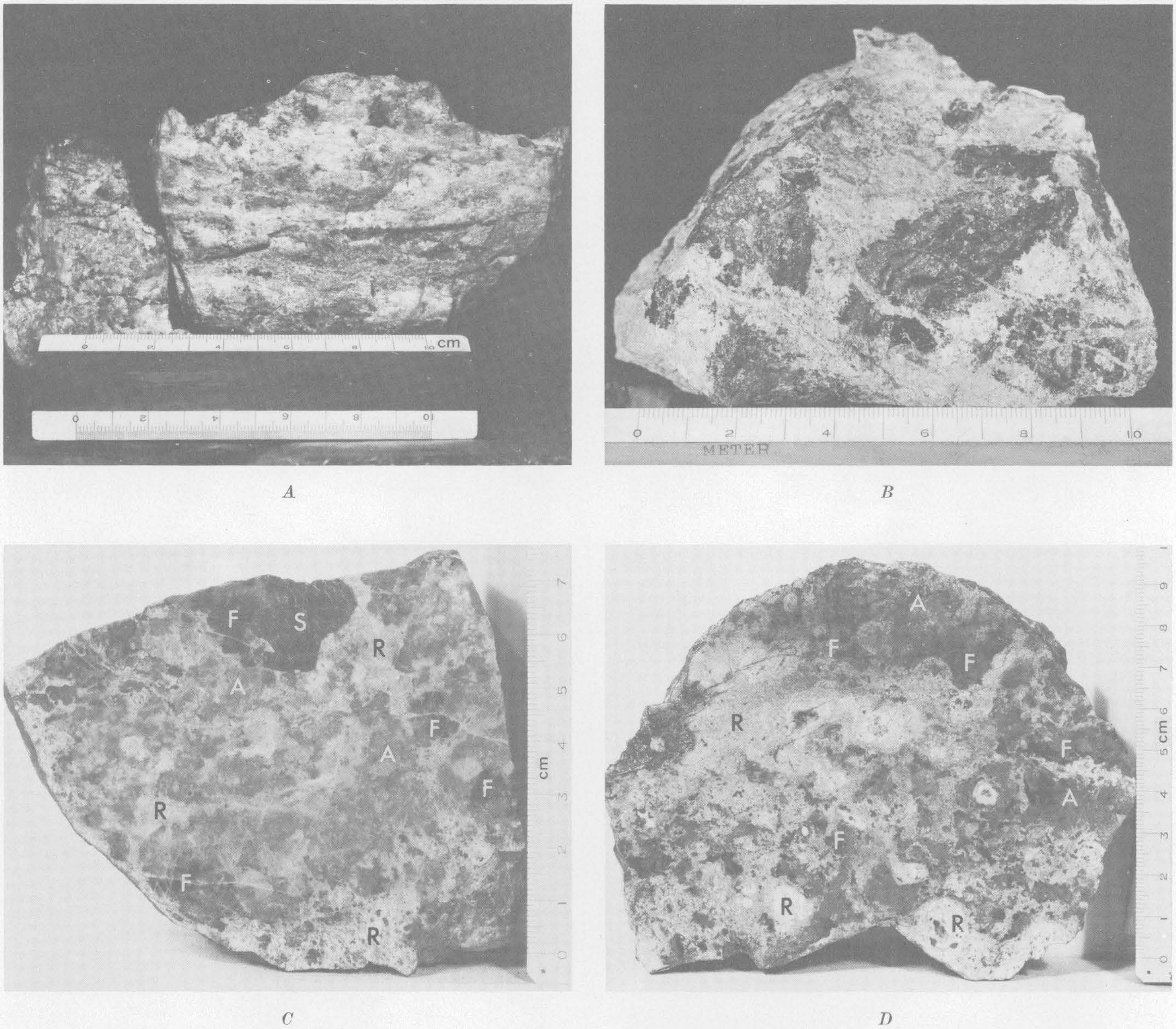


FIGURE 9.—Ore and gangue textures. *A*. Early quartz illustrating crude ribbon structure. Quartz specimen on right is partly replaced by rhodonite along and near partings. I-level, Washington vein, Sunnyside mine. *B*. Breccia of base-metal sulfide ore in rhodonitic gangue. Ore mainly sphalerite and pyrite with some galena in a quartz gangue. Some incipient replacement of quartz by rhodonite. Raise from American tunnel, Washington vein, Sunnyside mine. (See fig. 8*D*.) *C*. Polished slab of mixed manganese silicate gangue, illustrating guidance of replacement processes by hairline fractures. Early friedelite (F) is partly replaced by mixtures of alleghanyite and tephroite (A), which are replaced in turn by rhodonite (R) in lighter colored streaks and patches. The gangue encloses a fractured crystal of sphalerite (S). Sunnyside mine. *D*. Polished slab of mixed manganese silicate gangue, illustrating guidance of replacement along drusy channels lined with rhodonite crystals. Darkest patches are friedelite (F); other dark areas consist of alleghanyite and tephroite (A) in various stages of replacement by rhodonite (R). Sunnyside mine.

thin layers of sulfide, chiefly sphalerite. In other places, rhodonite, guided by the parting surfaces, has somewhat replaced the quartz. Pyrite is very sparsely disseminated and for the most part seems to represent iron derived from included fragments of wallrock.

The quartz, sphalerite, and galena ore in some shallow exposures at the Sunnyside locality consist of fine even-grained intergrowths (figs. 10 *A–D*) without clearcut evidence of a sequence in crystallization. Locally the sulfides are segregated in coarse-grained patches or lenses, and in some veins (fig. 8) they occur as practically gangue-free veins or lenses.

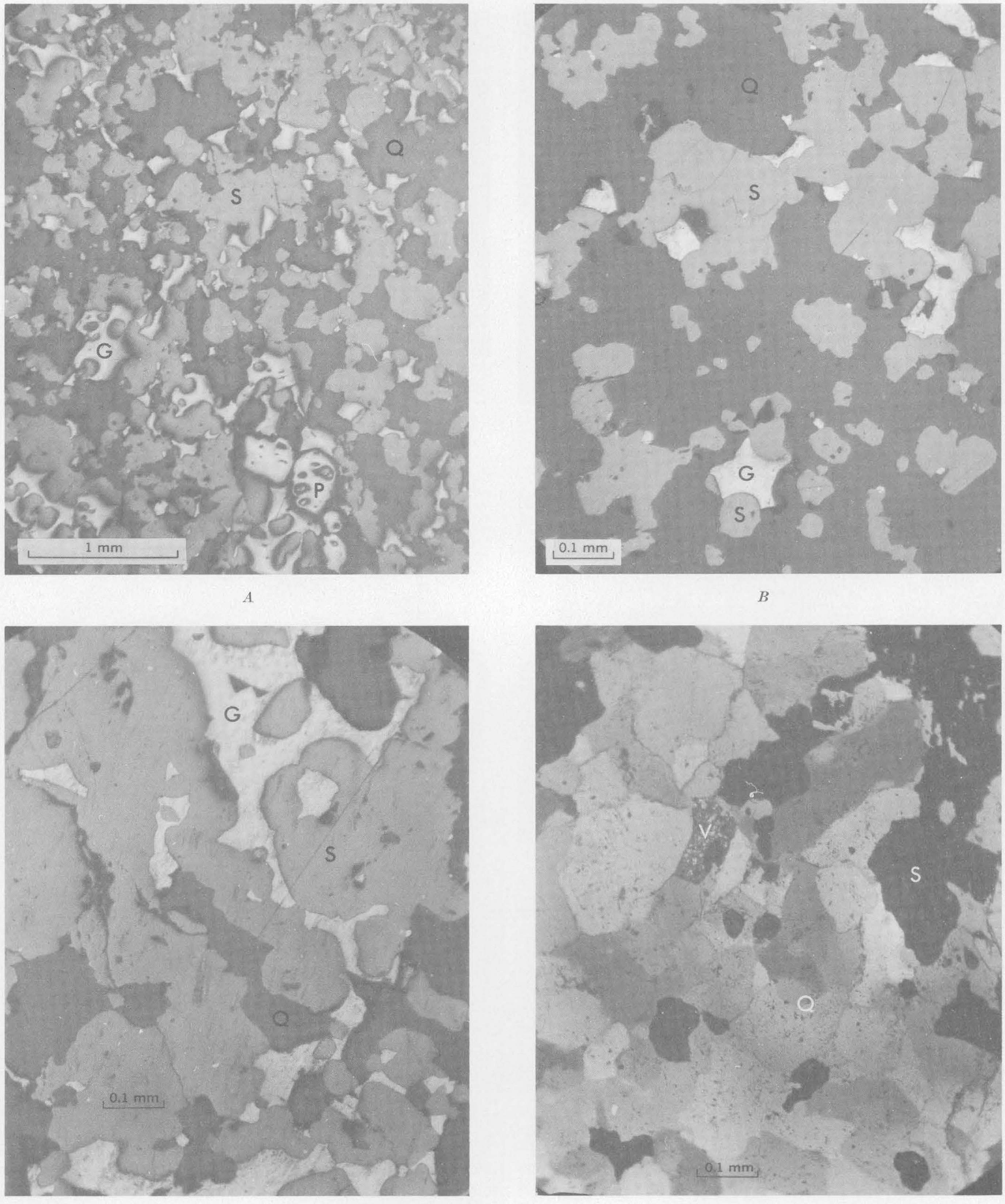


FIGURE 10.—Photomicrographs of ore and gangue minerals of the No Name vein. (For descriptions of individual photographs see facing page.)

The rhodonitic gangue with mixed silicates forms either distinct veins or a matrix of sulfide-ore breccia, whereas rhodonite, in addition to these forms, alone replaces earlier quartz gangues. A conspicuous breccia of fragments of quartz-pyrite-sphalerite-galena ore in a matrix of rhodonitic gangue is exposed in the lower levels of the Washington vein on and below Sunnyside I-level in the raise from the American tunnel (figs. 8D, 9B). The rhodonite has partly replaced the quartz that is associated with the sulfides and at places surrounds grains of the earlier sulfide. The replacement of quartz by rhodonite crystals is shown in figure 11*D*, a photomicrograph of a thin section of the quartz shown at the right in figure 9A. In wide partitions, the massive rhodonitic material contains irregular patches of the silicate mixtures consisting of friedelite, tephroite, and alleghanyite. These minerals have not been observed replacing quartz or wallrocks. The structural relations of these wide bodies of the mixed manganese silicate gangue indicate that they represent fillings of open spaces, and none of the thin sections of this mixed gangue contains remnants of pregangue material that might have been replaced.

The paragenetic relations of the several silicates show that friedelite was one of the earliest minerals, being replaced in succession by mixtures of tephroite and alleghanyite and finally by rhodonite (figs. 11*A–C*). Rhodonite veinlets locally cut across all previous minerals. Two textural types of replacement are represented, one where the replacement proceeded outward from crisscrossing fractures and another where replacement proceeded outward from drusy centers and formed irregular whorls and concentric bands (figs. 9*C*, *D*). How much of the original ribs of manganese silicate gangue consisted of mixtures of friedelite, alleghanyite, and tephroite and how much consisted of initial rhodonite is problematical. In some places, probably much of the wide ribs consisted originally of the low-silica minerals.

Rhodochrosite is a local replacement product of the rhodonite and of earlier quartz gangues and is found also in vugs as crystals perched on quartz. Patches of fluorite occur in nearly all gangues. Fluorite was observed with calcite filling vuggy patches of early quartz and also associated with rhodochrosite in replacements of other minerals. As noted by Ransome (1901, p. 177), a purplish fluorite was associated with late gold-bearing quartz. The common sulfides with chalcopyrite and tetrahedrite occur also with late quartz; the sphalerite with the late quartz is generally light in color, whereas the sphalerite in the early base-metal ore is almost black.

The complexities of intergrowths in veins that have been repeatedly mineralized are such that it was not possible in examining the early products of mineral intergrowths to distinguish whether fluorite, for example, accompanied all stages of mineralization or whether it was a replacement product only in some stages. Small grains of helvite found in base-metal ore associated with rhodonite that formed by replacement of earlier quartz is presumed to be a product of the rhodonite stage. Grains of sulfide, usually sphalerite but also alabandite, molded on crystals of helvite would accordingly be considered of probable late origin.

Associated chalcopyrite, rosin sphalerite, and tetrahedrite appear to be primarily minerals of the later quartz stages in ores from the Sunnyside veins, but these sulfides are found less frequently in banded and crustified rhodonite and rhodochrosite (fig. 12*B*). Chalcopyrite is known to be associated with sphalerite and galena in some early stage base-metal veins of the area; failure to find more than a few specks in some polished slabs of early sphalerite-galena ore from the Sunnyside veins may be a matter of its paucity or of chance. The ratio of copper to combined lead and zinc in ore milled is reported to be about 1:27 (King and Allsman, 1950, p. 70).

Minor accessory minerals of the rhodonitic veins also include alabandite in minute green grains associated with specks of pyrite or with helvite. A few other accessory minerals, such as neotocite or bementite, in the rhodonitic gangue must be of isolated occurrence and perhaps are of doubtful identity, for they could not be separated in sufficient quantity to be confirmed. Sulfobismuthites, molybdenite, native silver, and native copper were reported by Ransome (1901, p. 180–182) as minor accessory minerals in veins along the Sunnyside fault system in Placer Gulch. These are associated in part with barite and quartz, an association more typical of the Poughkeepsie Gulch vein system than of the Sunnyside and Ross Basin vein systems.

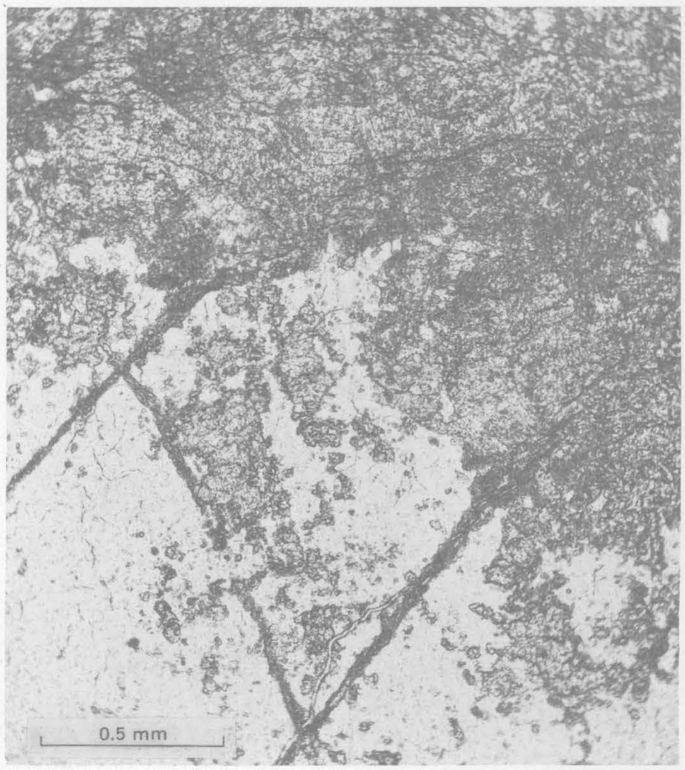
EXPLANATION OF FIGURE 10

A. Quartz -sulfide intergrowth of massive ore (b of figure 8*E*) illustrating fine-textured nature of some bodies of base-metal ore. Pyrite, P; sphalerite, S; galena, G; and quartz, Q. Reflected light.

B. Same as *A*, higher magnification, showing galena, G, interstitial to rounded grains of sphalerite, S, and quartz, Q. Reflected light.

C. Same as *B*, but showing coarser textured intergrowth of sphalerite, S, and galena, G, with minor quartz, Q. Illustrates that quartz-sulfide intergrowths have considerable range in grain size without appreciable change in mutual intergrowth pattern. Reflected light.

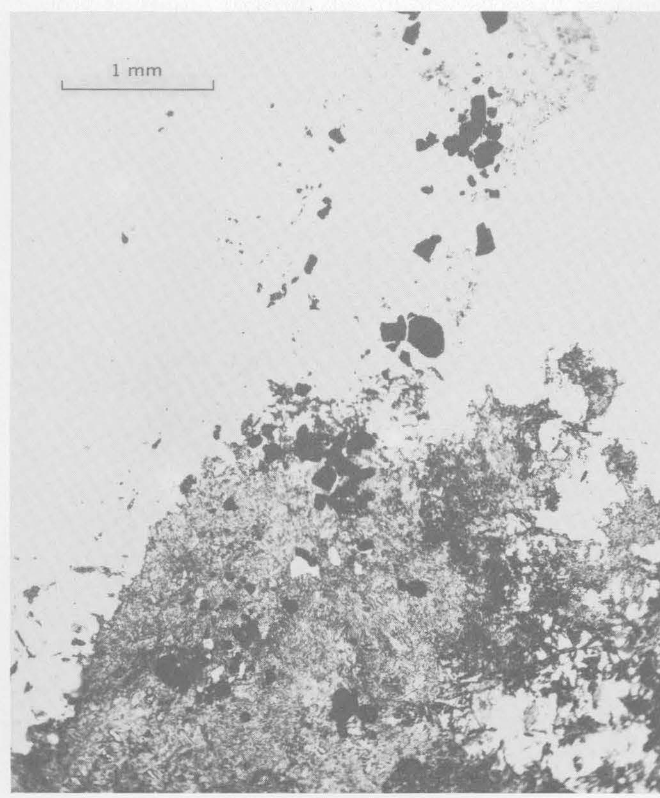
D. Quartz, Q, from near right wall of quartz vein (a of figure 8*E*) with sphalerite, S, and vesuvianite, V. Partly crossed nicols.



A

B

C



D

FIGURE 11.—Photomicrographs of mixed manganese silicate gangues. (For descriptions of individual photographs see facing page.)

The hanging wall and branch veins of the Sunnyside fault system, at the head of Placer Gulch, and the Golden Fleece vein, transverse to the Scotia vein of Treasure Mountain, all tend to confirm that the gold is a product of late quartz veining, usually with some associated rhodochrosite and less commonly rhodonite. With respect to the Sound Democrat vein at the head of Placer Gulch, Ransome (1901, p. 182) noted also that chalcopyrite is not abundant but where found was considered an indication of the presence of gold. This relation conforms generally to our observations of the occurrence of chalcopyrite in Sunnyside ores, that it is found more commonly with late quartz or rhodonite-rhodochrosite mixtures rather than with the early sphalerite-galena ores. In the Golden Fleece vein, some parts of which were accessible to examination in the course of this work, the gold is in a very narrow quartz vein with little rhodochrosite and minute specks of sulfides (fig. 12D). Small plates of gold occur along partings, and Ransome (1901, p. 183) also reported that the gold occurred in beautiful branching dendritic plates.

ORIGIN OF ORES AND GANGUES

VEIN DEPOSITS

The sulfide ores and gangues of the central parts of the Eureka district, as well as those of Poughkeepsie Gulch and Mineral Point, have a common evolution in that early quartz and base-metal sulfide deposition was interrupted by major refissuring and the introduction of manganiferous gangues. The gangues were followed in turn by siliceous, carbonatic, or baritic gangues containing lesser amounts of sulfides, which are commonly the principal sources of the precious metals. The minor quantities of the manganiferous gangues found in some veins might be considered fairly normal occurrences for certain manganiferous provinces of the western United States (Hewett, 1964). In the Eureka district, however, especially along the Sunnyside and Ross Basin faults and along the fault fissures of Treasure Mountain, the large bodies of the rhodonitic gangues and the abrupt termination of early quartz-sulfide ore deposition prior to their introduction constitute a problem in vein evolution. Ransome (1901, p. 132) commented on this as follows:

> The origin of the rhodonite, which is so abundant in many of the lodes of the northern half of the quadrangle, and its exact relation to the quartz and ore which accompany it constitute a puzzling problem, for which no satisfactory solution has been found. Such a solution must account for the presence of large lenticular or partition-like masses of rhodonite, carrying a few specks of low-grade ore, and dividing the ore bodies longitudinally into two or more parts, and for the presence of patches and stringers of rhodonite. In the Saratoga mine rhodonite has formed by metasomatic replacement of limestone. It is possible that in such lodes as the Sunnyside the large, solid masses of rhodonite within the vein may represent metasomatically altered horses of country rock. This, however, is merely a hypothesis, which requires confirmation before acceptance. It has undoubtedly been deposited also in open fissures as a true vein mineral.

Our own observations lead us to believe that much of the early rhodonitic mixed silicate gangue was deposited in open fissures, since wherever rhodonite has replaced country rock or quartz gangue, the relations are clearly shown and remnants of the replaced material are found mixed with the rhodonite.

Hulin (1929) suggested that reopening of the compound veins tended to concentrate products of a given stage, such as the rhodonite, depending upon the timing of these openings with respect to some evolutionary processes at the source, such as a magma. Another possible viewpoint is that reopening of the fissures and faults to great depth was not merely passively related to the timing of differentiation processes at the source, but rather that numerous releases of pressure brought about at depth by fissuring initiated some entirely new process of fractionation that concentrated manganese in solution (Burbank and Luedke, 1961). Under this hypothesis, problems arise as to the kinds of solutions involved, their sources, and reasons for the dominant precipitation of low-silica manganese minerals abruptly following quartz-rich sulfide ores.

Intermittent evolution of carbon dioxide from sources at depth is suggested as the possible catalytic agent of this abrupt change in vein filling. The general propylitic alteration of the country rocks over hundreds of square miles, with the introduction of enormous quantities of carbon dioxide prior to as well as during vein formation, is indicative of major sources of this fugitive substance at depth. Whether it came from rather mafic parent magmas or from other sources in the crust, such as carbonatites (Pecora, 1956), does not seem particularly significant to the problem at hand.

EXPLANATION OF FIGURE 11

A. Light-colored field of fine-textured friedelite, partly replaced by alleghanyite, and crisscrossed by rhodonite veinlets along hairline fractures. No Name vein, Sunnsyside mine. Plane polarized light.

B. Same as *A*, crossed nicols. Some granules of tephroite in alleghanyite are not distinguishable. Cross-twinning in alleghanyite visible at places.

C. Detail of alleghanyite twinning. Some of small rounded grains are tephroite. Crossed nicols.

D. Replacement front of rhodonite in clear quartz gangue containing a layer of scattered sulfide grains. Rhodonite has partly enveloped sulfide grains. Early quartz gangue of Washington vein, American tunnel, Sunnyside mine. Plane polarized light.

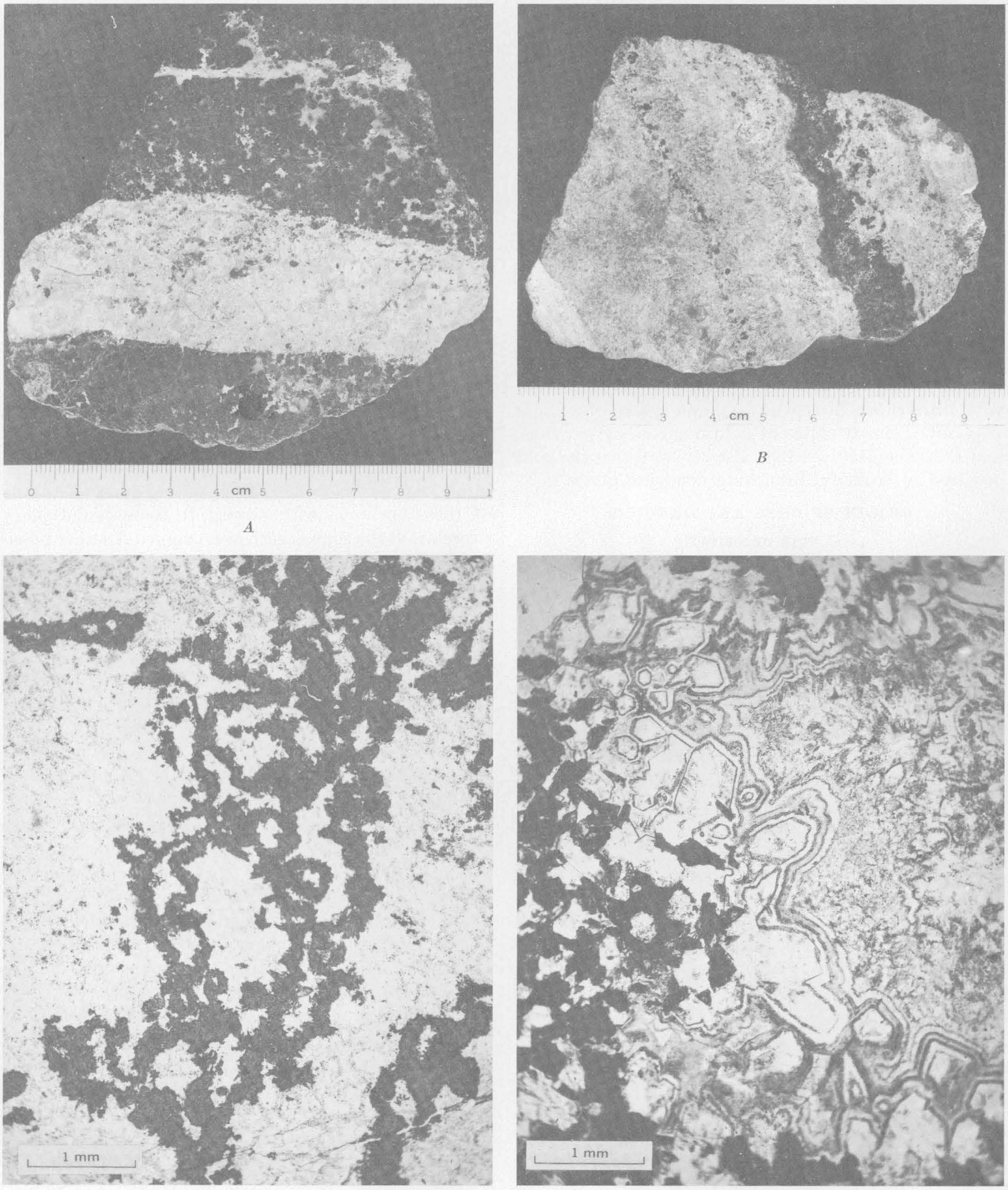


FIGURE 12.—Photographs and photomicrographs of ores and gangues. (For descriptions of individual photographs see facing page.)

Either in solution or as a free gas, carbon dioxide must have thoroughly penetrated all rocks and fractures from the surface downward to unknown depths. The first reopening of fissures resulted in explosive injections of clastic debris from depths in excess of a mile, and the evidence of the dikes indicates that carbon dioxide was a constituent of the propelling gases. As pointed out by Garrels and Richter (1955, p. 450), the volume of one mole of carbon dioxide and one mole of water at the surface are, respectively, 23,100 cc and 18 cc. At rather shallow depths of a few thousand feet, depending upon load and temperature, the density of carbon dioxide is equal to or slightly greater than water. The expansive force of a fluid rich in carbon dioxide is very great as it rises toward the surface. Hence, any fracturing of rock bodies at depth causing dilation of spaces would result in movement of carbon dioxide-bearing solutions into these spaces and toward the roots of faults and fissures. During vein formation with numerous repeated episodes of fracturing, this migration of fluids might be expected to continue intermittently, but not with the explosive intensity of earlier clastic dike injection.

The number and frequency of major and minor dislocations of vein walls is pertinent to any hypothetical pressure-dependent mechanism of differentiation in solutions that entered the roots of fissures. The periodicity of structural disturbances in decadent stages of volcanism probably varies greatly in different districts. Evidence from structures of the local veins, however, indicates that there were probably many minor episodes of readjustment of vein walls in addition to the major ones that are evident from megascopic examination of the veins (fig. 8). Microscopic examination of vein minerals commonly shows repeated fracturing and healing of mineral growths, which is especially noticeable in the various stages of quartz and rhodonitic gangues and in ribbon types of quartz veins; however, in some wide veins of quartz-sulfide intergrowths, these dislocations of mineral intergrowths tend to be more obscure. For example, a common patchy mottling of fine-textured quartz-sulfide intergrowths in some exposures of base-metal ore, such as sketched by Ransome (1901) and shown in figure 8B, may possibly represent dislocations of incipient crystal networks that have become healed by continued growth and recrystallization. Hence, both coarse and fine microscopic textures of of mineral intergrowth would seem to confirm numerous episodes of structural disturbance that probably resulted in transient releases of pressure near the roots of fissures and major faults.

Fractional concentration of manganese in carbonatic solutions from depth would be dependent upon several factors: (1) Release of carbon dioxide and other gases from altering solutions in country rock, or even from partly crystallized magmatic sources, would tend to fractionate the solutions and leave behind the less soluble compounds as the solutions moved toward open fissures or small fractures in the rocks, (2) solid solution and decomposition relations in some compounds, such as carbonates, tend to enrich escaping solutions in certain constituents; for example, calcium-manganese mixed carbonates subjected to isothermal loss of carbon dioxide pressure tend to become depleted in the manganese molecule, which is enriched in any fluid remainder (Goldsmith and Graf, 1957), (3) the formation of chlorite, epidote, pyrite, and iron oxides during alteration of the rocks, or under deuteric conditions, tends to fix much of the iron and magnesium as well as some sulfur in relatively stable compounds. Accordingly, intermittent releases of pressure on fractured rocks undergoing alteration by carbonatic solutions at depth could conceivably result in fractional enrichment of manganese in fluids that gained access to the roots of faults and fissures. The concentrations of MnO in normal rocks of the province appear adequate as a source.

In assuming that manganese could have been concentrated in some such manner in solutions relatively rich in carbon dioxide, a problem is raised as to why the earliest vein-forming mineral was chiefly quartz of low metallic content. Rarely, ankeritic carbonates have been found as a selvage of quartz veins in an area west of the Silverton cauldron, but no such occurrences were noted in the Eureka district. If alteration of country rocks was initiated at considerable depth during and prior to injections of clastic dikes, then the walls of some deep fissures could have been carbonatized prior to and during

EXPLANATION OF FIGURE 12

A. Photograph of polished slab of sulfide ore cut by quartz-rhodonite vein. Quartz is mottled with pinkish intergrowths of rhodonite, similar to those shown in photomicrograph *C*.

B. Photograph of banded rhodonite-sulfide intergrowths. Sulfides consist chiefly of tetrahedrite, chalcopyrite, and galena.

C. Photomicrograph of quartz-rhodonite intergrowths. Quartz in hand specimen mottled with salmon-pink patches from intergrown rhodonite. American tunnel level, Washington vein, Sunnyside mine. Plane polarized light.

D. Photomicrograph of quartz containing minor sulfides and free gold. Dark bands in quartz growth lines are dusty layers, mostly particles of rhodochrosite. Black patches are mixed sulfides and free gold. Golden Fleece vein, Treasure Mountain. Plane polarized light.

early stages of shallow vein formation. Knopf (1929, p. 44–45), for example, has shown that the attack of carbonatic solutions on ferromagnesian minerals in the walls of quartz veins at depth in the Mother Lode system of California could have supplied all the silica for the veins. Bodies of rock, either representing the ferromagnesian schists of the San Juan basement rocks or other country rocks could have become partly desilicated along solution channels prior to the manganese stage of mineralization. Such desilication of source rocks would also accord with the fact that the earlier manganese minerals that precepitated after refissuring of quartz-sulfide veins were those of relatively low silica content.

Conversion of the low-silica molecules to rhodonite in later phases of the manganese stage requires addition of silica in any volume-for-volume substitution; however, that some MnO is set free in this process probably accounts for late veining by rhodonite, quartz-rhodonite, or the quartz-rhodochrosite assemblages that carried some of the later silver-bearing sulfides and gold. As shown in table 14, both alleghanyite and tephroite contain more MnO per unit volume than rhodonite, whereas friedelite contains somewhat less. Thus, the direct conversion of friedelite to rhodonite requires addition of both silica and manganese oxide, according to the following equation based upon volume-for-volume replacement for 1cc of mineral:

3.07 g (solid friedelite) + 0.63 g (SiO_2 in solution) + 0.35 g (MnO in solution) → 3.68 g (solid rhodonite) + 0.212 g (HCl in solution) + 0.158 g (H_2O).

On the other hand, in converting tephroite or alleghanyite to rhodonite, 0.88 g per cc of MnO for tephroite and 0.99 g per cc of MnO for alleghanyite must be removed in solution:

4.00 g (solid alleghanyite) + 0.67 g (SiO_2 in solution) → 3.68 g (solid rhodonite) + 0.99 g (MnO in solution).

Hence, depending upon initial proportions of friedelite, tephroite, and alleghanyite, some excess MnO would be available to form additional rhodonite by reaction with siliceous solutions. The conversion of 1 cc of alleghanyite to rhodonite yields enough excess MnO to form nearly 0.5 cc of rhodonite. This relation probably accounts for the fact, noted by Ransome (1901, p. 177), that where veins normally filled with quartz traverse bodies of rhodonitic (mixed silicate) gangue, the vein filling tends to be rhodonite. However, some such veins cutting base metal sulfides as well as rhodonitic gangue prove to be microscopic intergrowths of quartz and rhodonite (figs. 12*A*, *B*). Similar quartz-rhodonite intergrowths were also found in the deep levels of the Washington vein (fig. 12*C*).

By the addition of CO_2, both alleghanyite and tephroite could be converted to rhodochrosite with excess MnO and SiO_2 per unit volume:

4.00 g (solid alleghanyite) + 1.38 g (CO_2 in solution) → 3.61 g (solid rhodochrosite) + 0.77 g (MnO in solution) + 1.00 g (SiO_2, as solid quartz, or in solution).

A common association of late drusy quartz in vugs with perched crystals of rhodochrosite could accordingly have been formed by late CO_2-bearing solutions containing little else in vein-forming substances. The conversion of rhodonite to rhodochrosite requires a small addition of MnO (table 14), which could have been derived from excess MnO released in the decomposition of the other silicates.

The question of whether or not carbon dioxide is an ore-forming fluid under shallow-earth conditions, a point raised by Garrels and Richter (1955), is not necessarily involved in the previous analysis of vein formation. The evidence of the veins points rather to the conclusion that most of the ore-forming substances were carried in siliceous or sulfur-bearing solutions and that solutions depositing early rhodonitic gangues were for the most part rather barren of valuable metals. Exceptions are to be noted in late phases of the rhodonite-rhodochrosite mineral sequence, during which admixtures with chalcopyrite, tetrahedrite, and quartz locally carried valuable amounts of silver and gold. As has been noted, these later vein assemblages probably represent in part reaction between siliceous ore-bearing solutions containing some carbon dioxide and previously deposited low-silica manganiferous gangues.

TABLE 14.—*Constituents, in grams per cubic centimeter, of manganese silicate gangues*

	Friedelite $6MnO \cdot 2Mn(OH,Cl)_2 \cdot 6SiO_2 \cdot 3H_2O$	Tephroite $2MnO \cdot SiO_2$	Alleghanyite $5MnO \cdot 2SiO_2$	Rhodonite $MnO \cdot SiO_2$	Rhodochrosite $MnO \cdot CO_2$
SiO_2	1.05	1.22	1.01	1.68	None
MnO	1.65	2.88	2.99	2.00	2.22
H_2O	.158	None	None	None	None
HCl	.212	None	None	None	None
CO_2	None	None	None	None	1.38
Specific gravity	3.07	4.1	4.0	3.68	3.61

On the possibility that the manganese-bearing solutions were similar to some recent hot-spring waters that continue to deposit manganese oxide at Ouray, about 8 miles northwest of the Eureka area, some samples of the spring deposits have been analyzed and are compared with the silicate deposits (table 15). (See also Hewett, 1964; Burbank and Luedke, 1961.) Correspondence between the silicate and oxide deposits is obvious in some samples, but the oxide deposits are higher in tungsten and barium and lower in the proportions of silica deposited. The hot-spring waters contain calcium and sodium sulfate and bicarbonate chiefly, with some chloride, and minor fluoride and boron, but are lacking in H_2S (table 15). If these spring waters correspond in composition to the much older manganiferous vein solutions, they evidently represent some further evolution, such as loss of CO_2, oxidation of H_2S, and greater dilution with meteoric waters. The presence of barium and tungsten in the spring deposits also shows some similarity to later stages of vein evolution. There are narrow baritic lead-silver veins with rhodochrosite near the sites of the hot springs, and possibly some constituents of the waters were leached from similar deposits at depth.

The ultimate sources of the manganiferous gangues and of the siliceous sulfide ores are problematical. Either a single source, different sources, or intermixing of solutions from different sources seem to be possibilities. The very low sulfide and metal content of the early silica-deficient manganiferous gangues would seem to indicate that the solutions did not have a common source with the quartz and associated metal sulfides, but intermixing of the two types of solution to some degree would then be required for vein evolution. The widespread permeation of all country rocks with carbonatic agents of alteration, which suggests possible different sources, would provide both shallower and less restricted sources of manganese-bearing solutions as compared with possible deep sources of sulfur and metals. Had the manganiferous solutions migrated rapidly into roots of the reopened faults and fissures, only minor mixing might have taken place with the siliceous sulfide solutions previously occupying narrow feeding channels. Reduction in the precipitation of manganese from the latest quartz and sulfide solutions could have resulted from the lack of time to build up manganese concentration again, from the sealing off of manganeous sources by plugging of fractures, or from the gradual reduction in pressures of carbon dioxide at depth through continued reaction with rock minerals. If both quartz-sulfide and later manganese-bearing solutions had common sources, the abrupt change from excess silica with sulfides to silica deficiency in the early manganiferous gangues would seem to require further explanation. This explanation

TABLE 15.—*Analyses of hot-spring deposits and water and of manganese silicate gangue of upper Tertiary veins, western San Juan Mountains*

[Samples 1-5: semiquantitative spectrographic analyses, in percent; M, greater than 10 percent; ----, not looked for. Sample 6: chemical analysis, in parts per million]

	Ouray hot-spring deposits			Manganese silicate gangue No Name vein	
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Si	----	X	----	M	M
Al	----	.X	----	0.3	0.3
Fe	7.0	X	0.7	.15	.15
Mg	.15	----	.07	.3	.3
Ca	----	X	----	.7	.7
Na	----	.X	----	.0	.0
K	----	----	----	.0	.0
Mn	15.0	XX	30	M	M
Ag	----	----	----	.003	.0015
Ba	.7	X	.7	0	.0007
B	----	----	----	.007	.0
Be	.015	.0X	.001	.0003	.0007
Cu	.0015	.0X	.03	.015	.015
Pb	.07	.00X	.7	.3	.3
Sb	.02	.0X	.3	.0	.0
Zn	.02	.0X	.2	.15	.3
W	.2	X	1.0	.0	.0
F	----	----	----	----	----

	Ouray hot-spring water Sample 6		Ouray hot-spring water Sample 6
SiO_2	49	F	3.0
Fe	.42	PO_4	.06
Mn	.92	B	.23
Ca	376	H_2S	0
Mg	6.1	Solids	1,760
Na	111		
K	8.0		
Li	1.0	pH	6.8
HCO_3	128	Temperature F	143°
SO_4	1,030	Discharge gpm	15
Cl	45		

DESCRIPTION OF SAMPLES

1. Lab. No. 58-1145: U. Oda, E. F. Cooley, analysts, U.S. Geol. Survey; collected by D. E. White and R. W. Lakin, U.S. Geol. Survey; from material being deposited at time of sampling, Pavillion spring.
2. Lab. No. 52-1637: R. C. Havens, analyst, U.S. Geol. Survey; collected by W. S. Burbank and C. T. Pierson, U.S. Geol. Survey; from old travertine, Pavillion spring.
3. Lab. No. 58-1139: U. Oda, E. F. Cooley, analysts, U.S. Geol. Survey; collected by D. E. White and R. W. Lakin; from oxide vein in fissure occupied by hot waters.
4. Lab. No. 287139: N. M. Conklin, analyst, U.S. Geol. Survey; collected by W. S. Burbank and R. G. Luedke; from 5-foot rib of No Name vein, Sunnyside mine.
5. Lab. No. 287137: N. M. Conklin, analyst, U.S. Geol. Survey; collected by W. S. Burbank and R. G. Luedke; from No Name vein, Sunnyside mine.
6. Lab. No. 850: H. C. Whitehead, analyst, U.S. Geol. Survey; collected by D. E. White and R. W. Lakin; from Pavillion spring.

would involve complex solution chemistry and causes of precipitation of the different mineral aggregates, problems beyond the scope of this report.

As suggested by White (1955, p. 148),

> In general, geologists have probably had an oversimplified picture of the origin and nature of ore-bearing solutions and many have favored the derivation of most hydrothermal ore deposits from a single type of solution. The present review of hot springs and related ore deposits supports the hypothesis that some deposits were formed by solutions closely related to volcanism but that others were probably formed by circulating meteoric and connate waters.

In environments where repeated faulting and fissuring have taken place over a period of time, there would seem to be no reason why solutions of somewhat different origin could not have entered the various fissures at different times. If solutions that secreted most of the manganese and some early silica of the veins are tentatively classed as metamorphic, of intermediate depth, and if the metals and sulfur along with carbon dioxide, chlorine, fluorine, barium, boron, arsenic, and antimony are considered of deep volcanic origin, then at least three major types of solutions including the shallow waters of meteoric origin may have been involved in local mineralizing processes.

COMPARATIVE EVOLUTION OF VEIN AND CHIMNEY DEPOSITS

The evolution of the chimney deposits differs in important particulars from that of most vein deposits. The spaces occupied by chimney sulfides were for the most part the product of leaching by acidified solutions and to some extent the result of replacement. By comparison, the prime space occupied by vein deposits was produced by mechanical action, although as fissures became clogged with the abundant gangues, replacement assumed more importance as a vein process. The proportions of space filling and replacement varied considerably in both types of deposits, but precise estimates of these processes are difficult to make. In some places, vein fillings have been largely replaced by new minerals, but in other places, only moderate exchanges have taken place in the sulfide minerals. In both chimneys and veins, the partial sealing or plugging of channels, with probable rises in temperature and pressure, seem to have favored replacement action.

In general, the environment of the chimney deposits was less subjected to tensional forces than the sites of veins in arched or domed areas. Accordingly, solutions feeding from narrow channels beneath chimney deposits were less diluted with meteoric waters or with carbonatic solutions that carried manganese. Thus, chimney sulfides contain chiefly barite and fluorite, together with products of rock decomposition, as common gangues. Rhodochrosite is found locally in chimneys as small crystals in vugs, locally associated with pyrite and free gold, but large bodies of the manganese silicates are unknown in chimney deposits. These differences perhaps emphasize the points made as to possible different sources of sulfides and certain gangues.

Mineralogical differences between the sulfides of chimneys and primitive veins could be either the result of differences in dilution of the solutions, of differences in kinds of metal complexes involved, or perhaps of differences in ultimate sources. The widespread pyritization of rocks in chimney environments would seem to indicate much greater concentrations of sulfur in the solutions that formed chimney deposits than in those that formed most veins. Differences in sulfide mineralogy could in some way be related to differences in solvent properties between more primitive sulfide solutions and the diluted vein solutions. The possibility that the chimney solutions came from different magmatic sources than those of the veins finds but little support in the closely associated intrusive igneous rocks. The quartz latite and rhyolite intrusives of the chimneys and associated volcanic pipes seem to represent only minor bodies of late differentiates, which are also found in scattered positions throughout all mineralized areas.

Neither veins nor chimneys afford any definite clues to the types of solvent complexes that carried metals, although it might be suspected that sulfur complexes rather than chloride complexes were more important in chimney solutions. Very likely some kind of bicarbonate solutions and their complexes were responsible for transportation of manganese in veins. The late formation of lead and zinc carbonates in the walls of some chimney deposits could be the result of local late evolution of carbonatic solutions in chimney ground, but on the whole, calcite is not an abundant gangue of the chimney ores.

The precipitation of the sulfides in both kinds of deposits was probably related in part to throttling of solutions from positions of higher to lower pressures with attendant fall of temperature. Dilution by meteoric waters may have been an important factor in shallower vein positions, but probably was not an important factor in chimney sites.

SUPERGENE AND HYPOGENE ENRICHMENT

On the higher mountain slopes, many of the outcropping deposits probably do not lie far below the Florida erosion surface, one of the more extensive interglacial surfaces of the region (Atwood and Mather, 1932, p. 27–28). The relation of physiographic development to the distribution of high-grade ores has been discussed at some length by Kelley (1946, p. 324–341). In summary, he found that only the very shallow ores of the Engineer Mountain divide could have been appreciably affected during the Florida cycle of erosion, the most favorable period in which the ores could have been enriched. The tenor of these shallow ores, however, is not proof of enrichment but is equally good evidence that local high gold and silver values in unoxidized ores at these altitudes could have been the result of hypogene zoning. Plotting of grade of known ore shoots with respect to altitude shows no correlation.

In summation of the indications of supergene enrichment in the vicinity of the Engineer Mountain divide, Kelley (1946, p. 340) stated,

the very shallow ores protected from severe glaciation and canyon cutting along the remote Engineer Mountain divide may indicate some enrichment in or just below the oxidized zone related to the Florida surface. Although ores containing argentite and proustite at the Polar Star mine, native silver at the Wyoming mine, and chalcocite at the Frank Hough mine may owe their richness partly to supergene deposition, it seems more than fortuitous that the Wyoming ores consistently contained bismuthites known to be argentiferous and hypogene elsewhere, and that hessite occurred in the Frank Hough ores.

These deposits on the Engineer Mountain ridge are also among the very few vein deposits in which clay minerals, diaspore, and other alteration products indicative of acid-sulfate attack are found in the walls. These deposits are comparable in many particulars to those in and near the chimney ore deposits of the Red Mountain district and may merely be indicative of near-surface conditions of primary mineralization. If, as inferred for Red Mountain, throttling and some vaporization of the ore solutions was a factor in this type of alteration, both the effects of vapor loss on shallow deposition of ore minerals and the oxidizing effects of acid-sulfate waters may account very largely for the observed enrichment and leaching. In ground from which the common bases of the rocks had been leached by solfataric activity, the effects of recent shallow leaching and oxidation might well appear exaggerated in relation to their true importance. The occurrence of rich silver-copper sulfides in deposits beneath the leached ground is not believed to be fortuitous, but rather to be typical of shoots formed under conditions where loss of temperature and vaporization was promoted by abrupt decreases in pressure on hypogene ore-bearing solutions.

A few veins have much more extreme local enrichments approaching the chimney type. The richer shoots tend to be confined to chimneylike channels in the plane of the vein that, in some places, are very narrow and recognizable from one mine level to another for hundreds of feet vertically. These richer shoots are usually accompanied by differences in local rock alteration and in mineralogy of the enriched sulfide masses. Minerals indicative of enrichment in bismuth or silver may become prominent rather than sparse microscopic constituents of the ores. Deep tunnels driven to cut beneath high-grade silver shoots have repeatedly found only normal base-metal ores or ores rather impoverished in silver. A number of veins of the Poughkeepsie Gulch and Gray Copper Gulch areas of the map area are representative of this type. A typical example is the Old Lout tunnel driven to undercut the rich shallow silver ores of the Forest and Old Lout veins (Kelley, 1946, p. 388–392). The ore shoot occurred at and near a junction of these two veins and formed a fanlike downward-converging channel that may have enhanced hypogene processes of enrichment in the ore shoot. The tunnel failed to cut any recognizable downward extension of this shoot at a level about 1,000 feet below the outcropping veins. The deeper vein matter consisted of average base-metal ore containing only a few ounces per ton in silver content. Some observers have considered that the root of the rich shoot may have raked laterally beyond the deep tunnel openings, but from common experience in the district and data gathered by Kelley, it seems more likely that the richer parts of the shoot had bottomed in the upper workings. The deposit may represent a typical example of sulfide enrichment by hypogene solution and redeposition where the later solutions converged in the narrowed and chimneylike funnel formed by the intersecting vein systems.

Most veins of the central part of the Eureka district contain comparatively unoxidized sulfides at or within a few feet of the surface. Locally, as on the high ridge between California and Placer Gulches, some small bodies of impure manganese oxides were formed by oxidation of rhodochrosite-bearing vein matter. These oxides seem to have little continuity in depth, and they seem to be preserved only where the normally rapid erosion has failed to keep pace with oxidation processes.

EXPLORATION AND MINING

The geologic mapping program of the U.S. Geological Survey in the vicinity of the Silverton cauldron is intended to provide background information to guide more detailed exploration and mine-development programs by individual mining companies. Local details are discussed where they illustrate typical examples, but no comprehensive review of all mines and prospects or of all exploration possibilities or contingencies is attempted. The history of mining development in individual areas provides additional background information of value in planning exploration or development programs. More specific information covering Poughkeepsie Gulch, Mineral Point, and Engineer Mountain areas is contained in a detailed geologic report by Kelley (1946). The mining developments in Poughkeepsie Gulch and Mineral Point areas were discussed further by Hazen (1949), and mining and milling developments in the Eureka district to 1948 were described by King and Allsman (1950). The occurrences of tungsten in individual deposits and the potential of its production in the Eureka district and adjoining areas were reviewed by Prosser (1910) and Belser (1956). Many mines and prospects that were active just before and during the year 1900 in the previously mentioned areas were described by Ransome (1901).

Most mines (pl. 7) in the Eureka district are small and have been explored to only shallow depths. The exceptions are the Sunnyside mine, which has provided about 70 percent of the dollar value of ore produced from the district, and the Gold King mine, which has provided about 13 percent. More than 100 other mines are scattered throughout the district, but none has provided more than 1 percent of the value of ore produced. The ore deposits in the map area range in altitude from a little below 10,000 feet to about 13,000 feet, and the size and grade of the ore bodies differ greatly from place to place.

Because past mine development and prospecting have been generally small-scale ventures and rather shallow in many parts of the Eureka district, sustained future operations seem practicable only by means of large investments in access tunnels and deeper exploration and development work. The successful development of some groups of veins will also depend on consolidation of numerous properties, just as has occurred in the later history of adjoining districts in the Silverton and Telluride regions.

The Lake Emma-Ross Basin area is the only part of the Eureka district which has been spot tested at depth. Because of its somewhat unique structural setting in the Eureka graben, however, mineralogic and geologic factors there may not necessarily apply to the success or failure of deep exploration and development in other areas of the district.

Mining developments in different parts of the Eureka and adjoining districts are summarized by geographic areas rather than individual mines. Aside from the Lake Emma-Ross Basin and Cement Creek-Bonita Peak areas, the district includes, roughly in order of their early activity and productivity, the Engineer Mountain area, the Poughkeepsie Gulch area, the Mineral Point area, and the California Gulch-Animas Forks-Wood Mountain area. Several other small areas tributary to productive mines or sites of recent exploratory operations include upper Placer Gulch and Brown Mountain-Ironton Park.

LAKE EMMA-ROSS BASIN AREA

The Lake Emma-Ross Basin area consists of a mile-wide belt of mineralized country rock extending from the Sunnyside fault (Mastodon and Gold Prince veins) at the head of Placer Gulch westward past Lake Emma and along the Ross Basin fault in the heads of Eureka Gulch and Cement Creek to the north branch of Ross Basin at the head of Poughkeepsie Gulch. This is one of the more obvious areas of future interest for deep-level exploration; however, the deepest practical tunnels beneath the area cannot be driven below an altitude of about 10,000 feet.

The Sunnyside mine, centering near the head of Eureka Gulch just above Lake Emma, is the largest in the Eureka district, and its workings total many miles. These workings and adjoining ones explore a vertical range of about 3,000 feet and a lateral range of 7,000 feet along several combined vein systems (pl. 8). The explored veins extend from the Lake Emma workings (fig. 13) northeast toward the head of Placer Gulch and northwest toward Ross Basin. Older stopes in the Sunnyside mine were more than 50 feet wide, but the average width of shoots was about 20 feet. The important Washington ore shoot was somewhat less than 1,000 feet long and had been explored through a vertical range of about 1,400 feet when mining was discontinued in 1938.

The Sunnyside operation started with the discovery of gold on the Sunnyside claim in 1873, and from 1875 until the early 1890's, the deposit was worked with varying success; treatment of the ore was by amalgamation and small stamp mills. After the better gold shoots were exhausted, J. H. Terry took over the property in about 1890 and in 1896 installed a table concentration plant yielding lead-zinc concentrate. This operation was gradually improved and extended, and more than half a million tons of ore was treated before the property was acquired by the Sunnyside Mining and Milling Co. in 1917. A 500-ton mill constructed in 1917 was the first commercial lead-zinc selective flotation plant in North America; its capacity was increased to 1,000 tons per day in 1928. The ore was delivered from the mine terminal at 12,300 feet near Lake Emma to the head of the mill at 10,000 feet near the Eureka townsite by a 2¾-mile tramway. About 2,500,000 tons of ore with a gross metal value (before treatment) of about 50 million dollars was mined during 15 active years between 1917 and 1948 (King and Allsman, 1950, p. 70). The average grade of ore fed to the mill at Eureka was 0.06 ounce gold and 3.5 ounces silver per ton, 4.3 percent lead, 6.5 percent zinc, and 0.4 percent copper. The history of these later operations is summarized by King and Allsman (1950, p. 70–71), and part of the production record is reflected in the Eureka district production figures (table 1).

Plans to develop and mine the Sunnyside at depth were initiated by the company before mining operations ceased in 1938. At that time, preparatory work had started on a 3-mile mill-level tunnel at an altitude of 10,220 feet, just above the mill site near Eureka; this work was halted in December 1938. The American tunnel, at a portal altitude of 10,617 feet, at the Gladstone townsite has since been extended somewhat less than a mile by Standard Metals Corporation to the downward extension of the Washington vein system, and a connection has been completed to the old workings above (1960–61). (See pls. 6 and 8.) This work has extended

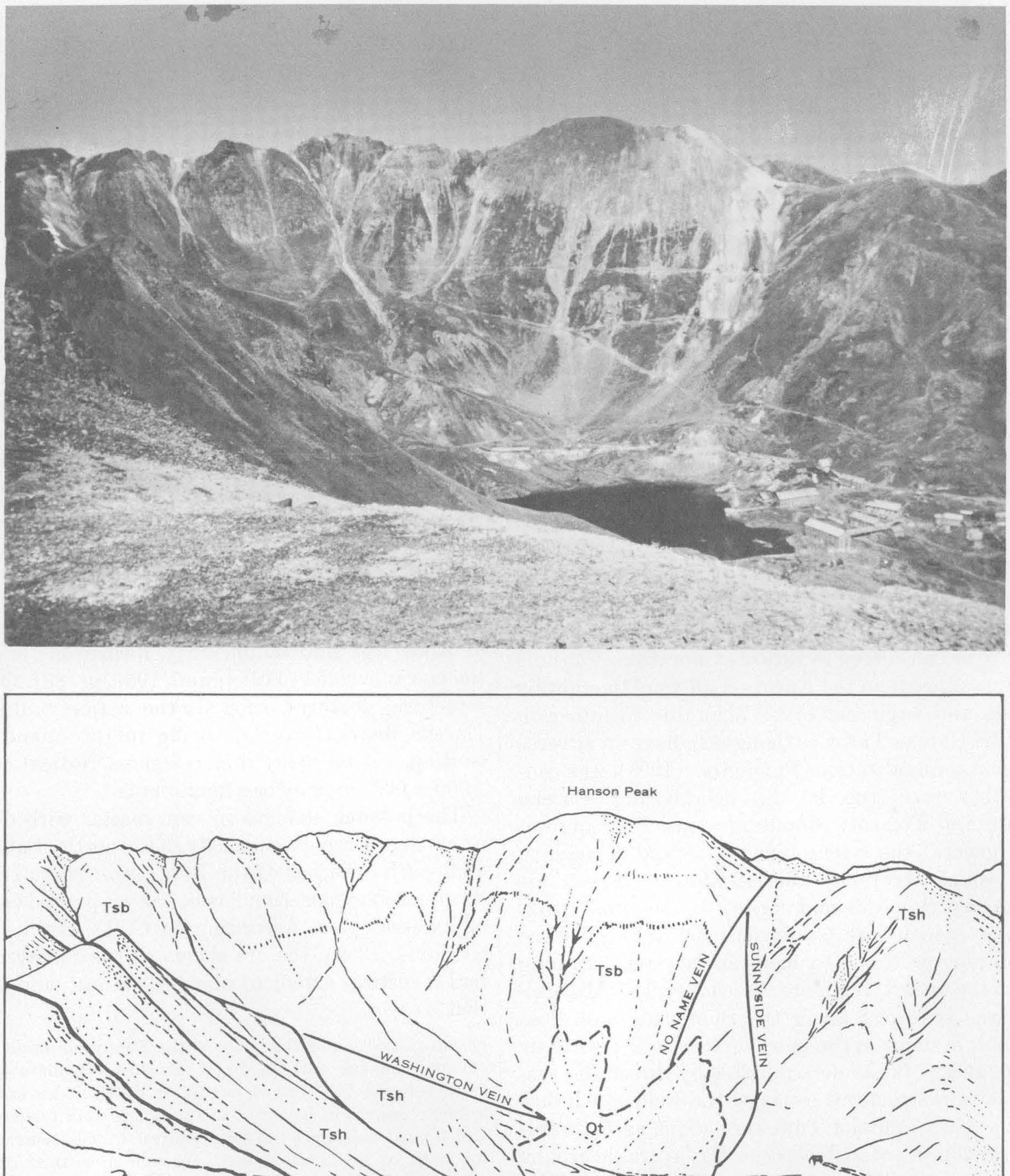


FIGURE 13.—Sketch and view looking northeast from east slope of Bonita Peak into Sunnyside Basin where the Ross Basin and Sunnyside vein systems join under talus at north edge of Lake Emma. Tsb, Burns Formation; Tsh, Henson Formation; Qt, talus. Photograph by J. H. Burbank.

vertical development on the vein to a total of more than 1,700 feet.

Several other properties in this area and near the head of Ross Basin were actively mined in the latter 1800's and early 1900's. The Great Mogul mine, near the head of the main Cement Creek valley, is said to have operated through three main adits and had workings aggregating about 20,000 feet; these workings are connected underground with those of the Sunnyside mine. The mine produced intermittently for a few years during the early history of the district. A 200-ton mill, built near Gladstone about 1906, was operated in 1907. The ore from the Great Mogul mine contained considerable pyrite and sphalerite and apparently could not be treated profitably. Other producers of silver-lead ore in upper Ross Basin include the Queen Anne and Columbia mines, described briefly by Ransome (1901, p. 257).

The principal veins in this area are associated with fractures (Eureka graben faults) that are presumed to extend to considerable depths. Mineralogic and geologic changes with depth that might have a bearing on changes in vein structure and ore deposits are considered in the following discussion.

Differences in wallrocks enclosing the vein constitute a factor to be considered in future exploration. Volcanic formations other than the Eureka Tuff were thought by geologists and engineers to be favorable to mineralization; the Eureka Tuff was thought to have an adverse effect upon mineralization. Purington (1908) was convinced this was true in the neighboring Eureka Mountain and Treasure Mountain areas. Pointing out that in general the strong Sunnyside and Cinnamon faults, which traverse the shallower flows, are underlain by rhyolites and latites, he observed "that the veins, which are so strong in the pyroxene andesite, narrow down to mere slickensided slipping planes in the underlying more siliceous rocks." Mineralization was strongest along the Sunnyside and Ross Basin fault systems in the more broken rock near their junction, and so far as determinable by direct observation at certain structural settings, the welded ash-flow materials of the Eureka Tuff were about as favorable to mineralization as the flow rocks. Unfavorable ground here would probably not be the result of change in wallrock at depth; at least, no unfavorable ground was observed at the intersection of the American tunnel extension with the Sunnyside vein system where the Eureka Tuff was found in the footwall.

Bejnar (1957, p. 171) applied statistical analysis to Ransome's production figures of 1901 to determine the favorableness to mineralization of different formations in the Silverton quadrangle. He showed that the San Juan Formation and the Burns Formation, as classified in this report, are the most favorable by far. In view of the areal distribution of the formations in ground above valley levels, the greater favorableness of the Burns rocks is bound to hold for most of the Eureka district. In some areas, the depth of burial of the Eureka Tuff, Picayune Formation, and San Juan Formation (if present at depth) would constitute an unfavorable factor with respect to vertical zoning and widths of veins.

Changes in the widths of the veins with depth are also a factor to be considered in future exploration. The relatively wide veins of the Sunnyside system at and near the surface, locally with a width of several tens of feet, seem to diminish in width downward where the fracturing was more confined and the resulting openings were smaller and more discontinuous. Ore shoots that may be found in other parts of this area will more probably be associated with softer walls, brecciated bodies of rock, and gougy fissures. Downward thinning has been observed in so many places in so many veins explored at depth that it may be predicted with some assurance; however, depths at which vein thinning takes place are difficult or impossible to predict. Development has been carried on in some veins west of the Silverton cauldron through a vertical range of 3,500 feet into sedimentary formations underlying the volcanic rocks (Hillebrand, 1957, p. 180). On strong structural features, such as the major faults of the Eureka district, open fissuring might extend equally as deep, but on many minor fissures vertical ranges of 1,000–2,000 feet may be a maximum.

The possible changes in vein matter with depth are of much concern, particularly in the north (Lake Como) and south branches of the Ross Basin part of this area where deep exploration has not as yet proved continuity of exposed ores. According to C. D. Hulin (written commun., 1932), the ore shoots of the Sunnyside mine had a vertical extent of about 2,300 feet, and he stated that

> casual inspection of the veins of the Sunnyside mine shows no obvious changes with depth. A detailed consideration of the ratio between the several metals at different horizons within a single ore shoot, however, brings out certain regular changes which must be assigned to zonal control. Calculations were made for each of six levels spaced through a vertical distance of about 800 feet within a single ore shoot. For each level the ratio of each metal to lead was calculated using all available samples. It was found that the ratio of gold, of silver, and unexpectedly of copper to lead showed respective regular decreases with increasing depth. Zinc, in contrast, showed no regular change in its ratio to lead, the ratio varying in a purely erratic manner from level to level.

This decrease in the ratio of copper to lead is not in accordance with commonly accepted zoning relations, but, as will be noted for other areas in the Eureka district and parts of adjoining districts, abnormal concentrations of copper, silver, and gold at rather shallow depths are very common in veins of this area. For the most part, these shallow shoots of rather high-grade ore represent the late stages of the compound veins (p. 39, 47).

Our observations of the Washington vein (Sunnyside mine) at the surface and at the new deep American tunnel level likewise suggest no apparent changes in the base-metal vein matter with depth, except in the amount of gangues. The very wide masses of rather barren quartz and rhodonite at the surface diminish with depth. Sphalerite is generally dominant in the ores, as shown by the ratio of zinc to lead of about 1½ to 1 in the average mill feed of the Sunnyside mine; however, in the ores of the Belcher, Bonanza, Queen Anne, and other mines of the Lake Como part of Ross Basin, zinc and lead are more nearly equal, and lead locally may somewhat exceed zinc in the exposed ore bodies extending to an altitude of more than 12,500 feet. These differences are not very significant, and it can be assumed that in general there will be little change of the metal ratio with depth and that zinc will be the dominant metal. Strong zoning of the base-metal constituents of the veins does not appear characteristic of local environments. On the other hand, diminution in the gold and silver content of veins may be expected with depth, as is generally true of epithermal types of deposits. The early base-metal and late silver-gold stages of mineralization should be considered in different categories with respect to vertical zoning effects.

CEMENT CREEK-BONITA PEAK AREA

The roughly triangular Cement Creek-Bonita Peak area, including Bonita and Emery Peaks near its center, lies south of the Lake Emma-Ross Basin area. It is bounded on the northeast by the Ross Basin fault, on the southeast by McCarty Basin, and on the west by Cement Creek and the South Fork of Cement Creek. The area is of particular interest because of its structural setting and because situated within it is the Gold King mine which was the second most important producer in the Eureka district. Also included in this area are the Lead Carbonate mine and smaller mines and prospects along the South and Middle Forks of Cement Creek, along the upper part of Eureka Gulch below Lake Emma, and within McCarty Basin. Some details of the geology of the Gold King and neighboring deposits as exposed in 1900 are given by Ransome (1901, p. 254–257).

The Gold King mine (pls. 7, 8), about a mile northeast of Gladstone, is credited with a production of 711,144 tons of ore that yielded $8,385,407 in gross value of gold, silver, lead, and copper (Colorado Mining Association, 1949, p. 126). None of the zinc in the ore was recovered. Mine workings reached a depth of 1,800 feet below the highest outcrops, but the ore came chiefly from the upper 1,000 feet of mine workings, above an altitude of 11,400 feet. A deep-level exploratory and development tunnel (American tunnel), starting near the old millsite at Gladstone at an altitude of 10,600 feet, was driven 6,233 feet northeastward, but it has not been connected with the workings more than 800 feet above (pl. 6). This tunnel has since been extended to the Sunnyside mine workings (1960–61), but no additional work has been done on the Gold King vein. A brief description of the veins and earlier operations is given by Ransome (1901, p. 254–256).

The old Gold King adit to the first level of the mine is at an altitude of about 12,160 feet on the slope of the gulch above the North Fork of Cement Creek. The adit was driven about 700 feet slightly west of north to the intersection of the Gold King lode. At this point of intersection, the Gold King vein is offset 30 feet by the so-called Red vein, the northeast extension of the Gold King being offset to the northwest. Judged from surface exposures of the Bonita Peak fault, the Red vein is along or near the faultline and, according to Ransome dips 75° NE. at this position. As shown on plate 8, most of the stopes of the Gold King mine lie west of and in the footwall of the fault zone. The second level was extended nearly 1,000 feet east of the fault, and in 1920 and later, some ore was mined from stopes mainly at and below this level.

The ore occurs in two nearly parallel stringer lodes, the Gold King and the Davis, of irregular N. 60° E. strike. The Gold King on the northwest dips 70°–80° SE., whereas the Davis is nearly vertical or dips somewhat northwest. The lodes are said to be about 50–80 feet apart in the upper levels and to converge at depth. According to Ransome, the Gold King lode was irregular, tending to split into two or more lodes of varying strikes and dips. About 400 feet west of the adit crosscut on the first level there was a large flat body of ore nearly continuous with the Gold King lode. Ransome interpreted this ore body as lying upon a large horse of altered country rock between irregular stringer branches of the Gold King lode.

The ore of the Gold King was mainly banded quartz and pyrite, but the lodes contained some bunches of fine granular galena, sphalerite, chalcopyrite, and unidentified silver minerals. The richest concentration of gold was in white quartz, but locally in the Davis lode, gold was also associated with pyrite. The Red vein contained bodies of rhodonite, but so far as known, it was not commercially mineralized in this vincity. The overall suite of minerals and vein textures indicate intermittent fracturing and reopening of the fissures, but for some obscure reason, the rhodonite seems to have been confined to cross fracturing along the Bonita Peak fault line. Possibly most of the minor sulfides other than pyrite belong to the late gold-quartz stage of mineralization in this area, formed after the base-metal and rhodonitic stages. The abundant pyrite could represent iron derived mainly from the highly fractured and silicified zone of wallrock.

The Lead Carbonate mine (King and Allsman, 1950, p. 77–79), about 2,000 feet south of the Gold King mine at an altitude of 11,356 feet, was developed on veins in a structural position similar to those of the Gold King system. The Lead Carbonate property (fig. 14) was prospected and had minor production in the early days of mining, but prior to 1946, the mine workings were less than 400 feet deep and 1,000 feet long. The mine was reopened in 1946, and for a period of several years was one of the principal producers in the vicinity of Gladstone. Until milling operations on the property began during 1947 with the construction of a 50-ton mill, the mine yielded 6,248 tons of ore with an average grade of 0.79 ounce gold and 9.7 ounces silver per ton, 6.05 percent lead, 5.9 percent zinc, and 1.03 percent copper (King and Allsman, 1950, p. 78).

The dominant structural features of the Cement Creek-Bonita Peak area are the Bonita fault ("sole") and McCarty Basin extension of the Toltec fault

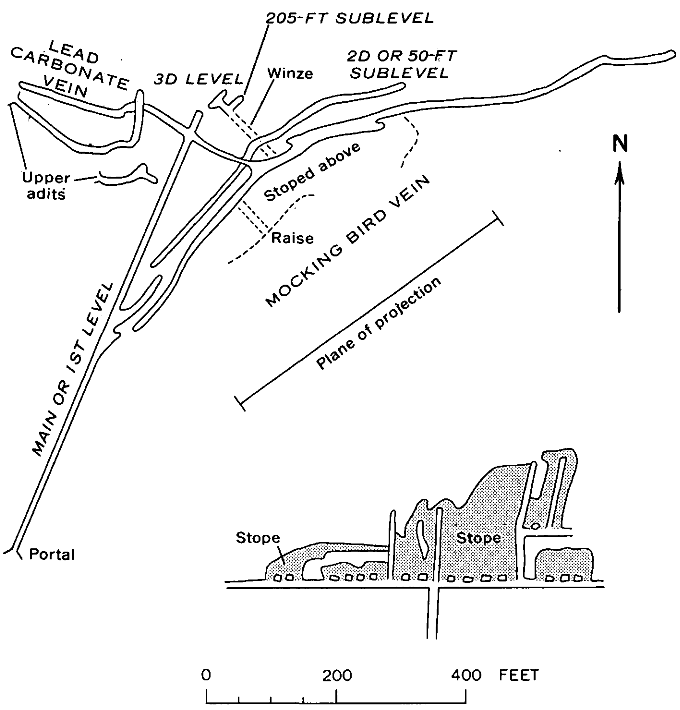


FIGURE 14.—Plan map and vertical projection of workings, Lead Carbonate mine.

("heel") of the boot-shaped Eureka graben (pls. 2, 6). The downdropped triangular wedge or keystone block, referred to as the Bonita Peak block, forms the southwest termination of the graben. The Bonita Peak block is broken into smaller blocks that have settled differentially but without very large displacements between them, as indicated by faulted tuff beds in the Henson Formation adjacent to Bonita Peak.

The interior of the Bonita Peak block is weakly mineralized. Remarkably, the Sunnyside strongly mineralized zone in the Lake Emma-Ross Basin area apparently does not extend into the block southwestward beyond Lake Emma. Both the Gold King and Lead Carbonate vein sets are strong outside the block but are weak within it. A series of short diagonal veins in the Ross Basin part of the block (pls. 2, 6) do indicate a probable trend line of the Gold King vein set south of the Bonita fault as an extension of the Mountain King and Mountain Queen vein sets north of the Ross Basin fault. The Lead Carbonate and nearby veins south of the Gold King set likewise are indicated in the hanging wall of the Bonita fault by altered sheeted zones roughly parallel to the general trend of the Sunnyside fault. It does not seem likely, however, that the strength and continuity of these trends and zones within the Bonita Peak block will improve appreciably at moderately greater depths. This assumption is attributed to the wedging action of the downdropped block which may have tended to tighten fissures within the graben block and to dilate the fissures outside the block. Most of the fissures probably originated from the same tensional stresses that formed the graben.

Local concentration of gold in ores of the Gold King and Lead Carbonate veins in the footwall of the Bonita fault just outside the Bonita Peak fault block probably indicates that there are favorable places to prospect along other east- or northeast-trending veins in the footwall at the southwest boundary of the block. In both the Gold King and Lead Carbonate vein systems, the gold-bearing ores extend about 1,000 feet outward from the wall of the Bonita Peak fault block, but no data are available as to the changes in gold content of the ore shoots either laterally or vertically. The Gold King ores seem to diminish in average gold content with depth, as is generally true elsewhere.

The Ben Franklin and other short veins along the edge of the block just west of where the Toltec fault crosses Eureka Gulch do not seem to have been notably enriched in gold, but records of production and grade of ore are meager.

In McCarty Basin on the southeast side of the Bonita Peak block, fissuring and mineralization seem to be relatively weak in the footwall of the fault extending southwest from the Bavarian vein (pl. 2), but this area has not been mapped and studied in detail.

The south corner of the Bonita Peak fault block beneath Emery Peak is of interest because it represents a junction between the Bonita fault and the extension of the Toltec fault (pl. 6) comparable to the junction between the Sunnyside fault and Ross Basin fault. The interior block here, however, forms a common hanging wall instead of a common footwall. This area has not been mapped and studied in detail, but there are veins of prospective interest south and west of Emery Peak.

ENGINEER MOUNTAIN AREA

The Engineer Mountain area lies astride the Engineer-Seigal Mountain ridge and includes mines 12,000–13,000 feet in altitude in Hinsdale, Ouray, and San Juan Counties (pl. 2). It is credited with a gross production of nearly a million dollars, of which about $600,000 came from the Frank Hough mine in Hinsdale County. The geology, mineral resources, and mine development and history have been described and discussed by Kelley (1946, p. 452) and Ransome (1901, p. 189).

Many of the ores mined were rather high grade and occurred in narrow veins having rich pockets; consequently, ore values were often high for the small tonnages produced. The Frank Hough mine is specifically credited with producing only about 5,100 tons of ore, but this figure may not be complete. This mine, in the headward basin of Palmetto Gulch, began operating in 1882 and eventually produced through a 425-foot shaft from which short levels were driven. The higher grade ore formed irregular or flat shoots in tuffs interbedded with flows in the Henson Formation and probably was formed by replacement and impregnation of the tuff. Fissures along the line of the ore body are said to have been rather tight where they passed into the underlying and overlying more massive volcanic flow rocks. The ore was notable for its high content of copper and silver, and many shipments contained as much as 25 percent copper and from 30 to 60 ounces of silver. A reported 3,081 tons of ore shipped between 1908 and 1920 yielded 1,572,824 pounds of copper, 226,734 pounds of lead, 483 ounces of gold, and 112,224 ounces of silver (Kelley, 1946, p. 455). Ores in other veins of this area were also high in silver and gold, but contained more lead and zinc and less copper proportionately.

The Polar Star mine on Engineer Mountain ridge, with an output estimated near $250,000, is probably the next most productive mine in this area. A quartz vein 3–4 feet wide was mined for rich silver and gold ores near the top of the ridge; below an altitude of 12,800 feet the ore is said to be of lower grade. Other mines include the Palmetto, Engineer, Wyoming, and Mammoth.

The problems of hypogene versus supergene enrichment of the ores in this very high area are considered on pages 54, 55 in this report and also by Kelley (1946, p. 324–341) and Ransome (1901, p. 132–141).

Northwesterly-trending structural features south and west of Engineer-Seigal Mountain ridge may have had some influence on individual veins of the general northeast-trending system (pl. 2) and may possibly have been in part responsible for local strength of mineralization beneath and on the ridge.

POUGHKEEPSIE GULCH AREA

Excluding production of the Mountain Queen mine, the total production from the drainage area of Poughkeepsie Gulch is estimated between $700,000 and $800,000 through the year 1946 (Hazen, 1949, p. 10–11). Poughkeepsie Gulch is a deep glaciated valley containing many mines and prospects (pl. 2), but there has been very little prospecting or exploratory activity in recent years. This area has been described geologically and economically by Hazen (1949), Kelley (1946), and Ransome (1901).

The largest single producing mine, the Old Lout, yielded bismuth-bearing silver and base-metal ore reportedly worth $300,000–$400,000 in gross value. This mine is of particular interest because it is one that has been explored at depth in this part of the map area. The older workings consist of an inclined shaft about 475 feet deep, and levels extend laterally from it. The collar of the shaft is at an altitude of 11,557 feet on the east lip of Poughkeepsie Gulch. A crosscut tunnel was driven at an altitude of 10,565 feet near the bottom of the gulch beneath the older shaft workings; this main tunnel is 1,865 feet long and has more than 1,700 feet of drifts, crosscuts, and raises extending from it. The inclined shaft developed the Old Lout vein near its Y-shaped intersection with the lower grade Forest vein. Very rich ore was mined in the upper levels, but the grade diminished with depth; at the lower tunnel level, a vein averaging 30 inches wide contained 0.05 ounce gold and 10 ounces or less silver per ton, 4 percent lead, 2 percent zinc, and 1 percent copper. There has been some debate whether the most favorable structural position was explored at depth. As shown by Kelley's geologic mapping (1946), the upper 400 feet of workings was chiefly in the Burns Formation, whereas the deeper workings were in the Eureka Tuff.

A similar early profitable history is recorded for many other and mostly smaller properties of the area, which were attractive chiefly during the period of high silver prices and when economic conditions permitted small operators to explore shallow shoots and mine very selectively.

The Lake Como area near the head of Poughkeepsie Gulch is in a structural province tributary to the north side of the large Ross Basin fault (pls. 2, 6). Kelley (1946) noted more than 150 prospects and mines within an area of about 1½ square miles, but none has been prospected deeper than about 200 feet. Numerous small rich ore pockets are said to have been found. The Alaska mine was reported by Ransome (1901, p. 195) to have produced about $90,000 of silver-bearing ore, most of which came from a single small ore shoot along or near a fault fissure. The fissures become stronger and more numerous to the south, and near Lake Como they contain wide veins composed of barren or low-grade quartz intergrown with rhodochrosite and rhodonite and enclosing lenses and streaks of base-metal sulfide ore.

As previously mentioned (p. 58), a concentration of north-striking veins on the north side of the Ross Basin fault in Ross Basin (pl. 2) may be worthy of further deep exploration because of the possibility that structural control caused some silver or gold enrichment. These veins are generally narrow except close to the fault where they widen abruptly for a few hundred feet (fig. 6*B*).

MINERAL POINT AREA

The Mineral Point area as defined by Kelley (1946, p. 419) covers about 3½ square miles between Poughkeepsie Gulch on the west, Engineer Mountain on the north, the California Gulch divide on the southeast, and the Canadian Lake basin on the southwest. It is a high rolling glaciated country (fig. 15) that has many small lakes and swamps and that is between 11,500 and 12,000 feet in altitude. Mining activities in this area have been discussed by both Kelley (1946) and Ransome (1901).

The principal mines were operated through shafts, mostly less than 300 feet deep; the largest of these mines are the Bill Young, Red Cloud, Ben Butler, San Juan Chief, and London (pl. 2). The Red Cloud vein along the south margin of this area is perhaps the most extensively developed both laterally and vertically. About 665 feet below the collar of the Red Cloud shaft in Burrows Gulch and connected by a raise to the lower mine workings is the Frisco (or Bagley) tunnel, which has its portal at an altitude of 11,430 feet in lower California Gulch south of this area. Kelley (1946, p. 444–445) remarked upon the apparent decrease in the number and complexity of vein systems, indicated on the Frisco-tunnel level map, compared with their number in the near-surface shaft workings above, and he considered that it might be due to differences in susceptibility to fracturing of the Eureka Tuff at the deeper level as compared with that of the flow rocks of the Burns Formation above.

Many veins in the Mineral Point area, as in neighboring areas, contained high-grade pockets of silver and gold ore in quartz or associated with sulfides. Accurate records of the production of the Mineral Point mines are not available, but the total yield was probably less than in the Engineer-Seigal Mountain and Poughkeepsie Gulch areas. Early records credit the Red Cloud mine with an output of about 800 tons of galena and gray copper ore during development work between 1874 and 1880; production after 1900 was through the Frisco tunnel. Small shipments have been made from some mines since 1900 and most recently from the London, Ben Butler, and Lucky Jack in 1948 and 1949. Some new development work was also done at the Lucky Jack property just northeast of Denver Lake (pl. 2) on ore consisting chiefly of sphalerite and silver-bearing galena.

CALIFORNIA GULCH-ANIMAS FORKS-WOOD MOUNTAIN AREA

The California Gulch-Animas Forks-Wood Mountain area includes the main glacial valley of California Gulch, Houghton Mountain, the Animas River valley at and above Animas Forks, and Wood Mountain (pl. 2). The more important prospecting and mining operations have been along the north wall of California Gulch from the Mountain Queen mine at the extreme head of the valley to the Columbus mine at Animas Forks. Veins in much of the area tend to split, to turn, or to jump diagonally from one set of fissures to another, and veins or fissure zones of one mine cannot be correlated with any assurance with those of another over any appreciable distance. The veins belong to three groups: one group at the extreme head of California Gulch in which the east-west trending set of upper Poughkeepsie Gulch tends to be dominant or to form junctions with a northeast-trending set, another group in the remainder of the area in which the northeast-trending fissure set is dominant, and a less pronounced group in the Animas Forks-Wood Mountain part in which a north-northwest-trending fissure set, consistent with the ring-fault belt of the Silverton cauldron, is prominent in addition to the northeast-trending set.

Through the early 1880's, the first period of activity in this area, which included the early operations at the Mountain Queen mine and the mines of the Mineral Point area to the north (pl. 2), the town of Animas Forks had several mills, one to treat ore from the Red Cloud mine, and a smelter. All, however, failed

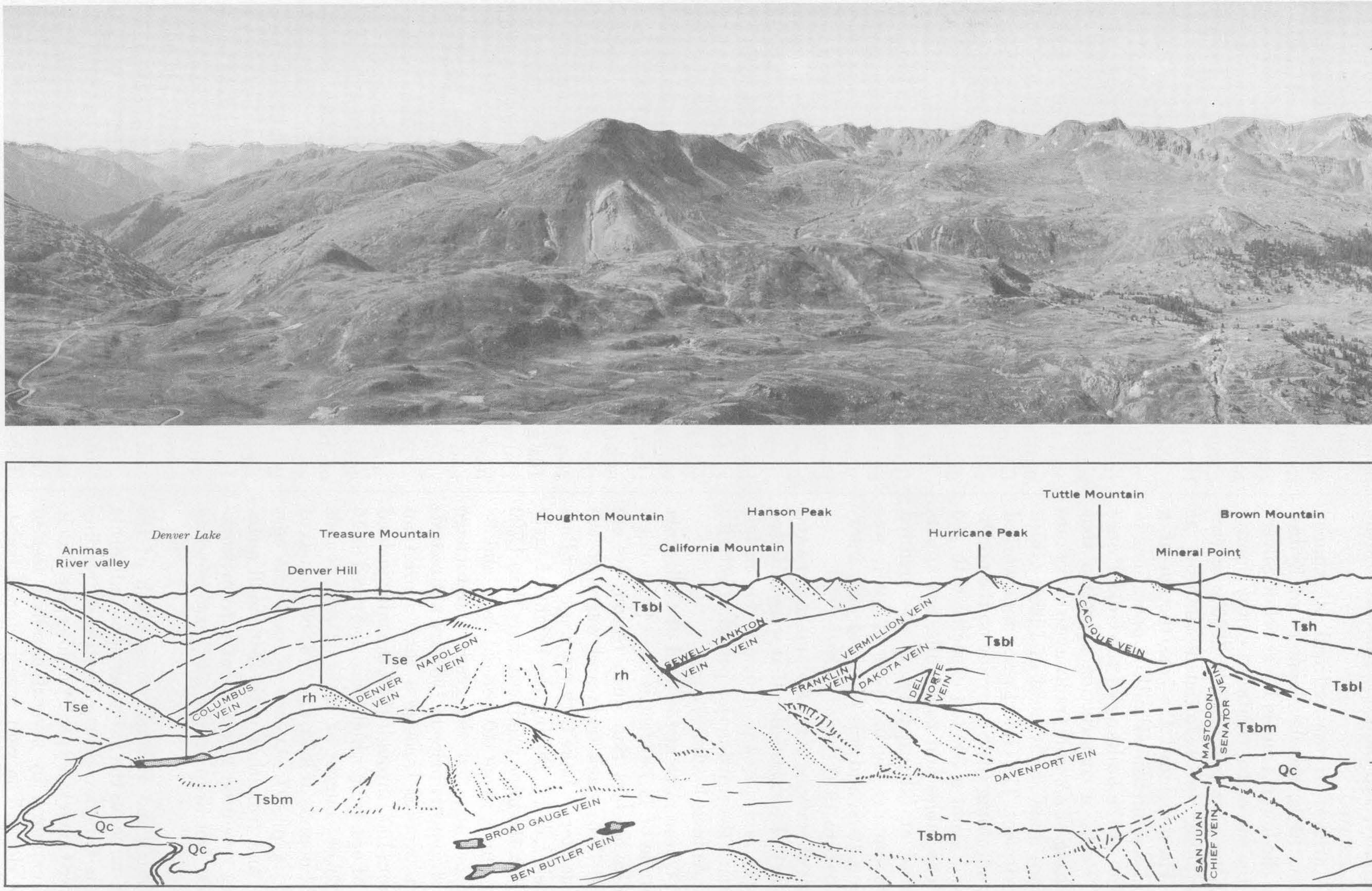


FIGURE 15.—Sketch and view, looking southwest, of some of the rock units and veins in the Mineral Point area. Tse, Eureka Tuff; Tsbm, Mineral Point dome rock of Burns Formation; Tsbl, flow-layered unit in the lower member of the Burns F ormation; Tsh, Henson Formation; rh, late intrusive rhyolite; Qc, colluvial deposits.

to operate successfully, and before the late 1890's the town was almost deserted.

Following the arrival of the railroad at Animas Forks in the late 1890's, the development of hydroelectric power on the lower Animas River below Silverton in 1906, and the successful treatment of the Sunnyside and Gold King ores in the early 1900's, several ambitious undertakings were initiated centering at Animas Forks. They included the construction of a larger tunnel and the intensified milling operations in California Gulch and the building of the Gold Prince mill at Animas Forks, a construction operation that included the building of a 2-mile tramway to carry ores of the Gold Prince mine at the head of Placer Gulch to the mill for treatment. The Gold Prince mine worked the vein systems adjoining the Sunnyside on the northeast. The mill had about a 500-ton capacity with 100 stamps and various tables and tube mills, but apparently never worked at full capacity. It was credited with appreciable tonnage during part of 1907, was inoperative during 1908, and was operated only intermittently from 1909 to 1910.

The more recent operations at the Columbus mine and other properties in California Gulch that were initiated by World War II and postwar demands for metals may be said to mark the third major period of activity centering around Animas Forks.

The Mountain Queen mine at the head of California Gulch at an altitude of 12,790 feet is one of the oldest mines in the entire western San Juan region; its ore was shipped in 1877 by pack train and wagon to the Crooke and Co. smelter at Lake City via Engineer Pass and Henson Creek (pl. 4). During the height of early activity, about 1882, the mine produced more than 1,700 tons of ore containing about 40 percent lead and 38 ounces of silver per ton, but the grade and tonnage of other specific shipments prior to 1900 are not recorded. The mine was worked through a shaft more than 400 feet deep. From 1900 through 1946, the mine yielded about 3,500 tons of ore, from which were recovered 82.16 ounces of gold, 26,663 ounces of silver, 25,401 pounds of copper, 531,931 pounds of lead, and 278,339 pounds of zinc (Hazen, 1949, p. 10). An access road was constructed in 1944, and from then until 1946 small quantities of ore were produced intermittently from workings less than 100 feet deep on the northeast-trending part of the vein.

The Indian Chief and Belcher veins, north of the Mountain Queen mine on the ridge between California and Poughkeepsie Gulches, belong to an east-trending vein set near Lake Como in upper Poughkeepsie Gulch. The Belcher is explored by several hundred feet of workings on the ridge. The vein zone included bodies of altered rock 50–150 feet wide. Veins of quartz and rhodonite with streaks and lenses of pyrite, sphalerite, and galena were formed in part by fissure filling and in part by replacement of the sheeted wallrock. As reported by Hazen (1949, p. 39), the vein consists of local and small segregations of lead-zinc ore in much gangue. Precious metals are erratically distributed in the vein.

Near the crest of the ridge north of the Belcher vein and about half a mile south of Tuttle Mountain, the junctions of the east-trending vein sets with the northeast-trending vein sets form a complex system of veins and a large altered and silicified patch of rock extending northeast along the Oberto-Starlight vein to the Silver Chord mine. Numerous small workings on these various veins and vein intersections indicate small production during prospecting operations.

Prospecting and mine development in California Gulch extend from the Little Ida and Burrows veins on the valley wall east of Tuttle Mountain north to the Vermillion mine in the "saddle" between Tuttle and Houghton Mountains. Bodies of silver-lead and lead-zinc ore were mined from the Little Ida property from adits between 12,500 and 12,700 feet in altitude. The largest ore bodies seem to be at Y-shaped junctions formed by intersecting northeast- and north-trending veins. In 1947, a new operation was started lower on the valley wall at about 12,000 feet in altitude to crosscut the Little Ida vein system. In the next few years, a minor quantity of ore was produced from operations on the westward extension of the Burrows vein, about 500 feet south of the Parallel vein and others of the Little Ida group. About 1,000 tons of ore was mined from the Burrows vein by other operators; the ore is reported to have contained about 16 percent zinc, 10 percent lead, and 3 ounces of silver per ton (King and Allsman, 1950, p. 58).

The Vermillion mine is at an altitude of 12,436 feet just north of the Burrows mine (Kelley, 1946, p. 445–447). Operations through a short crosscut tunnel were on the Vermillion Extension No. 1 near several intersecting veins. A deeper-level crosscut was started near the bottom of California Gulch (alt 11,869 ft), but this may not have extended beyond the Burrows vein. In 1910, the Vermillion Co. milled 2,736 tons of ore from which was recovered 27 ounces of gold, 5,250 ounces of silver, 1,998 pounds of copper, 217,500 pounds of lead, and 201,873 pounds of zinc (Kelley, 1946, p. 447).

The largest exploratory operation in California Gulch was the former Bagley adit, now generally known as the Frisco tunnel, about half a mile up California Gulch from Animas Forks at an altitude of 11,430 feet. This adit was projected to crosscut the vein systems of the Mineral Point area to the north. The tunnel cut the Dakota vein at about 5,800 feet in 1908. In all, about 9,000 feet of work was done, including drifts on four veins and a raise of 315 feet to the Red Cloud mine (p. 62). Although the location of the ore bodies is not fully known (Kelley, 1946, p. 439), in 1913 and 1914, 7,166 tons of ore was produced from the tunnel, from which was recovered 92.5 ounces of gold, 13,363 ounces of silver, 11,177 pounds of copper, 326,404 pounds of lead, and 119,451 pounds of zinc.

Since 1945, the Columbus mine, just above the junction of California Gulch and the Animas River valley at Animas Forks, has probably yielded the largest tonnage of ore of any operation in this immediate area. The mine is reported (Colorado Mining Association, 1949, p. 128) to have yielded as much as 6,000 tons of zinc-lead ore in a year. The grade of the ore was low and the cost of transportation to mills for treatment was high; operations were suspended several times and finally closed completely after premium payments for lead and zinc were discontinued in 1948.

The Columbus mine is on a large mineralized fault zone that trends N. 50° E. across Wood Mountain. It was operated through a 1,200-foot crosscut tunnel at an altitude of 11,230 feet, and all development work was within 500 feet of the surface. The quartz and base-metal sulfide vein occupies a steep and somewhat gougy fault fissure 10–20 feet wide. The ore mined was reported (King and Allsman, 1950, p. 61) to have contained 8–14 percent combined lead and zinc and 2 ounces of silver per ton; the copper content was low.

East of the Animas River valley, the Wood Mountain fault zone (pl. 2; fig. 3) has been the most productive in this part of the area. It has been prospected to a minor extent throughout its exposures to the east ridge of Wood Mountain on the Bob Ingersol claim. A quartz vein, in places 30–40 feet wide on the Eagle Bird claim at the head of the glacial cirque of Horseshoe Basin Creek, has a low metal content; small bodies of galena and sphalerite ore are exposed alongside this quartz and in some of the diagonal veins crossing the main vein or branching from it. The altitude difference between these veins and those at the Columbus mine at Animas Forks indicates a vertical range in sulfide shoots of about 2,500 feet. The possibility of lateral changes in mineralization is not entirely eliminated, however, as only shallow tunnels have penetrated the mountain.

The strongest single structural feature in this area is the Wood Mountain fault zone, which can be traced from the Columbus mine through and northeast of Wood Mountain for more than a mile in Hinsdale County; its downthrown block is on the south (pls. 2, 6). Northwest of the fault are several minor branching nearly parallel faults and fissures. The large amount of low-grade quartz along the main fissure following the high ridge of Wood Mountain suggests that at high levels considerable dilution of sulfide ore by relatively barren gangue is to be expected. The relative proportion of quartz gangue and silicified wallrock to sulfides will probably tend to decrease somewhat in depth. Veins on the southwest and west slope of Wood Mountain below an altitude of about 12,300 feet commonly contain much less quartz in proportion to vein carbonates and "talcy" gangues.

On Wood Mountain between the Wood Mountain and Cinnamon faults (pl. 2), many smaller fissures and faults form diagonal linkages between these two major faults. Several of the larger diagonal linking veins in the hanging wall of the Wood Mountain fault on the south ridge to Wood Mountain contain shoots of galena, sphalerite, and chalcopyrite ore with associated gangue of quartz and manganese- and iron-bearing carbonates. Massive rhodonite bodies particularly characteristic of veins southwest of this area are not so typical of the veins here, but the manganiferous carbonates may represent in part thoroughly recrystallized and carbonatized remnants of rhodonite bodies. This process in its incipient stages was described with respect to the rhodonite veins of the Sunnyside mine (p. 33).

Of particular prospecting interest in the Animas Forks-Wood Mountain area are the numerous small faults, fissures, veins, and sheeted or brecciated zones of north-west strike (N. 10°–20° W.) which gradually turn more northwestward to merge with fracture lines (N. 65°–70° W.) north of Mineral Point (pl. 2). In general, they belong to the ring system of the Silverton cauldron. Several small volcanic plugs and intrusive bodies lie within and along the belt of fracturing; it is noteworthy that the intrusive rhyolite of Denver Hill ends abruptly at a southeast-trending dike that parallels this belt. Ore shoots in several of the diagonal northeast veins on the southwest ridge of Wood Mountain are deflected toward or end abruptly at cross fractures of northwest strike. The effects of such cross fracturing on the northeast vein systems and ore shoots are worth particular attention in future exploration and development in this area.

TREASURE MOUNTAIN-EUREKA MOUNTAIN AREA

The area south of Animas Forks and California Gulch and bounded by the Animas River gorge on the east, by the ridge of California Mountain on the west, and by Eureka Gulch and the Sunnyside area on the south has been the scene of considerable mining and prospecting activity. Included in this area are the large glaciated valley of Placer Gulch, the high shallow cirquelike basin of Picayune Gulch, and the high ridgelike Treasure and Eureka Mountains.

Mine developments at the head of Placer Gulch, centering in the Gold Prince and other properties adjoining the Sunnyside fault zone, were by far the largest; they were mentioned briefly in connection with the milling operations at Animas Forks (p. 64). Mines in and tributary to Placer Gulch included the Hidden Treasure, Silver Queen, Sound Democrat, Mastodon, workings on the Evening Star and Morning Star veins, the Wexford adit on the Independence vein, and other small prospecting operations on the slopes of the gulch. Early history of some of these mines has been recorded by Ransome (1901, p. 179–182), but details of later development coincident with the larger milling operations in the vicinity are not fully recorded, and many of the mines are no longer accessible. Ore from some of the mines was treated in the larger mills, such as the Mastodon mill near the head of Placer Gulch, a few hundred feet south of U.S. Mineral Monument Placer Gulch, and the Gold Prince mill at Animas Forks. Several smaller mills were also constructed in the gulch to operate on locally derived ores. As in the case of the Gold Prince mill, none achieved sustained profitable operations on the lower grade ores of the area. The production record of the Placer Gulch mines is obscured in the total output of the Eureka district as this output is dominated by the Sunnyside and Gold King mines, but probably the ore treated or shipped has exceeded 100,000 tons, exclusive of the Gold Prince and other veins at the extreme head of the gulch, which were generally included as part of the production of the Sunnyside group.

On Treasure Mountain adjacent to Picayune Gulch and the Animas River valley are several mines that achieved some early fame as producers of high-grade silver and gold ores. The best known of these are the Golden Fleece, Scotia, and San Juan Queen mines (Ransome, 1901, p. 182–183). The Golden Fleece and Scotia claims, at an altitude of more than 12,300 feet on the central ridge of the mountain (pl. 2), yielded a free-gold ore consisting of dendritic gold in a gangue of quartz and manganiferous calcite. Early operations were prior to 1900, but in 1908 a new crosscut to the vein was driven below the older workings, and a small quantity of ore was produced from these veins in following years. Most of the higher grade ore came in part from the rather narrow N. 75° E.-trending Golden Fleece vein; the character of the ore is not on record. Some ore was produced also from the much wider and lower grade N. 45° E.-trending Scotia vein near the intersection with the Golden Fleece vein and less than 100–200 feet beneath the surface. (See pl. 2; fig. 6*F*.)

Since about 1937, parts of the Treasure Mountain area have been explored at depth through the Sandiago tunnel of the Treasure Mountain Gold Mining Co. located in Picayune Gulch at an altitude of a little more than 11,600 feet. These workings consist of a 1,600-foot crosscut northwest to the Scotia vein at a depth of about 1,000 feet beneath the surface and of about 700 feet of drifting to the southwest parallel to the Scotia fault. Further crosscutting and diamond drilling have been done to explore positions vertically beneath the old Golden Fleece workings. The ores found at depth in the wide northeasterly veins are similar to the ores exposed near the surface and are characteristically composed of quartz, rhodonite, and carbonate gangues, which, except for local shoots and pockets, generally have a low average lead and zinc content. Diamond drilling was also initiated in the search for continuation of gold-quartz vein matter in depth, but as of 1948, the development work had not established the size and structural relations of the diamond-drill showings.

The San Juan Queen mine, opened in about 1890, had about 500 feet of tunnel and some shaft workings. It yielded small lots of high-grade gold and silver ore. The vein strikes about east and dips steeply south. It has been explored near its intersection with the eastward continuation of the Great Eastern fault zone; some high-grade ore pockets were found near this intersection which are related to and localized by cross fissures near the northeast system of faults. Ransome (1901, p. 183) reported that as of 1900, about 10 tons of ore had been shipped, and that the best grade ore was said to carry about 5½ ounces of gold and 180 ounces of silver.

The Toltec vein and other vein systems along the large continuous Toltec fault zone are on Eureka Mountain tributary to the south side of Picayune Gulch (pl. 2). The Toltec lode was mentioned by Ransome (1901, p. 183) as having been prospected prior to 1900. It contains both low-grade shoots of base-metal ores and lenses of high-grade tetrahedrite ore. In 1907, exploration of the vein was renewed, and a crosscut was driven from near the highway in the Animas River valley to intersect the northeastern part of the vein. The results of this work are not known, but no appreciable production has been recorded. During World War II, an access road was built to a prospect tunnel on the vein at about 11,400 feet altitude just west of this lower tunnel, and small lots of lead-zinc ore were mined from near-surface workings. Wide exposures of low-grade ore, largely quartz with local pockets of galena and sphalerite, farther southwest near the crest of Eureka Mountain have been prospected only superficially.

The main structural element of the Treasure Mountain-Eureka Mountain area is the northeast-trending

Eureka graben bounded by the Sunnyside and Toltec fault zones. It is noteworthy that the pronounced widening of the veins in these fault zones is related at many places to changes in direction of the faults from one fracture system to another or to intersections of strong diagonal or cross fissures. A strongly developed system of cross fractures striking about east to southeast intersects the main northeast-trending faults and veins, and many of the main faults and veins tend to branch and to be diverted locally along these directions (pl. 2). For this reason, the argument advanced by Purington (1908)—that the narrowness of veins in the underlying Eureka Tuff was due primarily to unfavorable characteristics of the formation—loses some of its force. As yet, exploration of the wider segments of veins has been insufficient even at shallow depth to prove their worth as major sources of base-metal ore. As is true elsewhere, the bulk of the quartz-rhodonite vein matter contains less than 1 percent lead or zinc, but throughout the veins are disseminated sphalerite and galena and scattered higher grade lenses and shoots of massive ore.

The gold and silver shoots may or may not be associated with base-metal shoots. However, so few high-grade shoots of gold- and silver-bearing ores are known in this area, other than those in the Golden Fleece and San Juan Queen veins, that the entire pattern and structural control of the shoots is obscure. A few other shoots of undetermined size do exist, as indicated by past mining activities, spot assays of outcrops, and diamond-drill cores at some places. Both the Golden Fleece and San Juan Queen shoots are related to cross fissures near the northeast-trending system of faults. The cross fissures and veins are generally strong in the footwalls and have a strong tendency to turn and feather into the more easterly to northeasterly fractures. Several strong southeast-trending veins close to the footwall of the Scotia vein northeast of the Golden Fleece vein are obvious possible sites for testing. At the Golden Fleece, the gold ores extended perhaps as much as 500 feet into this footwall near the surface. At depth, therefore, exploration in the footwall of the several northeast-trending veins should probably be confined to a narrow belt near the respective northeast veins rather than vertically below exposed surface shoots. It may be assumed in general that these narrow shoots will pitch down the footwalls more or less in conformity to the dip of the faults or veins. Likewise, many short or narrow footwall fractures found at the surface are perhaps unlikely to be continuous in depth, but their pattern may be repeated in depth by separate or overlapping fissures in similar structural relations.

BROWN MOUNTAIN AREA

The Brown Mountain area at the northwest edge of plate 2 includes the Saratoga, Kentucky Giant, Guadaloupe and Lucky Twenty, and Lost Day mines on the west flank of Brown Mountain adjacent to Ironton Park and between Gray Copper Gulch and Abrams Mountain. These mines have been worked intermittently since the early 1880's.

The Saratoga mine is mainly in the Devonian and Mississippian limestones and the underlying Precambrian quartzite near the level of Ironton Park. As described by Ransome (1901, p. 240–245), the mine is credited with a mineral production valued at about $125,000, chiefly from low-grade pyritic bodies containing pockets of oxidized silver-bearing galena ore. The ore occurred in veins and replacement masses apparently associated with a pipelike body of thoroughly altered limestone and quartzite near the intersections of many closely spaced fissures and faults of northeasterly strike. Attempts to treat the low-grade pyritic ore by roasting and lixiviation to recover gold and silver were unsuccessful. The mine and the ores have been of particular interest, however, in that this is about the only place in the map area in which the effects of limestone on ore deposition can be seen. Small "flats" or winglike offshoots of ore extend for a few feet or tens of feet along the bedding where small veins cut the limestones and overlying shale and tuff beds. In addition, large bodies of pyrite, sandy and loose running, were encountered in several places. The workings have long been rather inaccessible. Some of the shallow workings were reopened during the early 1930's, but no bodies of ore favorable to modern treatment were found.

The Kentucky Giant and Indiana mine workings are in the volcanic rocks on the slope of Brown Mountain north of Gray Copper Gulch between 10,385 and 11,000 feet in altitude. Some bodies of lead-zinc and gray copper ore were stoped from the upper workings in the early days of mining; a later crosscut, the Concave tunnel, was driven beneath the older workings at an altitude of about 10,375 feet. Two nearly parallel veins have been developed; the Topeka-Kentucky Giant vein on the west dips steeply west and the Indiana vein on the east dips east. The Indiana vein has been prospected by an exploratory tunnel about 1,100 feet long and 200 feet higher than the Concave tunnel. In all, more than a mile of development work has been done on these veins. Local high-grade shoots of copper-silver ore in average base-metal ore in the veins are similar to ore occurrences at some of the mines, such as the Old Lout, in Poughkeepsie Gulch to the east.

The Lost Day mine is about half a mile northeast of the Kentucky Giant and is at an altitude of 11,500–

11,600 feet. The north-striking vein is exposed in a landslide block that has slumped downhill on underlying tuff layers which locally dip 15°–30° westward; extension of the vein to the north and south is obscured by more landslide debris. The vein where exposed has been oxidized to depths of 15–20 feet, which possibly suggests that the present exposures are a surface remnant not entirely removed during glacial erosion in the Pleistocene.

Practically all recent operations at the Lost Day mine have been confined to shallow opencuts and tunnels. About 100 tons of oxidized silver-bearing lead ore was removed from bulldozer cuts when the vein was exposed. A vein 5 feet wide containing partly oxidized galena was exposed during these operations, and 200 tons of ore shipped during 1947 (King and Allsman, 1950, p. 45) contained 10–12 ounces of silver and 0.02 ounce of gold per ton and 30 percent lead. There was no zinc or copper in the ore. During 1916–17, the mine also shipped 1,032 tons of ore having an average content of 45.4 percent combined lead and zinc.

The Guadaloupe and Lucky Twenty tunnels on the west slope of Mount Abrams in Hendrick Gulch were driven to explore and mine several veins in the Burns and San Juan Formations (Kelley, 1946, p. 368–370). The Guadaloupe vein, the principal objective of the operations, was worked prior to 1900 from an adit at an altitude of about 11,070 feet. Several hundred feet of drifting and stoping was done on three nearly parallel veins in a silicified and kaolinized altered belt about 100 feet wide. The York tunnel, 400 feet northwest of the original tunnel, crosscut 650 feet to the vein, which lies in altered intrusive quartz latite. Some stoping was also done from short drifts at this tunnel level. The Lucky Twenty tunnel, at an altitude of 10,315 feet in Hendrick Gulch, was driven in 1923 and 1926–27 to a vein thought to be the Guadaloupe vein at about 1,960 feet from the portal; several other veins were also cut in the tunnel, and one about 1,430 feet from the portal was drifted to the south. Because of the steep but irregular easterly dip of the Guadaloupe vein in the higher workings, there is some doubt as to the identity of the veins cut in the Lucky Twenty tunnel.

Ore mined from the upper workings on the Guadaloupe vein was characterized chiefly by high copper and silver and very low lead and zinc contents, whereas the veins in the Lucky Twenty tunnel contained chiefly lead-zinc ores. The reported production for the Guadaloupe mine since 1906 is about 406 tons of ore containing 9.54 ounces of gold, 17,761 ounces of silver, and 158, 528 pounds of copper. Several high-grade lots of ore contained 21–28 percent copper and about 50 ounces of silver to the ton. The character of both the ore and alteration in the upper workings indicates that the deposits are allied to the Old Lout, Kentucky Giant, and a few other deposits in the Eureka district.

A pile of ore on the dump of the Lucky Twenty tunnel assayed by the U.S. Bureau of Mines (Hazen, 1949, p. 17) contained 0.005 ounce gold and 0.45 ounce silver per ton, 0.1 percent copper, 2.5 percent lead, and 5.55 percent zinc. In contrast to this, ore probably cobbed at the York tunnel about 655 feet above contained 0.01 ounce gold and 21.65 ounces silver per ton, 11.2 percent copper, 0.1 percent lead, and 0.75 percent zinc. These differences are considered typical of the effects of hypogene enrichment, probably in part as the result of selective leaching and redeposition of metals from bodies of sulfides below the enriched zone.

REFERENCES CITED

Atwood, W. W., and Mather, K. F., 1932, Physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 166, 176 p.

Barton, P. B., Jr., and Toulmin, Priestley, III, 1961, Some mechanisms for cooling hydrothermal fluids: U.S. Geol. Survey Prof. Paper 424–D, p. D348–D350.

Bastin, E. S., 1923, Silver enrichment in the San Juan Mountains, Colorado: U.S. Geol. Survey Bull. 735, p. 65–129.

Bejnar, Waldemere, 1957, Lithologic control of ore deposits in the southwestern San Juan Mountains, *in* New Mexico Geol. Soc. Guidebook 8th Field Conf., Southwestern San Juan Mountains, Colorado, 1957: p. 162–173.

Belser, Carl, 1956, Tungsten potential in the San Juan area, Ouray, San Juan, and San Miguel Counties, Colorado: U.S. Bur. Mines Inf. Circ. IC 7731, 18 p.

Brown, W. H., 1926, The mineral zones of the White Cross district and neighboring deposits in Hinsdale County, Colorado: Colorado School Mines Mag., v. 15, no. 11, p. 5–15.

Burbank, W. S., 1930. Revision of geologic structure and stratigraphy in the Ouray district of Colorado, and its bearing on ore deposition: Colorado Sci. Soc. Proc., v. 12, no. 6, p. 151–232.

——— 1932, Geology and ore deposits of the Bonanza mining district, Colorado: U.S. Geol. Survey Prof. Paper 169, 166 p.

——— 1933a, The manganese minerals of the Sunnyside veins, Eureka Gulch, Colorado: Am. Mineralogist, v. 18, no. 12, p. 513–527.

——— 1933b, Vein systems of Arrastre Basin and regional geologic structure in the Silverton and Telluride quadrangles, Colorado: Colorado Sci. Soc. Proc., v. 13, no. 5, p. 135–214.

——— 1933c, Relation of ore deposition to igneous activity and environment [Colorado], *in* Am. Inst. Mining Metall. Engineers, Ore deposits of the Western States (Lindgren volume): New York, Am. Inst. Mining Metall. Engineers, p. 307–311.

——— 1935, Camps of the San Juan: Eng. Mining Jour., v. 136, no. 8, p. 386–389, 392.

——— 1940, Structural control of ore deposition in the Uncompahgre district, Ouray County, Colorado, with suggestions for prospecting: U.S. Geol. Survey Bull. 906–E, p. 189–265.

——— 1941, Structural control of ore deposition in the Red Mountain, Sneffels, and Telluride districts of the San Juan Mountains, Colorado: Colorado Sci. Soc. Proc., v. 14, no. 5, p. 141–261.

——— 1950, Problems of wall-rock alteration in shallow volcanic environments, *in* Van Tuyl, F. M., and Kuhn, T. H., eds., Applied geology, a symposium: Colorado School Mines Quart., v. 45, no. 1B, p. 287–319.

——— 1951, The Sunnyside, Ross Basin, and Bonita fault systems and their associated ore deposits, San Juan County, Colorado: Colorado Sci. Soc. Proc., v. 15, no. 7, p. 285–304.

——— 1960, Pre-ore propylitization, Silverton caldera, Colorado: U.S. Geol. Survey Prof. Paper 400–B, p. B12–B13.

Burbank, W. S., Eckel, E. B., and Varnes, D. J., 1947, The San Juan region, *in* Vanderwilt, J. W., and others, Mineral resources of Colorado: Denver, Colo., Mineral Resources Board, p. 396–446.

Burbank, W. S., and Luedke, R. G., 1961, Origin and evolution of ore and gangue-forming solutions, Silverton caldera, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 424–C, p. C7–C11.

——— 1964, Geology of the Ironton quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ–291.

Coats, R. R., 1940, Propylitization and related types of alteration on the Comstock Lode [Nev.]: Econ. Geology, v. 35, no. 1, p. 1–16.

Collins, G. E., 1931, Localization of ore bodies at Rico and Red Mountain, Colorado, as conditioned by geologic structure and history: Colorado Sci. Soc. Proc., v. 12, no. 12, p. 407–424.

Colorado Mining Association, 1949, Mining year book 1949: Denver, Colo., 176 p.

Cross, Whitman, Howe, Ernest, and Irving, J. D., 1907, Description of the Ouray quadrangle [Colorado]: U.S. Geol. Survey Geol. Atlas, Folio 153.

Cross, Whitman, Howe, Ernest, and Ransome, F. L., 1905, Description of the Silverton quadrangle [Colorado]: U.S. Geol. Survey Geol. Atlas, Folio 120.

Cross, Whitman, and Larsen, E. S., 1935, A brief review of the geology of the San Juan region of southwestern Colorado: U.S. Geol. Survey Bull. 843, 138 p.

Cross, Whitman, and Purington, C. W., 1899, Description of the Telluride quadrangle [Colorado]: U.S. Geol. Survey Geol. Atlas, Folio 57.

Eckel, E. B., 1961, Minerals of Colorado—A 100-year record: U.S. Geol. Survey Bull. 1114, 399 p.

Garrels, R. M., and Richter, D. H., 1955, Is carbon dioxide an ore-forming fluid under shallow-earth conditions?: Econ. Geology, v. 50, no. 5, p. 447–458.

Goldsmith, J. E., and Graf, D. L., 1957, The system CaO-MnO-CO_2, solid-solution and decomposition relations: Geochim. et Cosmochim. Acta, v. 11, no. 4, p. 310–334.

Graton, L. C., and Bowditch, S. I., 1936, Alkaline and acid solutions in hypogene zoning at Cerro de Pasco: Econ. Geology, v. 31, p. 651–698.

Hazen, S. W., Jr., 1949, Lead-zinc-silver in the Poughkeepsie district and part of the Uncompahgre and Mineral Point districts, Ouray and San Juan Counties, Colo.: U.S. Bur. Mines Rept. Inv. RI 4508, 110 p.

Hemley, J. J., 1959, Some mineralogical equilibria in the system K_2O–Al_2O_3–SiO_2–H_2O: Am. Jour. Sci., v. 257, no. 4, p. 241–270.

Hemley, J. J., Meyer, Charles, and Richter, D. H., 1961, Some alteration reactions in the system Na_2O–Al_2O_3–SiO_2–H_2O: U.S. Geol. Survey Prof. Paper 424–D, p. D338–D340.

Henderson, C. W., 1926, Mining in Colorado: U.S. Geol. Survey Prof. Paper 138, 263 p.

Hewett, D. F., 1964, Veins of hypogene manganese oxide in the southwestern United States: Econ. Geology, v. 59, no. 8, p. 1429–1472.

Hillebrand, J. R., 1957, The Idarado mine, *in* New Mexico Geol. Soc. Guidebook 8th Field Conf., Southwestern San Juan Mountains, Colorado, 1957: p. 176–188.

Howe, Ernest, 1909, Landslides in the San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 67, 58 p.

Hulin, C. D., 1929, Structural control of ore deposition: Econ. Geology, v. 24, no. 1, p. 15–49.

Irving, J. D., and Bancroft, Howland, 1911, Geology and ore deposits near Lake City, Colorado: U.S. Geol. Survey Bull. 478, 128 p.

Kato, Takeo, 1928, Some characteristic features of the ore deposits of Japan, related genetically to the late Tertiary volcanic activity: Japanese Jour. Geology and Geography, v. 6, p. 31–48.

Keenen, J. H., 1941, Thermodynamics: New York, John Wiley and Sons, 499 p.

Kelley, V. C., 1946, Geology, ore deposits, and mines of the Mineral Point, Poughkeepsie, and Upper Uncompahgre districts, Ouray, San Juan and Hinsdale Counties, Colorado: Colorado Sci. Soc. Proc. v. 14, no. 7, p. 289–466.

King, W. H., and Allsman, P. T., 1950, Reconnaissance of metal mining in the San Juan region, Ouray, San Juan, and San Miguel Counties, Colorado: U.S. Bur. Mines Inf. Circ. IC 7554, 109 p.

Knopf, Adolf, 1929, The Mother Lode system of California: U.S. Geol. Survey Prof. Paper 157, 88 p.

Larsen, E. S., Jr., and Cross, Whitman, 1956, Geology and petrology of the San Juan region, southwestern Colorado: U.S. Geol. Survey Prof. Paper 258, 303 p.

Luedke, R. G., and Burbank, W. S., 1960, Ring-fractured bodies in the Silverton caldera, Colorado: U.S. Geol. Survey Prof. Paper 400–B, p. B13.

——— 1961, Central vent ash-flow eruption, western San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 424–D, p. D94–D96.

——— 1962, Geology of the Ouray quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ–152.

——— 1963, Tertiary volcanic stratigraphy in the western San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 475–C, p. C39–C44.

McQuiston, F. W., Jr., 1948, Milling practice at Idarado Mining Company: Am. Inst. Mining Metall. Engineers Tech. Pub. 2349, 6 p.

Moehlman, E. S., 1936, Ore deposition south of Ouray, Colorado: Econ. Geology, v. 31, no. 4, p. 377–397; no. 5, p. 488–504.

Morey, G. W., and Fleischer, Michael, 1940, Equilibrium between vapor and liquid phases in the system CO_2-H_2O-K_2O-SiO_2: Geol. Soc. America Bull., v. 51, no. 7, p. 1035–1058.

Pecora, W. T., 1956, Carbonatites, a review: Geol. Soc. America Bull., v. 67, no. 11, p. 1537–1556.

Prosser, W. C., 1910, Tungsten in San Juan County, Colorado: Eng. Mining Jour., v. 90, p. 320.

Purington, C. W., 1898, Preliminary report on the mining industries of the Telluride quadrangle, Colorado: U.S. Geol. Survey 18th Ann. Rept., pt. 3, p. 745–850.

——— 1905, Ore horizons in the veins of the San Juan Mountains, Colorado: Econ. Geology, v. 1, p. 129–133.

——— 1908, Treasure Mountain, Colorado: Mining and Sci. Press, v. 97, p. 23–25.

Ransome, F. L., 1901, A report on the economic geology of the Silverton quadrangle: U.S. Geol. Survey Bull. 182, 265 p.

——— 1909, The geology and ore deposits of Goldfield, Nev.: U.S. Geol. Survey Prof. Paper 66, 258 p.

Richmond, G. M., 1954, Modification of the glacial chronology of the San Juan Mountains, Colorado: Science, v. 119, no. 3096, p. 614–615.

Robie, E. H., 1926, Selective lead-zinc flotation at Sunnyside: Eng. Mining Jour., v. 121, p. 756–762.

Rubey, W. W., 1951, Geologic history of sea water: Geol. Soc. America Bull., v. 62, no. 9, p. 1111–1147.

Smith, R.L., 1960a, Ash flows: Geol. Soc. America Bull., v. 71, no. 6, p. 795–842.

——— 1960b, Zones and zonal variations in welded ash flows: U.S. Geol. Survey Prof. Paper 354–F, p. 149–159.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1961, Structural evolution of the Valles caldera. New Mexico, and its bearing on the emplacement of ring dikes: U.S. Geol. Survey Prof. Paper 424–D, p. D145–D149.

Thompson, R. M., 1950, The probable non-existence of alaskaite: Am. Mineralogist, v. 35, nos. 5–6, p. 456–457.

Tweto, Ogden, and Sims, P. K., 1963, Precambrian ancestry of the Colorado mineral belt: Geol. Soc. America Bull., v. 74, no. 8, p. 991–1014.

Vanderwilt, J. W., and others, 1947, Mineral resources of Colorado; Denver, Colo., Mineral Resources Board, 547 p.

Varnes, D. J., 1948, Geology and ore deposits of the South Silverton area, San Juan County, Colorado [pamphlet of address delivered at Colorado Mining Association Annual Meeting, Denver, 1948]: 12 p.

——— 1963, Geology and ore deposits of the South Silverton mining area, San Juan County, Colorado: U.S. Geol. Survey Prof. Paper 378–A, 56 p.

Warner, L. A., Holser, W. T., Wilmarth, V. R., and Cameron, E. N., 1959, Occurrence of nonpegmatitic beryllium in the United States: U.S. Geol. Survey Prof. Paper 318, 198 p.

Weinig, A. J., and Palmer, I. A., 1929, The trend of flotation: Colorado School Mines Quart., v. 24, no. 4, p. 52–54.

White, D. E., 1955, Thermal springs and epithermal ore deposits, *in* Pt. 1 *of* Bateman, A. M., ed., Economic Geology, 50th anniversary volume, 1905–1955: Urbana, Ill., Econ. Geology Pub. Co., p. 99–154.

——— 1957, Thermal waters of volcanic origin: Geol. Soc. America Bull., v. 68, no. 12, pt. 1, p. 1638–1658.

White, D. E., Anderson, E. T., and Grubbs, D. K., 1963, Geothermal brine well—mile-deep drill hole may tap ore-bearing magmatic water and rocks undergoing metamorphism: Science, v. 139, no. 3558, p. 919–922.

White, D. E., and Sigvaldeson, G. E., 1962, Epidote in hot-spring systems, and depth of formation of propylitic epidote in epithermal ore deposits: U.S. Geol. Survey Prof. Paper 450–E, p. E80–E84.

White, D. E., and Waring, G. A., 1961, A review of the chemical composition of gases from volcanic fumaroles and igneous rocks: U.S. Geol. Survey Prof. Paper 424–C, p. C311–C312.

Wisser, Edward, 1960, Relation of ore deposition to doming in the North American Cordillera: Geol. Soc. America Mem. 77, 117 p.

Woolsey, L. H., 1907, Lake Fork extension of the Silverton mining area, Colorado: U.S. Geol. Survey Bull. 315, p. 26–30.

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