# Gold-bearing Polymetallic Veins and Replacement Deposits—Part I

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Chapter C

# Gold-bearing Polymetallic Veins and Replacement Deposits—Part I

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By DANIEL R. SHAWE and THOMAS B. NOLAN

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# Gold-bearing Polymetallic Veins and Replacement Deposits—Part I

## Bald Mountain Gold Mining Region, Northern Black Hills, South Dakota

*By* James J. Norton

**Abstract**

The Bald Mountain gold mining region, near the Homestake mine in the northern Black Hills, South Dakota, is important in its own right, for it yielded about 2,100,000 troy ounces of gold between 1891 and 1959. The ore occurs as Tertiary replacement deposits in the Upper Cambrian and Lower Ordovician Deadwood Formation, quite unlike the Homestake deposits, which are Precambrian and formed in carbonate facies of banded iron-formation. The Precambrian rocks are exposed in a small area surrounded by Cambrian and younger Paleozoic rocks. This part of the Black Hills also contains many Tertiary intrusions, mostly rhyolitic to monzonitic.

The Bald Mountain ore deposits are subhorizontal shoots that replaced dolomitized beds outward from vertical fractures. Two stratigraphic zones contain most of the deposits. Ore shoots are as much as 1,500 meters long, 100 meters wide, and 6 meters thick. Most of the gold apparently occurs as submicroscopic particles in pyrite, which probably accounted for the serious recovery problems in the early years of mining. Oxidized ore was the first to be successfully treated, but recovery methods for the unoxidized ore later came into use. Average grade was 0.2 oz Au/ton and 0.4 oz Ag/ton. Ore of much lower grade in deposits suitable for open-pit operations and heap leaching has been explored and mined in the 1980's, but this report does not cover these activities.

The hydrothermal systems causing mineralization were driven by heat from Tertiary intrusions. Because the ore constituents are similar to those of the Homestake mine, their source is likely to have been Precambrian deposits of the Homestake type. Hydrothermal fluid acquired these constituents while moving generally upward through the Precambrian siliceous rocks, and precipitated them upon encountering Cambrian carbonate rocks. The numerous Tertiary intrusions must have generated other hydrothermal systems at different times and different places, but these would have been barren unless they passed through a source of ore constituents. The system forming the Bald Mountain ores probably was of moderate size and may have been supplied by a nearby Precambrian source.

Exploration is likely to find additional ore in the vicinity of the old mines, and investigations by modern techniques might also lead to the discovery of other groups of deposits of the same kind elsewhere. An even more interesting possibility is that a deposit of the Homestake type may be found at an accessible depth.

## INTRODUCTION

The importance of the Black Hills, S. Dak., in gold mining does not rest solely with the famous Homestake mine. Other deposits in the region have produced more than 3 million troy oz of gold. Most of these deposits are geologically quite different from the Homestake deposit and are of early Tertiary rather than Precambrian age, yet they are also most abundant only a few kilometers from the Homestake mine. The possibility that the gold of the Tertiary ores came from Precambrian deposits suggests that investigation of the Tertiary deposits may ultimately facilitate exploration for concealed Precambrian ore.

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The principal mines in the Bald Mountain region work ore formed by replacement of siliceous dolomite beds in the Deadwood Formation of Late Cambrian and Early Ordovician age. Most of these mines are in the Portland and Ruby Basin districts on the southwest rim of a Precambrian area that contains the Homestake mine (fig. C1). Outlying deposits to the northwest and west, labeled on figure C1 as the Two Johns mine and the Annie Creek area, are ordinarily treated as part of the Portland district. An outlying mine to the east, the Wasp No. 2 (fig. C1), is in the only highly productive deposit in what has generally been called the Yellow Creek area. The "Bald Mountain region" of this report extends from the Two Johns mine southeast through the Portland and Ruby Basin districts, and for some purposes will include the area around the Wasp No. 2.

The Portland district was called the Trojan district by Allsman (1940, p. 24), and the Ruby Basin district was called the Bald Mountain area by Irving (1904). Irving's usage causes some confusion because Bald Mountain is also the name of the mining company that later acquired most of the deposits in the Portland district, and worked them as the "Bald Mountain mine." In the Ruby Basin district, most of the deposits were consolidated under the ownership of the Golden Reward Company. The principal sources giving names and other information about individual mines are Shapiro and Gries (1970), U.S. Bureau of Mines (1954), Allsman (1940), and Irving (1904).

The first major geologic report describing the Bald Mountain region was by Irving (1904), based on field work in 1899. The description of the area by Connolly (1927) contains important data about the mineralogy of the ores and its influence on extractive difficulties. Allsman (1940) is the chief source of information about mining through the year 1938. A thesis by Miller (1962), mostly about the work of the Bald Mountain Mining Company, has a comprehensive account of operations through 1959, when the mine was closed. Shapiro and Gries (1970) compiled information from all previous work and made geologic maps at a scale of 1:12,000.

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Note: In this report and throughout this Bulletin series, metric units are used generally, except that gold amounts are given as either troy ounces (oz) or as metric tons (t) (1,000,000 troy ounces = 31.1 metric tons and 1 metric ton = 32,151 troy ounces), and gold grades are given as ounces of gold per short ton (oz Au/ton). Descriptions of placer gold deposits give gold grades as ounces of gold per cubic yard (oz Au/yd$^3$). No standard conversion exists for oz Au/yd$^3$ to oz Au/ton, because of variation in the density of placer gravel. The term "fineness" is used to indicate the proportion of pure gold in native gold, which is almost universally alloyed with lesser amounts of mostly silver. For example, a fineness of 860 indicates 860 parts per thousand pure gold. The term "tenor" is commonly used interchangeably with grade. Map and cross section elevations, and mine levels, are given in feet.

## HISTORY

The gold rush to the northern Black Hills began with the discovery of rich placers at Deadwood in 1875. The first lode claims on what became Homestake property were located in that same year, and fossil placer deposits in basal conglomerate of the Deadwood Formation were found at about the same time. The original discovery at Bald Mountain was by A.J. Smith in 1877 (Smith, F.C., 1898, p. 420). The northern Black Hills also has gold deposits in Mississippian limestone and in Tertiary intrusions, but these remained unrecognized until the 1890's.

Nearly all the gold mined prior to 1891 came from the Homestake and other Precambrian deposits, from conglomerate in the Cambrian and Ordovician Deadwood Formation, or from modern placers. Recovery of gold from Bald Mountain ores was inadequate with the grinding and amalgamation of the time, and experiments with other techniques were at first discouraging. The primary ore, which is pyrite rich, was especially difficult to treat, but in much of the ore the pyrite was oxidized to iron oxides, freeing the gold sufficiently to make it more amenable to recovery. Success in recovering the gold arrived about 1890 and mining began to flourish when the Golden Reward chlorination plant and the Deadwood and Delaware smelter started operation (Smith, 1898, p. 421). Cyanidation soon came into use and eventually became the principal process, although the Bald Mountain Mining Company for a few years before World War II also gave primary ore a preliminary roast (Miller, 1962, p. 45-46). Experience in later years showed that most of the primary ore could be treated, without roasting, by means of fine grinding and modern cyanide techniques (Miller, 1962, p. 48).

In the 1980's, low-grade ore of the region became attractive for open pit mining and heap leaching. One mine came into operation and others are expected to do so before the end of the decade. This report contains no data from this new period of exploration and mining.

## PRODUCTION

An extensive search of the literature has resulted in the production estimates shown in table C1. The table gives the gold output as about 2,100,000 oz; it may have been as low as 2,050,000 oz or as much as 2,250,000 oz. The silver estimate of 3,800,000 oz has an uncertainty of perhaps as much as 300,000 oz, and is as likely to be low as it is to be high. The total value at prices for gold and silver in the early 1980's would be about $1 billion.

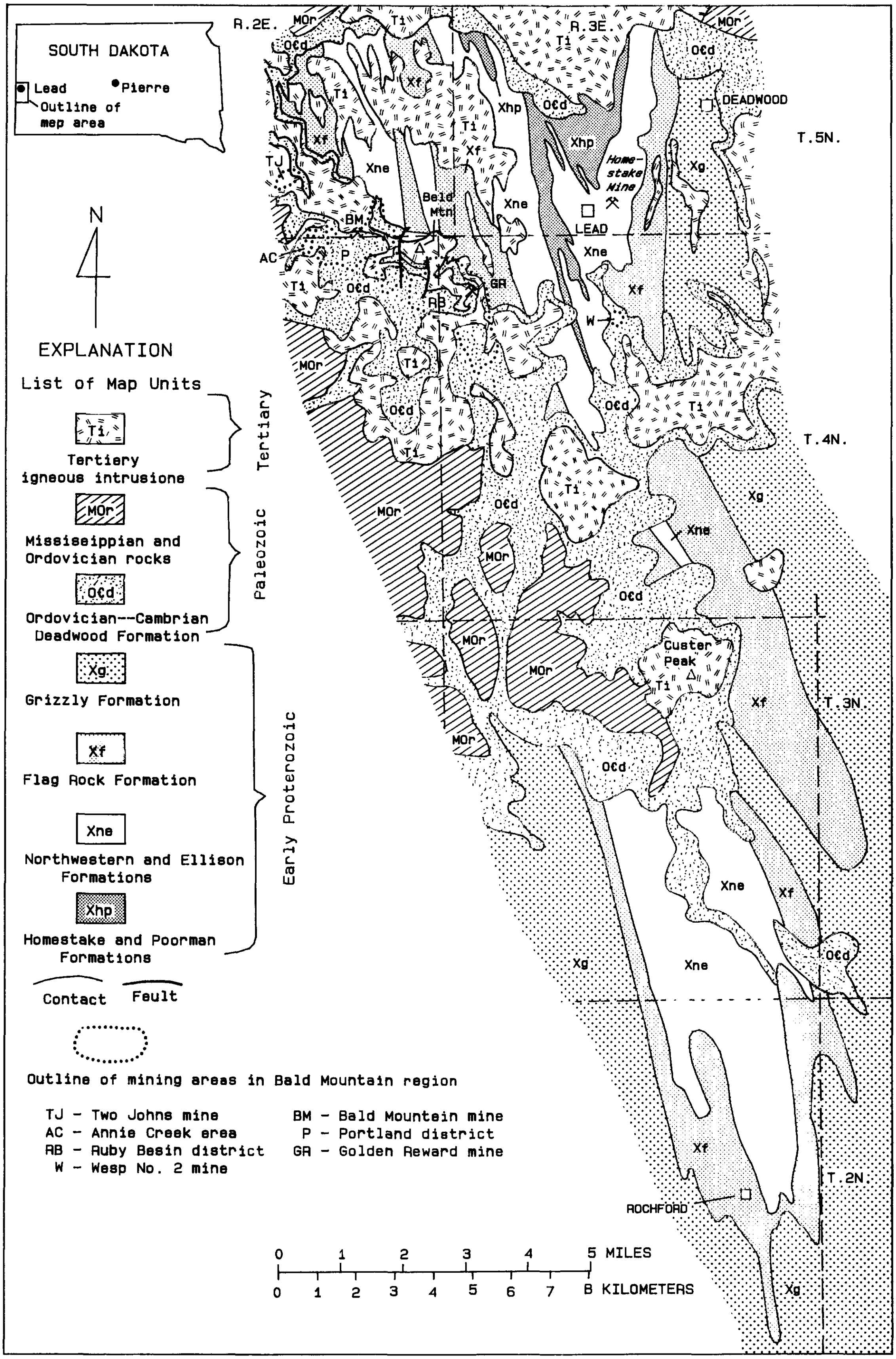


**Figure C1.** Generalized geologic map of a part of the northern Black Hills, South Dakota.

**Table C1.** Estimated production of gold and silver in the Bald Mountain mining region from its discovery in 1877 to the end of underground mining in 1959

| Years | Mines | Ore (tons) | Gold (oz) | Silver (oz) | Sources of data |
|---|---|---|---|---|---|
| 1938-1959 | Bald Mountain | 2,120,000 | 342,000 | 706,000 | U.S. Bureau of Mines Minerals Yearbooks (1938-1959); Miller (1962, fig. 17). |
| 1934-1937 | Bald Mountain | 394,000 | 60,000 | 61,000 | Allsman (1940, p. 28); Miller (1962, fig. 27)[1]. |
| 1901-1933 | Bald Mountain[2] | 1,659,000 | 360,000 | [3]667,000 | |
| | Mogul[4]--------- | 908,000 | 213,000 | 440,000 | |
| | Golden Reward | 957,000 | 371,000 | 734,000 | |
| | Lundberg, Dorr, and Wilson--- | 219,000 | 44,000 | 60,000 | Allsman (1940); Miller (1962). |
| | Reliance------- | 188,000 | 27,000 | 10,000 | |
| | Wasp No. 2----- | 1,176,000 | 101,000 | 159,000 | |
| | Others--------- | 7,000 | 1,000 | 1,000 | |
| TOTALS 1901-1959----- | | 7,628,000 | 1,519,000 | 2,838,000 | |
| [5]1878-1900 | Golden Reward, Mogul, and other mines. | Insufficient data | 600,000 | 1,000,000 | Estimated from Allsman (1940) and reports of South Dakota Inspector of Mines (1891, 1893, 1894, 1897, 1899, 1902, 1903). |
| TOTALS (rounded)----- | | | 2,100,000 | 3,800,000 | |

[1]According to Allsman, the gold output was 127,000 oz, but published data for the total Black Hills production and for production from the Homestake and other mines indicate that Miller's 60,000 oz is more likely to be correct. For silver, Allsman's figure of 61,000 oz is used instead of Miller's 71,000 oz because Miller's graph looks as if it may have a 10,000-oz error for 1937.

[2]From Allsman (1940, p. 28), but without the output of 1934-1937 or the production from six mines treated as "others" because, to judge from Miller (1962, p. 115), they were not Bald Mountain properties.

[3]Miller (1962) implied that an additional 650,000 oz Ag was produced by Bald Mountain properties. See appendix.

[4]Production for 1901 is not known.

[5]Probably no significant production prior to 1891.

The average amount of recovered metal from 1901 to the close of mining in 1959 was about 0.2 oz Au/ton and 0.4 oz Ag/ton of ore.

The production has generally been suspected of not being as large as shown in table C1. The published record has deficiencies: some reports are incompatible with others, the quality of information appears to have a wide range, and for some years preceding 1901, no production records now exist. To remove doubt about the table, fuller details about how it was compiled are in an appendix to this report. As the appendix shows, each conflict between two estimates has been resolved by choosing the lower estimate. This has been done not for the sake of conservatism but because the lower estimate in each case appears more likely to be the correct one. If the higher estimates had been used, the figure for total gold production would be increased by about 180,000 oz and that for total silver production by about 660,000 oz. The published record described in the appendix is complete enough and persuasive enough to allow a conviction that the totals in table C1 of 2,100,000 oz of gold and 3,800,000 oz of silver are reasonably reliable.

## REGIONAL GEOLOGY

Figure C1 is a highly simplified geologic map showing regional relationships in the northern Black Hills. In the north part of the map area, Precambrian rocks with Tertiary intrusions occupy an area surrounded by Paleozoic rocks and other Tertiary intrusions. This area is in a broad dome in which the base of the Cambrian rocks was raised more than 300 m (Shapiro and Gries, 1970, pl. 7). The Homestake mine is in the Precambrian rocks at Lead, and the Bald Mountain region is to the southwest in the Deadwood Formation. To the south of the Bald Mountain region is a broad area covered by gently dipping Paleozoic rocks, some of them intruded by Tertiary igneous rocks. Yet farther south, the Precambrian rocks reappear, and they continue far beyond the map area.

The Precambrian rocks consist mostly of micaceous phyllite or schist. Dips on the limbs of folds are very steep throughout the area, and the folds are isoclinal. The stratigraphy has been most rigorously worked out at Lead by geologists of the Homestake mine, particularly Noble and Harder (1948), whose stratigraphic nomenclature is used here. The oldest unit at Lead, and so far as known the oldest on figure C1, is the Poorman Formation, which consists of carbonate-bearing graphitic phyllite in the cores of anticlines and on the flanks of synclines. It has been observed only in the eastern part of the Lead Precambrian area, and mostly near its north boundary because the folds plunge to the south. Above this is the Homestake Formation, a carbonate facies of banded iron-formation that is too thin to show separately at this scale but is especially important because it is the host for the Homestake ore. Next younger is the Ellison Formation, which contains quartzite and phyllite. On figure C1, the Ellison is combined with the overlying Northwestern Formation, a phyllite unit that is cut out by an unconformity in much of the area. Above the unconformity is a heterogeneous unit called the Flag Rock Formation by Noble and Harder (1948). It is mostly a sericitic phyllite, but also has metamorphosed chert beds, iron-formation, and other rocks. The youngest Proterozoic formation at Lead was called the Grizzly Formation by Noble and Harder (1948). They mapped it only in a small area, in which it consists almost entirely of fine-grained gray sericitic phyllite without distinctive characteristics. Bayley (1972a) used the name for rocks in a much broader area where metagraywacke is a prominent constituent of the formation.

West of Lead and north of Bald Mountain, understanding of the Precambrian geology is based on a reconnaissance map by Bayley (1972a) showing only the Ellison and Flag Rock to be exposed, and in folds parallel to those at Lead.

In the southern part of the area of figure C1, near Rochford, Bayley (1972b) mapped an exceedingly complex anticlinorium—for which some of his structural interpretations are unclear, for lack of cross sections. On figure C1, Bayley's map has been greatly simplified so as to show the anticlinorium to have a core of Ellison and Northwestern Formations surrounded by the Flag Rock and Grizzly Formations. In the report on the Rochford district, Bayley (1972b) raised the Flag Rock to group rank and introduced new names for all formations of the area, but on his regional map (Bayley, 1972a) he retained the Noble and Harder (1948) nomenclature. In the east-central part of the area of figure C1, Bayley's map (1972a) indicates a large anticlinal body of Flag Rock Formation closing to the south and surrounded by the Grizzly Formation.

The pattern of the Precambrian rocks north and south of the broad area of Paleozoic covering rocks on figure C1 suggests a rather simple series of north-northwest-trending folds. The pattern indicates a southerly plunge, for the rocks in the cores of anticlines are oldest to the north and progressively younger to the south. From figure C1, it appears that the structure and stratigraphy can be projected with some confidence beneath the Paleozoic cover, but this appearance is almost certainly deceptive. The map is probably no more than an aid in visualizing how the Precambrian rocks of the Lead area may be related to those to the south. The Paleozoic cover shown in the middle of figure C1 extends over an area of about 130 $km^2$, which is the size of a 7½-minute topographic quadrangle in the Black Hills. Experience in geologic mapping of 10 such quadrangles elsewhere in the Black Hills, mostly by J.A. Redden, J.C. Ratté, and this author, has shown that the Precambrian geology of an area of this size cannot be reliably predicted from knowledge of the geology to the north and south.

The oldest Paleozoic unit is the Deadwood Formation, a marine unit that has an average thickness of about 120 m in the northern Black Hills. At the outcrop, it is almost entirely Upper Cambrian, although its top is above the Cambrian-Ordovician boundary (Shapiro and Gries, 1970, p. 14–15). The most comprehensive treatment of the stratigraphy of the formation is in a thesis by Kulik (1965). The rocks include sandstone, shale, conglomerate, limestone, and dolomite with lateral changes in thicknesses and in lithologic composition that Kulik (1965) attributed to transgressions and regressions. Irregularities on the Precambrian surface influenced compositions and thicknesses in the lower part of the formation. Differences in source areas and other local environmental differences may have caused lateral changes elsewhere. Detailed interpretation of the stratigraphy is hampered by sparsity of outcrops, especially of the shaly middle part of the formation. Further complications result from faults and from Tertiary dikes and sills (Shapiro and Gries, 1970). In the Bald Mountain region, the physical stratigraphy of the Deadwood Formation could be known in considerable detail if the mining had been done at a time when close geologic control was customary, or so it seems from Miller's report (1962, p. 87); however, the compilation of available subsurface data by Shapiro and Gries (1970) indicates that the opportunity has been largely lost.

In several reports, the Deadwood Formation has been divided into unnamed lower, middle, and upper members, but not all writers used the same boundaries between members. They all agreed in placing the basal conglomerate and a sandstone or quartzite in the lower member. The conglomerate is rarely more than 3 m thick and is generally much thinner or even absent, but it reaches a thickness of as much as 15 m (Slaughter, 1968, p. 1442), especially near buried hills of resistant Precambrian rock. The sandstone or quartzite has an average thickness of 8 m, but the range in thickness is from less than 1 m to at least 35 m (Shapiro and Gries, 1970, p. 14, 22). The lower member, in the usage of Shapiro and Gries (1970, p. 14–16), also includes a 15-m thickness of limestone, dolomite, limestone-pebble conglomerate, and thin layers of shale. Their middle member is 50 m thick and is shale with lenses of limestone-pebble conglomerate. Their upper member, also about 50 m thick, consists largely of rather thin beds of sandstone and limestone, and at the top it has a massive sandstone called the "*Scolithus* sandstone" from its worm borings. In places on the south side of the Lead window, this sandstone is as much as 35 m thick (Darton and Paige, 1925, p. 6).

The Deadwood Formation is overlain by three thin Middle Ordovician to Lower Mississippian units, totaling about 50 m in thickness, which on figure C1 are not separated from a younger Mississippian unit, the Lower Mississippian Pahasapa Limestone, which is about 170 m thick. The lowest of these units consists of shale and siltstone of the Middle Ordovician Winnipeg Formation that is overlain by the second unit, the Whitewood Dolomite, of Late Ordovician age. The third unit is the Upper Devonian and Lower Mississippian Englewood Formation, which is mostly limestone. The Ordovician rocks are cut out by an unconformity at the base of the Englewood in the southern part of the area of figure C1. The Pahasapa Limestone, which was deposited in the widespread Madison sea, is the youngest Paleozoic unit exposed in the area covered by figure C1. Elsewhere in the Black Hills, the Pahasapa is overlain by units representing all geologic systems from the Pennsylvanian through the Cretaceous. These units once covered the entire region. Evidence from a volcanic pipe in the northern Black Hills indicates that Upper Cretaceous rocks remained uneroded until at least the end of the Paleocene (Redden and others, 1983).

The Pahasapa Limestone contained ores of economic importance in the Ragged Top and Carbonate mining districts west and northwest of the Lead area and outside the area of figure C1. Otherwise, the chief reason here for interest in the Pahasapa and the other post-Cambrian sedimentary rocks is that they may conceal ore deposits in Cambrian and Precambrian rocks.

The early Tertiary igneous rocks shown on figure C1 are part of a belt of intrusions that crosses the northern Black Hills (Redden, 1975). These rocks include quartz monzonite, monzonite, rhyolite, and their porphyritic equivalents, and also phonolite and grorudite (aegerine rhyolite). The bodies include stocks and laccoliths, and a great many sills and dikes. In much of the Portland district, the total thickness of sills is greater than the thickness of the sedimentary rocks of the Deadwood Formation in which they were emplaced (Shapiro and Gries, 1970, p. 58).

Sandstones and claystones of the Oligocene White River Group appear in many places in the area, but are not shown on figure C1. Most of the post-Oligocene history of the region is one of erosion.

## ORE DEPOSITS

The ore deposits of the Bald Mountain region are replacement bodies of Tertiary age in the Deadwood Formation, especially in its siliceous dolomite. They extend outward from mineralized vertical fractures, which are suspected to have been feeders for hydrothermal solutions. The description of the deposits by Irving (1904) is still the chief original source of geologic information, but knowledge of the stratigraphic position and structural arrangement of the deposits has been increased by Miller (1962) and by Shapiro and Gries (1970). Smith (1897; 1898) and Connolly (1927) investigated the mineralogy of the gold in order to determine why the gold was difficult to extract from the ore. Numerous other publications describing the geology are based mainly on these sources.

Most of the ore came from subhorizontal shoots in dolomitic beds. The long dimension of the ore shoots is parallel to the vertical fractures, which strike generally to the north in the Ruby Basin district and to the northeast in the Portland district. Lengths of ore bodies range from a few meters to about 1,500 m. Ore bodies that follow a group of vertical fractures instead of a single fracture form zones that may be as much as 100 m wide. The maximum thickness of individual ore bodies is 6 m. Most of the ore bodies lie immediately below shale beds or sills, which are generally regarded as having impeded the upward flow of hydrothermal fluid. Irving (1904, pl. 11) published large-scale cross sections showing the various shapes and spatial relations to the host rocks.

Ore occurs also in quartzite in the lower part of the Deadwood, where it replaces carbonate cement (Shapiro and Gries, 1970, p. 30–31). Such ore was important in at least one mine in the Portland district, in probably several in the Ruby Basin district, and at the Wasp No. 2. These ore bodies in quartzite were smaller, more irregular in shape, and perhaps thicker relative to their widths than those in the dolomitic beds.

The zone of interbedded carbonate rocks and shale above the lower quartzite was the principal site of ore bodies in the Ruby Basin district, and was also important in the Portland district and at the Two Johns mine. A similar zone in the upper part of the Deadwood, below the *Scolithus* sandstone, was most important in the Portland district. The two zones are about 100 m apart stratigraphically, but the actual distance between them is increased by intervening sills. The two zones are known in the region as the "lower contact" and the "upper contact"; Shapiro and Gries (1970, p. 29) traced these terms to early usage for ore bodies at the lower and upper contacts of a sill. This nomenclature has been preserved and even extended to other districts in the northern Black Hills, largely through the writings of geologists. Ore bodies in the middle member of the Deadwood Formation have been assigned, following a whimsical logic, to the "intermediate contact."

Much of the ore is oxidized, and the distinction between oxidized and primary ore is of economic importance because the gold is far more readily extracted from the oxidized ore. The primary ore has an abundance of very fine grained pyrite, the color of which causes the ore to be named "blue ore," in contrast to the "red" or "brown" oxidized ore. Most of the ore is highly siliceous, chiefly from quartz but also chalcedony, although some dolomite was mineralized without the introduction of silica (Shapiro and Gries, 1970, p. 32). Fluorite is widespread in small amounts, and gypsum and arsenopyrite have been found in several places. Other introduced minerals are rare. Shapiro and Gries (1970, p. 33–34) made the point that the carbonate rocks of the Deadwood Formation are rarely dolomitic except in mineralized areas, and suggested that dolomitization was an early part of the mineralizing process even though the dolomite later was almost completely replaced.

How much of the gold is in tellurides and how much is in native form is uncertain. Sylvanite has been reported by several authors, but free gold has seldom been seen, and then only in oxidized ore (Connolly, 1927, p. 94). Chemical analyses long ago by Smith (1897; 1898) showed both primary and oxidized ores as containing enough tellurium to indicate that the gold is in sylvanite, and he suggested this as the cause of the extraction problems. His opinion prevailed until the mineralogic investigations of Connolly (1927, p. 72–94), who said (p. 75–77) that tellurium is absent in most of the ore, and even if it were present, roasting of the ore, which would drive off the tellurium, should have achieved more success than it had. His experiments with a sample of primary ore from the Golden Reward mine showed the gold to be closely associated with the finest grained pyrite, probably as inclusions too tiny to be seen under a microscope. Connolly favored roasting the ore to alter the pyrite and fracture the quartz, so that with subsequent fine grinding the gold would become accessible to cyanide solutions. Connolly also reasoned that in oxidized ore the oxidation process performed the same functions as roasting, and that the milling problems of early years were caused mostly by the fine grain size. As a consequence of these and further experiments, the Bald Mountain Mining Company set up a roasting operation that raised the recovery of gold in Two Johns primary ore from 20 to 80 percent (Miller, 1962, p. 47). After World War II roasting became too costly, and Two Johns ore and some other primary ore could not be treated by the fine grinding and cyanidation that sufficed for other primary ores. Whether or not this characteristic was caused by gold being in tellurides is not known.

No mineralogic investigation of the Bald Mountain ores has been reported since 1927. A modern study would greatly increase knowledge of the mineralogy, the distribution of chemical constituents, the ore-forming processes, and how to improve extraction of the gold and silver. Adequate sampling may now be difficult in the old mines, but Irving's collection still exists at Yale University (B.J. Skinner, written commun., July 21, 1983), and perhaps more samples can be found in other universities and mining schools.

## Origin

The ore-depositing process, in its broader aspects, seems to have been simple. Carbonate rocks were replaced by silica and pyrite, and at the same time an economically important amount of gold was deposited. The obvious transport medium was a hydrothermal fluid driven by heat from the Tertiary magmas. Much of the fracturing was caused by distention of the rocks during the intrusive activity (Noble, 1952). Heat and fracturing, however, may have been the only contributions of the magmas. The water could have been convecting meteoric water or connate water from the Phanerozoic rocks. It is argued here that the hydrothermal fluids obtained critical parts of their solute from a source chemically similar to the ore-bearing parts of the Homestake Formation—that is, a source with magnesium, iron, sulfur, gold, and silver. Silica could have been obtained from almost any of the Precambrian rocks.

In discussions of the ore controls, the literature has emphasized the orientation of fractures and the presence of dolomite, and these are indeed important in guiding the mining and in searching for ore shoots. It seems inevitable, however, that a hydrothermal fluid would have permeated fractures and carbonate beds suitable for mineral deposition among the many available in the

Paleozoic section, but its solute might have been dispersed in deposits of less than ore grade. For this reason, the orientation of fractures and presence of dolomite are not necessarily critical in regional exploration.

A larger question than that of local ore controls is what controlled the positions of the large mineralized systems defined by the mining districts. This is also a much more difficult question because the Precambrian geology beneath the Bald Mountain region is too poorly known to indicate likely locations of source areas for the constituents of the Tertiary deposits; further, the geometric arrangement and magnitude of the hydrothermal systems, especially the directions and amounts of lateral movement, are at best known only in the mined areas. The Precambrian rocks are so nearly impervious that any significant flow of hydrothermal fluid must have been through fractures. In the Cambrian rocks, the geology of the ore deposits indicates movement through fractures, but the relation between these fractures and fracture patterns in the Precambrian rocks is unknown. Because the Tertiary intrusions are numerous and generally rather small, the system of convecting fluids must have been complex. Furthermore, published ages of the intrusions (Redden, 1975, p. 47) indicate that the period of high temperature, and thus of convecting activity, may have lasted for as long as 20 m.y. At any one time, the fluids were likely to have been enriched in sulfur, gold, and silver only in some parts of the region and to have been barren elsewhere, and the routes of travel of the fluids were likely to have changed during the millions of years of activity. Fluids that lacked access to a source of sulfur and to a source of gold or other valuable metals would yield no ore deposits, and thus not leave noticeable evidence of their existence.

In these circumstances the convecting cells probably were small, and the constituents of the Bald Mountain ores are likely to have come from nearby sources. The impermeability of the Precambrian rocks except through fractures implies that the cells descended only a short distance below the contact with Paleozoic rocks, probably at most a few hundred meters, indicating a shallow depth for the source rocks. Hence, the chief control over the positions of the Bald Mountain deposits may have been proximity to source rocks. A second control was the geometry of the fracture systems that governed the routes of travel of the solutions, but about this little can be inferred. A suggestion (Burnham and Ohmoto, 1981, p. 71) that ancient hydrothermal systems can be traced out by work on the isotopic composition of oxygen and hydrogen seems impractical for the complex geologic environment of the northern Black Hills.

Hydrothermal fluid probably had little ability to react with the Precambrian rocks because nearly all of them are micaceous or quartzose and not easily changed. The solutions reacted with enclosing rocks primarily where they first encountered carbonate rocks in the Deadwood Formation. That is, the lowest carbonate rocks above the Precambrian-Cambrian contact were an important control. At the sites of the ore deposits, the movement of the fluid seems to have been largely vertical (Irving, 1904, p. 156–157), but this does not mean that source rocks are necessarily directly beneath the ore deposits, because hydrothermal flow could have been lateral at or below the Precambrian-Cambrian contact.

The sulfur and the iron of the pyrite did not necessarily enter the ore bodies at the same time. The iron may have been introduced earlier, during dolomitization of limestone. Dolomitization had been assumed to long precede the mineralizing process until Shapiro and Gries (1970, p. 34) pointed out that dolomite seems to be rare except in mineralized areas. This observation implies that the first effect of hydrothermal fluid was to substitute magnesium for calcium in limestone. The only published chemical analysis of a dolomite bed from the region, which was made by W.F. Hillebrand for Irving (1904, p. 121), shows not only a high content of MgO but also 6.47 percent FeO and 0.64 percent $Fe_2O_3$. Irving described the sample as containing magnetite and glauconite, but the low content of ferric iron shows these to be sparse. Furthermore, the content of $CO_2$ is, in molecular terms, only slightly less than the total of CaO, MgO, FeO, and MnO. Hence most of the ferrous iron in this sample is in the carbonate mineral, and probably was deposited at the same time as the magnesium. The iron content is very nearly the same as in the only sample of typical sulfide ore for which both chemical and mineralogic data have been published (Irving, 1904, p. 141–142). Little or no iron need have been introduced with the sulfur if Irving's analyses are representative of the region. The introduction of sulfur could have been a later event, after evolution in the composition and behavior of the solutions caused them to dissolve magnesium, calcium, and $CO_2$, and to deposit silica and sulfur, as well as enough gold and silver to make ore.

The introduced constituents at Bald Mountain are in large part major constituents of the Homestake Formation and the ore bodies it contains. The Homestake Formation is a banded iron-formation consisting of quartz and either iron-magnesium carbonate or, above the almandite isograd, an iron-magnesium silicate, grunerite-cummingtonite. The ore bodies have chlorite as an abundant ferromagnesian mineral, and they are rich in iron sulfide minerals, as well as gold and silver. The silver:gold ratio is much lower than in the Bald Mountain deposits, reflecting either a difference in the source rocks for the Bald Mountain constituents or differences in the geochemical behavior of the Tertiary fluids. Rye and Rye (1974) showed the isotopic composition of the sulfur in Tertiary deposits to indicate derivation from a Precambrian source, but only one of their samples came from the Bald Mountain region.

Rye and Rye (1974) also showed, chiefly from isotopic data, that most of the Homestake mineralization was Precambrian. The age had previously been in question except that some mineralization was known to have been Tertiary because pyrite-calcite veins cut Tertiary dikes (Noble, 1950). Rye and Rye (1974), however, showed the ore-forming constituents to be best explained as products of hot springs that were active at the time of the original deposition of the Homestake Formation. They suggested a similarity with the metalliferous brine deposits from hot springs in the Red Sea, where contemporaneous sediments are also iron-rich. Noble (1950) emphasized evidence that the Homestake ore bodies are concentrated in cross folds, and showed that they are near the almandite isograd, where carbonate minerals were metamorphosed to amphibole. To account for these circumstances, Rye and Rye (1974) called on redistribution of the metals, the sulfur, and silica to form the ore bodies during metamorphism. This redistribution is unlikely to have been extensive because almost none of the ore is outside the Homestake Formation.

Tertiary deposits of gold or other metals occur on all sides of the Lead area, mostly in the Deadwood Formation. The Bald Mountain gold mining region has had by far the largest production, but other districts have had important mines. Near the northeast edge of the Lead Precambrian area, the Deadwood contains gold deposits, a lead-zinc deposit, and a deposit once mined for pyrite. To the southeast are gold mines in Tertiary intrusions and silver-lead deposits in the Deadwood. To the west, gold has been mined from the Pahasapa Limestone, and to the northwest are silver-lead deposits, also in the Pahasapa.

In the rest of the Black Hills, sulfide-ore deposits are much more scattered, and production from them has been far smaller. The proximity of the Tertiary deposits of the northern Black Hills to the Homestake deposit is unlikely to be a coincidence. Instead, it suggests that the hydrothermal fluids that formed the Tertiary ores obtained material from the Homestake ores or from similar deposits that are not now exposed. The total gold production from the Tertiary ores is about 2.5 million oz, which is only a small fraction of the Homestake production of about 35 million oz through 1983. A loss of gold from the Homestake deposit could have been noticed only from physical or mineralogic evidence for reworking in the Tertiary. Evidence for such loss has not been observed (D.R. Shaddrick, oral commun., 1974), but the loss would be too small to be readily detected in this geologically complex environment. The Homestake deposit did have some Tertiary pyritic mineralization, of little importance in terms of quantity, but no one has shown that it cannot have been caused by leaching of material from the main ore bodies. Noble (1950, p. 248–249) stated that the pre-rhyolite iron sulfide mineral is mostly pyrrhotite and the post-rhyolite mineral is pyrite, and that the change is sharp enough to allow interpretation of the pyrrhotite as Precambrian and the pyrite as Tertiary, although he favored other conclusions. He also stated that for about 200 to 300 m below the base of the Deadwood pyrrhotite is absent and the iron sulfide is pyrite, which is also the principal sulfide mineral of the Tertiary ores.

The existing data suggest that the gold of the northern Black Hills originally entered sediments from hot springs in Early Proterozoic time, and since then has only been redistributed. The first redistribution brought the Homestake ore bodies to essentially the form they have now. The second redistribution resulted in the Tertiary deposits.

## Implications for Exploration

The implications for exploration are at three levels: first, the probable existence of unmined ore in or near the old mines; second, the possibility of discovering another group of deposits of the same kind; and third, a chance that the Bald Mountain deposits reflect the existence of Precambrian deposits at depth but perhaps not too deep for exploration and mining.

Miller (1962), in his descriptions of the mines of the Bald Mountain region, mentioned several places that contain unmined ore. From his remarks one can infer a total of a few million tons, which, if the grade is similar to that of earlier mined ore, would contain several hundred thousand ounces of gold. This material was not strictly ore at the time the mines were closed (for otherwise the mines would not have been closed), but they may be reserves now. The known deposits have been investigated by mining companies in the 1970's and 1980's. Miller (1962) and other authors have stressed the need for exploration of the middle member of the Deadwood Formation; they also mentioned ore south of old workings in the Ruby Basin district as well as in parts of the basal quartzite. Diamond drilling accompanied by detailed reconstruction of the stratigraphy and structure seems a necessity. An important issue is how much primary ore remains unmined because it once could not be treated at a profit but could be now.

A search for new districts of the Bald Mountain type would require recognition of places that had a Tertiary metalliferous hydrothermal system that left little or no evidence of its existence at what is now the surface. Outside the Bald Mountain region, the principal known gold deposits in the Deadwood Formation are north-northwest of Lead, which also is where the Homestake

Formation passes beneath Cambrian rocks. The potential for subsurface discoveries has long been obvious, but possibly has not been adequately tested since the end of the price of $35/oz gold. The presence of gold deposits in the Pahasapa Limestone at Ragged Top and silver at Carbonate, which are northwest of the Bald Mountain region, has led to exploration of the underlying Deadwood, but without known success.

The area south of the Bald Mountain region consists of Paleozoic rocks and many Tertiary intrusions. Certainly hydrothermal systems were once active in this area; the critical question is whether or not they deposited ores. According to Darton and Paige (1925, p. 22–23), the larger intrusions are all sills and laccoliths lying above the older Paleozoic units. Noble and others (1949, p. 340) agreed with the essentials of the Darton and Paige interpretation, but added that these bodies probably consist of many intrusions with sedimentary partings. Possibly these intrusions conceal metal deposits. If detailed geochemical exploration has been attempted in or around these heat sources, the results have not been made known.

This same area, as well as the area north of Bald Mountain, may have unexposed Precambrian deposits. The most attractive locality is the immediate vicinity of the Portland and Ruby Basin districts, because they have concentrations of known Tertiary deposits formed by hydrothermal systems that probably drew their gold from a nearby source. If the region lacked minable deposits but, instead, had only a geochemical anomaly indicating leakage of metals from Precambrian rocks, it would have stirred up exploration enthusiasm and visions of finding another Homestake deposit. A point basic to this article is that the Bald Mountain region actually constitutes a geochemical anomaly, differing from conventional anomalies by being rich enough in gold to have been mined.

The simplified geology of figure C1 suggests that the Precambrian rock units of the Rochford area, which are similar to those near the Homestake mine, extend northward beneath Paleozoic rocks into the area north of Bald Mountain. Magnetic data support this view (Kleinkopf and Redden, 1975). The Homestake Formation may, however, be deeply buried or may lens out entirely before reaching this area. The map (fig. C1) shows that all the outcropping Precambrian units in this belt are younger than the Homestake Formation, and it implies that the circumstances are the same beneath the Paleozoic cover. This interpretation depends on Bayley's (1972b) assignment of iron-formations at Rochford to his Flag Rock Group. One of these iron-formations was regarded by Noble and Harder (1948, p. 954–955) as Homestake Formation and an adjacent phyllite as the Poorman Formation, with tops of beds the opposite of Bayley's sequence. Rye and Rye (1974, p. 300–301) determined that the sulfur in these units has the same isotopic composition as in the Homestake and Poorman Formations at Lead. It is difficult to devise a structural explanation for how the two Rochford units could be equivalent to the Homestake and Poorman, but the complexity of Bayley's map does not rule out the correlation with certainty. Whether or not the unit at Rochford is stratigraphically equivalent to the Homestake, it is lithologically the same, it has been mined for gold, and could have deposits beneath Paleozoic cover.

The Precambrian geology of the western part of the Lead area is inadequately known. Regional information is obtainable only from the reconnaissance map by Bayley (1972a) and from a map by Noble (1952) that shows contacts of Precambrian units but does not say what those units are. Even the distribution of the Tertiary intrusions is drastically different on the maps by Bayley (1972a), Noble (1952, figs. 8 and 9), Noble and others (1949, fig. 5), and Darton and Paige (1925). On figure C1, the Tertiary rocks are from Noble (1952), and the Precambrian rocks are as shown by Bayley (1972a), but with some use of Noble's contacts. The main body of Tertiary rocks was interpreted by Noble and others (1949) as a stock, called the Cutting stock. Noble (1952) showed this to be a multiple intrusion with many schist screens, and regarded it as the cause of the doming of the Lead region. Darton and Paige (1925) in their structure sections showed this large Tertiary body as having a floor not far beneath the surface. Gravity data support the interpretation as a stock by indicating widening at depth (Kleinkopf and Redden, 1975). The Tertiary rocks have highly irregular shapes on the maps of Noble (1952), and one must suspect similar vertical irregularities. The distribution of Precambrian rocks in screens and along bottoms of the intrusions probably can be determined only by well-planned and carefully interpreted drilling.

The areas suggested as possibly having concealed Precambrian deposits are so large that they bring up the question of how to identify promising areas of more manageable size. Geophysical surveys should be helpful in tracing iron-formations and in judging the depth and shape of the bottoms of the larger Tertiary intrusions. Geochemical exploration would be handicapped because the trace-element suite of the Tertiary deposits is not yet known, or at least not published. The apparent simplicity of the metal suites and the low metal contents in both Bald Mountain and Homestake ores raise doubts about how much of a halo they could create and how detectable that halo would be. On the other hand, Mahrholz and Slaughter (1967) identified useful geochemical patterns in the Homestake mine; Allcott (1975, p. 70) mentioned tellurium as a pathfinder element for Tertiary mineralization; and arsenic is closely associated with gold at Homestake and also occurs at Bald Mountain (Irving, 1904, p. 141). Clues to possible geochemical relationships between Tertiary and Precambrian ores may be obtainable from the Wasp No. 2 deposit, which is in Cambrian rocks near enough to down-plunging parts of Homestake ore shoots so that its gold may have come from Homestake ore bodies.

With so many deficiencies in information, exploration drilling for either Precambrian or Tertiary ore deposits is unlikely to be attempted except in the vicinity of known ore. What is needed is geologic, mineralogic, and geochemical investigations of kinds that will enlarge knowledge of the regional geology, the mineralization processes, and how exploration should be done.

## FINAL COMMENT

A notable aspect of the published information about the Bald Mountain region is that nearly all the available data about the ore deposits were acquired many years ago. Most readers of this article will notice the anachronistic tinge of much that it contains. The geologic data about the Bald Mountain ore deposits come chiefly from Irving's publication of 1904, and much of the rest is from the 1927 publication by Connolly. Irving's 1904 volume also had an account of the Homestake geology by S.F. Emmons and of the petrography by Irving. Their results on Homestake became outdated by a long series of investigations that culminated in the 1950 article by Noble. A major reappraisal then came from the isotopic studies of Rye and Rye (1974) and Rye and others (1974). Similar attention to the Bald Mountain region would almost certainly greatly improve the understanding of the deposits and the exploration outlook.

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## APPENDIX—DISCUSSION OF TABLE C1

The chief sources of information used in compiling table C1 are U.S. Bureau of Mines Minerals Yearbooks (1938–1959), Allsman (1940), Miller (1962), and Annual Reports of the South Dakota Inspector of Mines (1891–1903). The estimating procedure for some years or groups of years involved calculating the difference between the total South Dakota production and the known or probable production from sources outside the Bald Mountain region, especially the Homestake mine. The U.S. Bureau of Mines data for South Dakota's annual production since the beginning of mining are in Norton and Redden (1975, table 3). Homestake production data are in a report by Slaughter (1968, table 1) and in U.S. Bureau of Mines Minerals Yearbooks.

The production figures for 1938–1959 are the most reliable. The Bald Mountain Mining Company's tonnage of ore and output of gold and silver were published in the Minerals Yearbooks for 1938–1945. In subsequent years the Bald Mountain Mining Company was the only producer other than Homestake. Its output of gold and silver is the difference between the South Dakota total and the Homestake production; a graph by Miller (1962, fig. 27), who was an official of the company for many years, confirms the results. Miller's graph also shows the tonnages of ore for these later years.

For 1934–1937 Allsman (1940) and Miller (1962) are in substantial disagreement on the production of gold. The Miller (1962) graph indicates an output of 60,000 oz. Allsman (1940, p. 28) placed it at 126,930.39 oz, which implies a much higher grade than normal. Inasmuch as all except about 60,000 oz of the gold produced in South Dakota in the 1930's can be accounted for from other sources, the Miller figure is accepted as probably correct.

The records for 1901–1933 are mostly statistics furnished to Allsman (1940) by C.W. Henderson, whose name appears in the literature as a compiler of South Dakota gold and silver data at least as far back as 1908 (in annual reports by the U.S. Geological Survey, Mineral Resources of the United States). Miller (1962, table 8) also gave details of the production, but nearly all his figures are the same as Allsman's. Miller's data are in conflict with other sources on one important issue: he gave a silver production of 2,522,590 oz for the Bald Mountain and Mogul mines between 1901 and 1959, and this is about 650,000 oz greater than the 1,874,000 oz indicated by the data of Allsman and the Minerals Yearbooks. Because Miller's graph (1962, fig. 27) for 1912–1959 is compatible with other sources, the discrepancy must be in the period 1901–1911. The total Black Hills silver production for 1901–1911 was 1,960,000 oz, of which probably more than 500,000 oz came from the Homestake mine and about 1,400,000 oz is readily accounted for from other mines. Hence, the extra 650,000 oz reported by Miller is excluded from table C1. Another anomaly is in Allsman's (1940, p. 39) recorded 205,663 oz silver produced from the Golden Reward mine in 1901, which has been included in the amounts reported in table C1 even though the total Black Hills silver production in that year supposedly was only 78,000 oz. A later paragraph will bring up the possibility that this discrepancy is a result of confusion in the Black Hills totals for 1900 and 1901.

Gold and silver production data are much less complete for the 19th century. Clearly, however, mining operations were at a substantial scale in the 1890's. The field study in 1899 by Irving (1904) resulted in descriptions of 51 deposits. The annual reports of the South Dakota Inspector of Mines (1891–1901) show that the Golden Reward was a major mine in the 1890's and many smaller mines were active in the Bald Mountain region.

The mine-inspector reports and old records of the U.S. Bureau of Mines enabled Allsman (1940) to make production estimates that can be used to gauge the pre–1901 output of the Bald Mountain region, although uncertainties arise from differences in the ways in which he presented the estimates for individual mines. Only for the Mogul did he give a direct estimate of the pre-1901 production, which he placed at $3 million worth of gold and silver bullion. For the Golden Reward, he estimated the production over the whole history of the mine to be $21 million; the recorded production from 1901 onward (table C1) would have been worth about $8,100,000, which leaves $12,900,000 as the value of the earlier production. A similar calculation for the Wasp No. 2 mine puts the early production at only $300,000. For the Bald Mountain mine, Allsman (1940, p. 27–28) stated that the production for 1901-1937 added to "a rough estimate of the early production" indicates a total of about $12 million, but actually the production he showed for 1901–1937 would have been worth somewhat more than $12 million, thus leaving nothing for the earlier years. Whatever the cause of this odd result, it seems clear that Allsman had evidence for only small pre-1901 production.

Allsman's estimates indicate a value for the pre-1901 production of about $16 million. From this value the quantity of gold can be calculated from the formula

$$20.67x + abx = 16{,}000{,}000$$

in which 20.67 is the dollar value of gold per ounce, $x$ represents ounces of gold, $a$ the price of silver per ounce, and $b$ the ratio of silver to gold by weight. The average price of silver produced in the Black Hills from 1890 through 1900 was about $0.70 per oz. The ratio of silver to gold from the Golden Reward and Mogul after 1900 was 2.0. If this may be taken as representative of the region in earlier years, the pre-1901 output of gold was 725,000 oz. A somewhat lower, and more probable, silver:gold ratio would increase the gold estimate by only a few thousand ounces.

Another way of estimating the pre-1901 production is by use of the annual reports of the South Dakota Inspector of Mines. Copies of these reports for the years 1891, 1893, 1894, 1897, 1898, 1899, 1902, and 1903 were furnished by the South Dakota School of Mines and Technology. The 1899 report is available only in an undated special edition of the Black Hills Mining Review, probably published in 1900. Other early reports, with the possible exception of the 1892 report, are unobtainable according to a review of the records that was published in the 1944 report. The 1898 report lacks production data. In the 1899 report, the production figures are questionable because they total $9,131,000, which is far greater than the $6,558,000 in records of the U.S. Bureau of Mines (Norton and Redden, 1975, table 3).

The report for 1891, which to judge from an article by Smith (1898, p. 421–422) was the first year of successful mining, shows a production of $170,000 from the Bald Mountain region. By 1893 the production exceeded $1 million, but it fell back to $760,000 in the following year. In 1897 the production went slightly above $2 million. It was about the same in 1899, if the reported total of that year should be discounted as much as appearances imply. In 1902, the production was still a little more than $2 million. These figures indicate a production of about $8 million from 1897 through 1900, and about $5 million from 1891 through 1896, and thus a total pre–1901 production of $13 million. This is equivalent to about 600,000 oz of gold. Whether or not this estimate is better than the 725,000 oz calculated from Allsman's figures is questionable, but because 600,000 oz seems to be the maximum that can be supported by published data, it is used in table C1.

If a silver:gold ratio of 2.0 is assumed for those years, the silver production was 1,200,000 oz, but the ratio was probably lower because some of the extractive plants did not recover silver. The only independent means of estimating the pre–1901 silver production is to subtract the probable production of other districts from the total Black Hills production. For the period 1891–1899 the circumstances are rather simple: the total for the Black Hills was 1,192,000 oz; the Homestake and other mines outside the Bald Mountain region probably produced at least 400,000 oz; and thus the Bald Mountain region can at most have yielded 800,000 oz. This simplicity disappeared in 1900. In that year the total Black Hills silver production supposedly was 536,000 oz, which is much greater than in any year before or since then; yet the high figure is unexplained in the literature. Furthermore, the records show the production as dropping to 78,000 oz in the following year, which is equally peculiar because Allsman (1940, p. 39) reported 205,663 oz from the Golden Reward alone, and the Homestake, Mogul, and other mines must have contributed a large additional amount of silver. Then, in 1902, the recorded Black Hills production rose to 340,000 oz before diminishing in subsequent years to much lower levels. An apparent mixup in the 1900 and 1901 results has caused a sizable share of the production that was attributed to 1901 in the compilation of table C1 to be assigned to 1900 in the yearly totals. In both 1900 and 1901, the actual production is likely to have been about 300,000 oz. The Bald Mountain production in 1900 may be guessed at 200,000 oz. Adding this to the 800,000 oz estimated for earlier years yields the 1,000,000 oz used in table C1.

# Gold Deposits in the Park City Mining District, Utah

*By* Calvin S. Bromfield

**Abstract**

The Park City mining district was discovered in about 1868, and through 1982 it produced about 1.45 million ounces of gold, 253 million ounces of silver, 2.7 billion pounds of lead, 1.5 billion pounds of zinc, and 128 million pounds of copper. The district lies near the intersection of the north-trending Wasatch Range and the west-trending Uinta arch where intermediate-composition Tertiary stocks have intruded Precambrian, Paleozoic, and Mesozoic sedimentary rocks aggregating about 3,000 meters in thickness. Tertiary volcanic rocks occupy the east part of the district.

The sedimentary rocks were folded and thrust faulted during the Cretaceous Sevier orogeny. The broad north-trending Park City anticline, on which the district is centered, formed at that time. The sedimentary rocks and Tertiary volcanic rocks were broken by high-angle faults during the Tertiary to form an east-northeast-trending zone along which the ore deposits subsequently were localized.

The intrusive igneous rocks are porphyries that contain phenocrysts of plagioclase, hornblende, biotite, and pyroxene, in varied amounts. The intrusive rocks have been propylitized widely. Locally near stocks the sedimentary rocks were contact-metamorphosed to form marble, hornfels, and rocks characterized by calc-silicate minerals.

Ore deposits formed as fissure veins and generally long, narrow, meandering manto-type replacement deposits mostly in favorable carbonate units; these deposits formed at about 36–33 Ma, at the time of emplacement of the intrusive and extrusive rocks. The common ore minerals are galena, sphalerite, and pyrite. Tetrahedrite-tennantite is widespread and is the main ore mineral for silver. Chalcopyrite occurs widely in small amounts; it is abundant in the Pearl vein in the Mayflower mine, the major gold-producing deposit of the district. Enargite, jamesonite, bournonite, and boulangerite are minor ore minerals. Quartz and calcite are the dominant gangue minerals; hematite, chlorite, anhydrite, rhodochrosite, rhodonite, and manganocalcite are less abundant. Gold values ranged from 0.019 to 0.13 oz Au/ton in the replacement ore bodies, and gold values averaged about 0.35 oz Au/ton in veins in the Mayflower mine.

The ores were deposited from low-salinity (0.3–11 wt. percent NaCl equivalent) fluids at temperatures of 300–220 °C. Sulfur isotope data suggest a magmatic-hydrothermal source for the ore deposits.

## INTRODUCTION

The Park City mining district, located about 30 km southeast of Salt Lake City (fig. C2) is one of the three largest metal-mining districts in Utah. Long famous as a "bonanza lead-silver camp," the district has also produced substantial amounts of zinc, as well as lesser copper. As with similar silver and base metal districts in the western Cordillera, there has been important byproduct gold production. Ore has come from classic manto-type deposits, from other bedded replacements, and from veins in both sedimentary and igneous rocks.

The Park City region lies on the east flank of the Wasatch Range and extends from the crest of the range, marked by Clayton Peak and Scott Hill, east of the valley of the Provo River and the West Hills, and south from Silver Creek to Bonanza Flat (fig. C3). The heart of the district covers an area of about 30 km$^2$ near the center of this region (fig. C3).

### History of Mining

Who made the first discovery in what is now the Park City mining district is not certainly known, but among the first claims recorded were the Young America lode claim on December 23, 1868, and the Green Monster claim in January 1869. The first production came from the Flagstaff mine (mine and claims not shown on fig. C3), a shipment of 40 tons of silver-lead ore in 1871. However, it was with the discovery of the Ontario vein in 1872 that large-scale mining in the district began. By the mid-1880's, ore bodies were discovered to the west along the projection of the Ontario vein structures, and the Daly, Daly West, and the Judge (Anchor) mines soon ranked with the Ontario as major producers in the district. Meanwhile, although claims had been staked on Treasure Mountain (Treasure Hill on modern maps, fig. C3) as early as the 1870's, only with the consolidation and establishment of

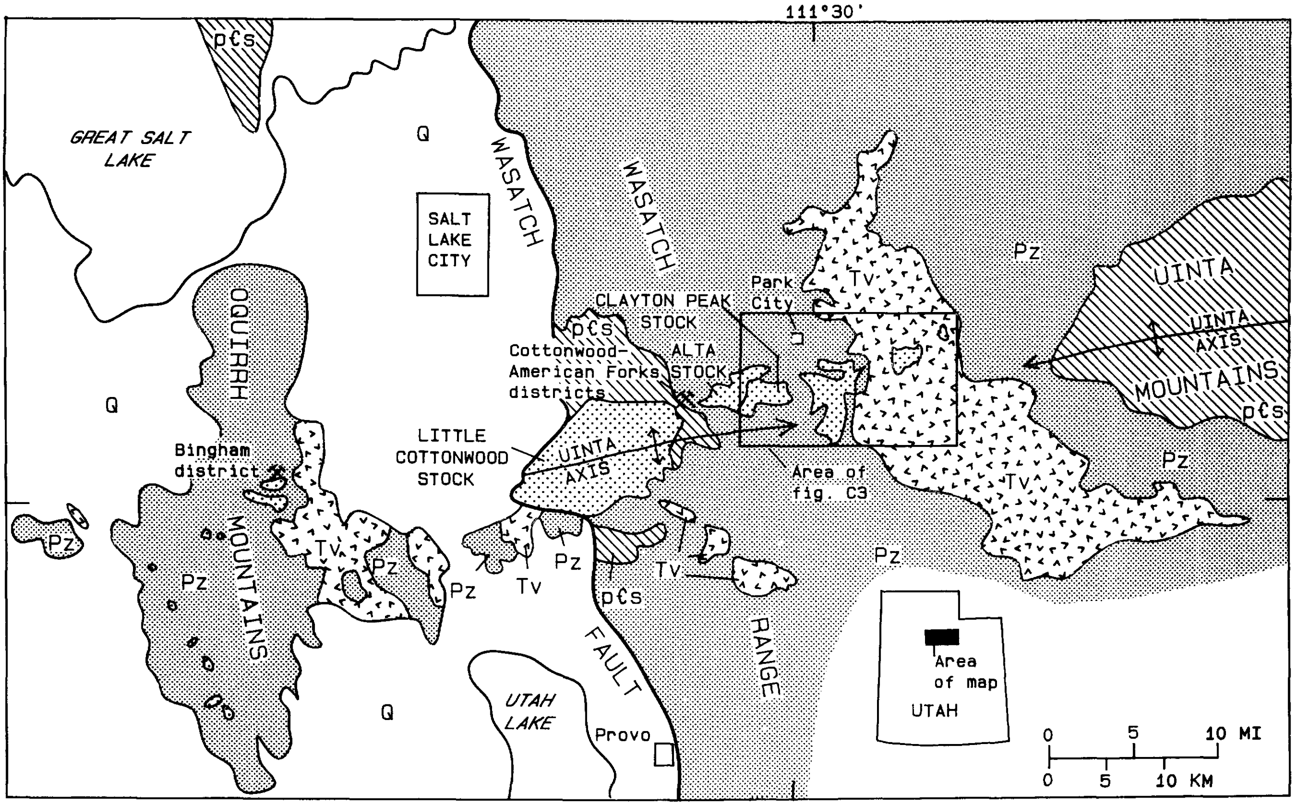


**Figure C2.** Regional setting of the Park City mining district (fig. C3) and Wasatch intrusive belt (intrusive bodies shown by stipple pattern). Q, Quaternary alluvium; Tv, Tertiary volcanic rocks; Pz, Paleozoic sedimentary rocks, locally including Mesozoic in Wasatch and Uinta Mountains areas; pЄ s, younger Precambrian sedimentary rocks, including younger Precambrian metamorphic rocks northwest of Salt Lake City.

the Silver King Mining Company in the early 1880's did development of the bonanza lead-silver manto deposits begin, for which the district was later famous. Replacement ores were also mined during this period in the Daly West and Judge (Anchor) mines. In 1920, the Park Utah ore bodies were discovered on the possible eastward extension of the Ontario-Daly vein zone. To the north of the Park City East ore bodies, a silver-bearing vein was discovered and mined on the Park City Consolidated ground in the period 1928–1942 (mines shown on fig. C5).

The Mayflower-Pearl vein system, the farthest southeast of the major producing mines, has yielded more gold than all the other Park City mines together (table C2). Although claims were located here in 1873 (Boutwell, 1912), they were worked only intermittently until 1932, when the property was obtained by and reorganized under the New Park Mining Company. The chief production was from 1962 to 1972, when the mine was leased from New Park by Hecla Mining Company. The mine, closed in 1972, was being reopened in 1982 by Noranda Mining Company. The production of the district is summarized in table C2.

## GEOLOGIC SETTING

Along its western front the Wasatch Range rises in a bold escarpment from the Salt Lake Valley. At the western foot is the Wasatch fault zone, a great frontal fault system along which the range was uplifted 1,000 m or more between middle Tertiary time and the present. Erosion that deeply etched the rising mountains has revealed a complex internal structure of folds and faults. The dominant geologic feature exposed is a broad west-trending uplift, generally considered to be the westward extension of the Uinta axis or arch. This great uplift cuts transversely across the north trend of the Wasatch Range, is truncated to the west by the Wasatch fault system, and plunges to the east forming a structural saddle, or sag, between the Wasatch Range and Uinta Mountains. In the central Wasatch Range, folded and faulted sedimentary and volcanic rocks, ranging in age from Late Proterozoic to Tertiary, have been intruded by middle Tertiary plutons of intermediate composition. The plutons, emplaced on and near the axis of the Uinta arch, form a west-trending belt extending 45 km across the central Wasatch Range (fig. C2). Important ore

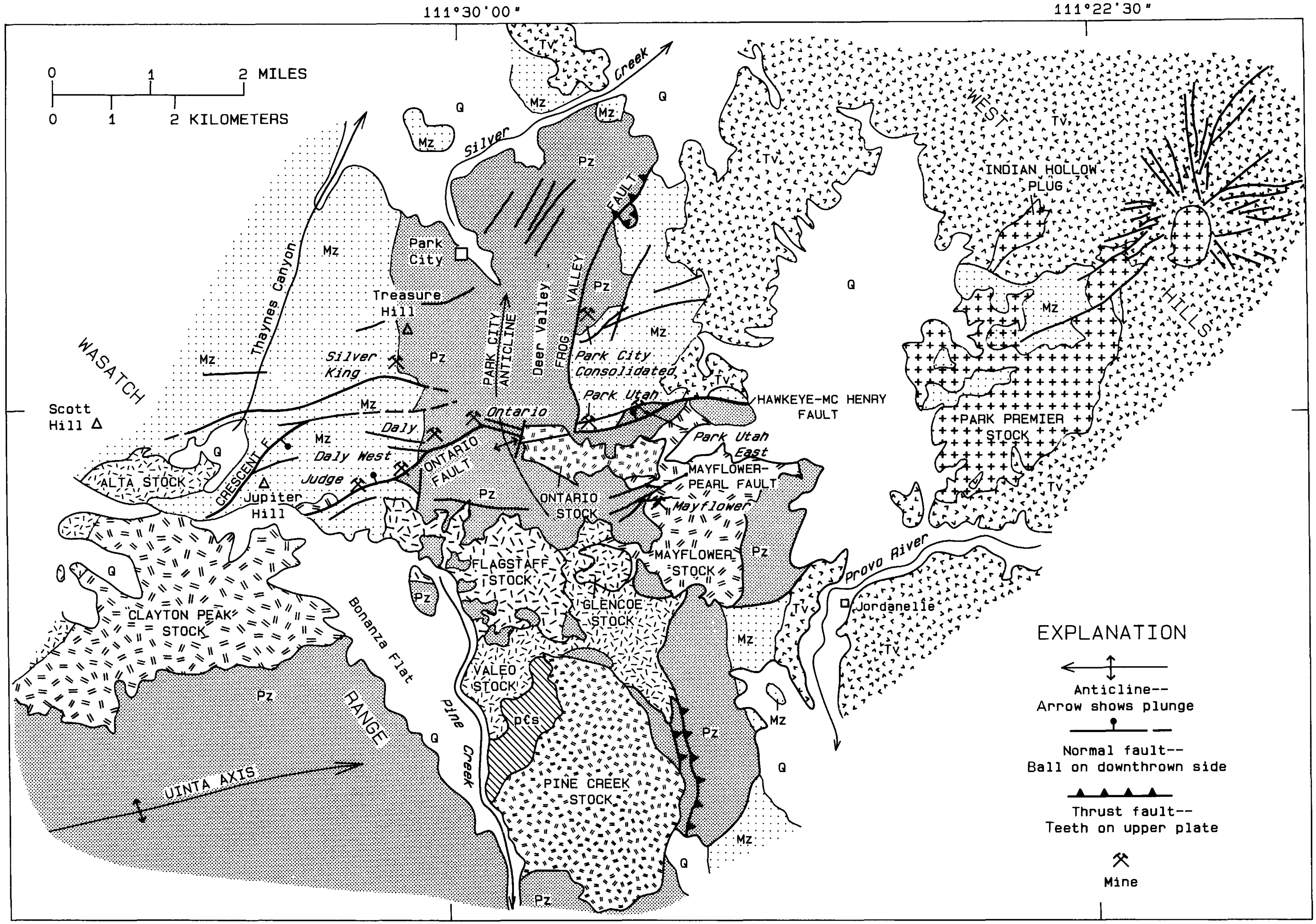


**Figure C3.** Generalized geology of the Park City area. Q, Quaternary alluvium; Tv, Tertiary Keetley Volcanics; Mz, Mesozoic sedimentary rocks; Pz, Paleozoic sedimentary rocks; p€s, Precambrian sedimentary rocks. Tertiary stocks are labelled.

**Table C2.** Production of principal mines, Park City district, 1875 through 1982

[Data from Erickson, 1968; Garmoe and Erickson, 1968; Quinlan and Simos, 1968; Barnes and Simos, 1968; and U.S. Bureau of Mines (1924–31; 1932–78)]

| Mine (ore bodies shown in fig. C5) | Years | Ore (tons) | Gold | Silver | Lead | Zinc | Copper | Au:Ag |
|---|---|---|---|---|---|---|---|---|
| | | | (oz) | | (pounds) | | | |
| Ontario | 1875–1978 | 2,822,081 | 50,700 | 58,119,001 | 229,283,401 | 294,044,608 | 6,113,468 | 1:1,029 |
| Silver King | 1882–1951 | 4,698,609 | 202,224 | 86,126,781 | 1,334,765,435 | 331,859,041 | 45,801,007 | 1:426 |
| Daly | 1886–1950 | 554,088 | 18,717 | 12,734,946 | 11,166,664 | 10,877,183 | 371,628 | 1:675 |
| Daly West and Judge. | 1899–1968 | 4,265,346 | 79,051 | 51,264,289 | 744,384,966 | 401,616,365 | 31,831,461 | 1:632 |
| Park Utah | 1920–1951 | 1,238,778 | 168,264 | 21,690,467 | 104,032,694 | 136,311,084 | 6,003,021 | 1:128 |
| Park City Consolidated. | 1929–1942 | 532,155 | 30,598 | 8,764,593 | 20,966,691 | 32,993,610 | Not recov. | 1:288 |
| Mayflower-Pearl | 1936–1972 | 2,610,666 | 904,313 | 14,644,051 | 263,546,534 | 280,141,927 | 38,847,113 | 1:16 |
| Totals---- | | 16,721,723 | 1,453,867 | 253,344,128 | 2,708,146,385 | 1,487,843,818 | 128,967,698 | |

deposits of silver, lead, and zinc, spatially associated with the intrusive belt, have been mined in the Park City mining district, on the east side of the Wasatch Range, and on the northeast flank of the Uinta arch. Smaller but significant deposits have been mined in the Little and Big Cottonwood, and American Fork mining districts, which lie a short distance west of the Park City district (fig. C2).

## Sedimentary Rocks

The sedimentary rocks of the Park City region range in age from Late Proterozoic to Holocene and aggregate about 3,000 m in thickness. The sedimentary rocks are shown graphically in the stratigraphic section in table C3. Pennsylvanian to Jurassic(?) rocks underlie the north half of the area; Mississippian, Cambrian, and Proterozoic rocks crop out chiefly in the southeast corner of the area near the Pine Creek stock, where they have been elevated by doming and inflation resulting from intrusion. Surficial deposits of Quaternary age—including talus, rock streams, older and younger alluvium, and glacial deposits—locally cover older rocks.

The stratigraphy of the central Wasatch Range has been discussed by Calkins and Butler (1943), Baker (1947), and Crittenden and others (1952); also the Mississippian rocks have been described by Crittenden (1959). The reader is referred to those reports for details.

## Igneous Rocks

Unconformably overlying the sedimentary rocks along the east edge of the area is a series of Tertiary volcanic rocks known collectively as the Keetley Volcanics (table C3). The volcanic rocks were erupted onto and buried a surface of strong relief in early Oligocene time. They rest on rocks ranging from the Pennsylvanian Weber Quartzite to the Triassic Thaynes Formation. Subsequent erosion removed the volcanic rocks from the main part of the district, and they now occur only on the eastern periphery of the area (fig. C3). Two shallow intrusive bodies in this area, the Park Premier stock and the Indian Hollow plug, cut the volcanics and may mark source vents for part of the younger volcanics. Volcaniclastic rocks make up the greater part of the field and include lahars, pyroclastic breccias, flow breccias, volcanic conglomerates, and tuffs. Flows are subordinate in volume. The rocks, which range in composition from andesite to rhyodacite, show ubiquitous phenocrysts of plagioclase and hornblende, in places biotite, and less commonly pyroxene in a fine-grained groundmass. Potassium feldspar does not occur as phenocrysts; but, as indicated by chemical and X-ray analyses, it is present in the groundmass.

A geologically short history of intrusion and extrusion is indicated by radiometric data. K-Ar ages determined on biotite from intrusive and volcanic rocks suggest that the igneous activity occurred 36 to 31 Ma (early Oligocene), whereas K-Ar ages determined on hornblende suggest a somewhat longer period, between 41 and 31 Ma (late Eocene-early Oligocene) (Bromfield and others, 1977).

Several stocks, which are part of the Wasatch intrusive belt, occur in the south part of the district, south of the belt of productive ore deposits (fig. C3). On the southwest is the Clayton Peak stock, which crops out over an area of 8–10 $km^2$. Typically, the stock consists of fine-grained equigranular rock composed of 50 percent plagioclase, 15–25 percent orthoclase, 3–8 percent quartz, and 15–25 percent mafic minerals which comprise varied proportions of biotite, hornblende, and

**Table C3.** Stratigraphic column, Park City mining district

| Age | Unit | Thickness (meters) | Lithologic character |
|---|---|---|---|
| Quaternary | Alluvium | 0–30 | Gravel, sand, and silt along larger drainages. |
| | Older alluvium | | Gravel, sand, silt; caps terraces adjacent to larger drainages. |
| | Glacial moraine | | |
| | Unconformity | | |
| Oligocene | Keetley Volcanics | 0–500 | Lahar, tuff, flow-breccia, and flow rocks, of intermediate composition with phenocrysts of plagioclase, hornblende, and biotite. |
| | Unconformity | | |
| Jurassic(?) and Triassic(?) | Nugget Sandstone | 250 | Pale-orange, medium-grained crossbedded sandstone. |
| Triassic | Ankareh Formation | 500 | Upper member of red and purple mudstone and fine-grained sandstone; middle member of white to pale-purple massive pebbly quartzite; purplish-gray and pale-red sandstone and mudstone; lower member of purplish-gray and pale-red sandstone and mudstone. |
| | Thaynes Formation | 330-400 | Brown-weathering, fine-grained limy sandstone and siltstone, interbedded with olive-green to dull-red shale and gray fine-grained fossiliferous limestone. Several limestone horizons are favorable for ore replacement. |
| | Woodside Shale | 200-250 | Dark- and purplish-red shale, siltstone, and very fine grained sandstone. |
| Permian | Park City Formation | 165-200 | Pale-gray to dark-gray limestone and dolomite, tan sandstone and dark cherty sandstone and siltstone containing a medial phosphatic shale member. Contains several productive ore zones. |
| Pennsylvanian | Weber Quartzite | 400-460 | Pale-gray, tan weathering quartzite and limy sandstone with a few thin interbedded limestone layers. |
| | Round Valley Limestone | 55-100 | Pale-gray limestone, interbedded with a few thin quartzite or sandstone layers; sparse chert, silicified orange-pink fossils in places. |
| Mississippian | Doughnut Formation | 150 | Dark-gray cherty limestone, dolomite, and shaly limestone; siliceous rusty to gray-green argillite at base. |
| | Humbug Formation | 140 | Dark- and light-gray limestone interbedded with tan sandstone. Contains favorable replacement ore zones in the Ontario mine. |
| | Deseret Limestone | 135 | Dark- and light-gray coarse-grained cherty limestone and dolomite. |
| | Gardison Limestone | 85 (incomplete) | Medium- to dark-gray thick- to thin-bedded limestone and dolomite. |
| | Fitchville Formation | 25 (incomplete) | Dark-gray medium- to thick-bedded dolomite. |
| | Unconformity | | |
| Cambrian | Ophir Formation | | Olive-drab to green micaceous sandy shale; a few thin beds of micaceous quartzite. |
| | Tintic Quartzite | 230 | Buff- to rusty-weathering vitreous quartzite; pebbly in part. |
| | Unconformity | | |
| Late Proterozoic | Mineral Fork Tillite | 190 | Rusty-weathering dark-gray or black sandy mudstone or graywacke characterized by scattered rounded cobble and boulder clasts; black shale and minor thin sandstone layers. |

pyroxene. Generally, the rock may be classed as low-quartz granodiorite or quartz monzodiorite. East of the Clayton Peak stock and separated from it by a glacial moraine cover in Bonanza Flat, an area of porphyry underlies a few tens of square kilometers along the southeastern margin of the district, extending roughly 6 km from east to west and 8 km from north to south (fig. C3). The porphyry is a composite stock or cluster of stocks made up of at least six separate intrusions, namely the Ontario, Valeo, Mayflower, Glencoe, Flagstaff, and Pine Creek stocks (Bromfield, 1968). These stocks are distinguished on the basis of distinct and consistent textural differences. Contacts between stocks are sharp, and in places are marked by chilled selvages or intrusive breccia. Plagioclase and hornblende are dominant phenocrysts, and biotite is common; pyroxene is a sparse constituent in some rocks. Distinctive rounded quartz phenocrysts are characteristic of the Valeo and Glencoe stocks. Potassium feldspar occurs only in the generally microgranular groundmass, together with plagioclase and quartz. The porphyries are chiefly granodiorite but range in composition from quartz monzodiorite to granodiorite.

## Structure

The principal structural feature in the Park City district is a broad, flat fold known as the Park City anticline, a second-order anticline lying transverse to the east-trending Uinta arch (fig. C3). The axis of the Park City anticline plunges gently north toward Silver Creek. To the south, along the central and southern course of the anticline, the axial region is interrupted by multiple stock intrusions. Within the main part of the district, the Park City anticline broadly determines the outcrop pattern of strata, and although the fold is broken by several transverse faults, its course can be inferred from the general distribution of strata. Thus, the axial area is marked by extensive outcrops of Pennsylvanian Weber Quartzite. Younger sedimentary rocks of Permian to Jurassic age dip northwesterly and easterly respectively, on opposite flanks of the fold. To the east, volcanic rocks of the Keetley Volcanics overlie the sedimentary rocks.

The rocks are cut by normal faults, and more rarely by reverse or thrust faults. East-northeast-trending faults of displacement ranging from a few meters to at least 500 m are the most numerous and important economically, as they provide the loci of mineralization for many vein and replacement deposits in the district. Some of the more important of these include the Ontario-Daly fault system, and to the east the Hawkeye-McHenry fault system (probably in part the eastward continuation of the Ontario-Daly fault zone), the Crescent fault, and the Mayflower-Pearl fault system (fig. C3).

Only a few reverse or thrust faults are known in the district. The Frog Valley fault in the main part of the district can be traced north from the Hawkeye-McHenry fault in McHenry Canyon, along the east side of Deer Valley (fig. C3). Although the fault plane is concealed, the trace of the fault suggests a plane dipping west. At its north end, the fault brings Weber Quartzite over Park City, which is in turn thrust over Woodside Shale.

Thrust faults in the south part of the Park City area were first described by Baker and others (1952). Erosion of the up-arched strata around the south and east side of the Pine Creek stock has exposed two thrust faults, one above the other (fig. C3). Both faults thin the normal stratigraphic succession and bring younger formations over older. Scattered within the porphyry stocks are numerous isolated small roof pendants of Paleozoic rocks older than the Weber Quartzite; more extensive masses of both Paleozoic rocks and the Proterozoic Mineral Fork Tillite are exposed in beds that have been elevated, probably by doming around the intrusives.

Thrust faults and folds in the Park City district formed during the Cretaceous episode of compression called the Sevier orogeny. High-angle faults are mostly of Tertiary age.

## Alteration

In contrast to many mining districts, large areas of bleached and iron-stained, altered rocks are not a conspicuous part of the landscape in the Park City district. Nevertheless, in places, changes have taken place in both sedimentary and igneous rocks.

Sedimentary rocks ranging from shale to limestone have been considerably affected by contact metamorphism adjacent to the Clayton Peak stock. Along the ridge east and west of Jupiter Hill (fig. C3), and from north of Scotts Pass to the Scott Hill area, the metamorphosed sedimentary rocks form a band ranging from 300 to 900 m in width. In this area, limestone in the Thaynes Formation has been marbleized, and red shale in the Thaynes and Ankareh Formations has been converted to gray-green to black argillite or hornfels. On the ridge at the head of Thaynes Canyon (fig. C3), carbonate beds contain specular hematite, epidote, grossular garnet, and other calc-silicate minerals.

Underground in the Daly West and Judge mines, which are immediately north of the intrusions (fig. C3), the Park City Formation is bleached and in part recrystallized (Jenney, 1906; Barnes and Simos, 1968).

The sedimentary rocks of the Silver King mine area appear relatively fresh and unaltered at the surface, and according to W.J. Garmoe and J.G. Simos (written commun., 1968), this is true in the mine, even near the ore bodies.

In general, sedimentary rocks adjacent to the porphyry stocks are little affected by contact metamorphism. However, underground in the Park Utah and Ontario mine areas, Garmoe (1958) noted minor epidote, wollastonite, diopside, introduced silica, and some bleaching in carbonate rocks older than the Weber Quartzite.

Alteration of igneous rocks in the Park City district was common in some of the porphyry stocks but is absent or minor in the Clayton Peak stock. The Pine Creek stock, in the southern part of the district, however, was not altered and is relatively fresh. Mild to strong propylitic alteration was widespread in the Ontario, Mayflower, Valeo, and Flagstaff stocks. The propylitic alteration consisted of alteration of biotite and hornblende to aggregates of chlorite, iron oxides, and calcite. In areas of more intense propylitization, plagioclase was altered to calcite, and in places epidote replaced both feldspar and mafic minerals. Disseminated pyrite is locally present. More intense alteration, including pyritization, sericitization, silicification, and formation of hydrothermal phlogopitic mica, was limited to an irregular zone about 1 km in width centered around the surface projection of the Mayflower-Pearl vein system (fig. C4). A possible continuation of this zone to the southwest is suggested by a pyritized zone about 1.6 km to the southwest, in the headwaters of the south fork of Pine Creek (fig. C3), along the projected strike of the Mayflower-Pearl system.

# ORE DEPOSITS

## Age of Deposits

The ore deposits in the Park City mining district, as well as in the Little and Big Cottonwood and the American Fork mining districts to the west in the central Wasatch Mountains (fig. C2), are all closely related to the Wasatch intrusive belt. Inasmuch as the ore deposits are known to be hydrothermal deposits, they are inferred to be related to the igneous rocks. That this relationship was instinctively recognized from the earliest days of the camp is shown by prospectors' close attention to dikes or igneous "contacts." In detail, however, the period of mineralization appears to have been later than the time of intrusion, because important ore bodies occupy fault

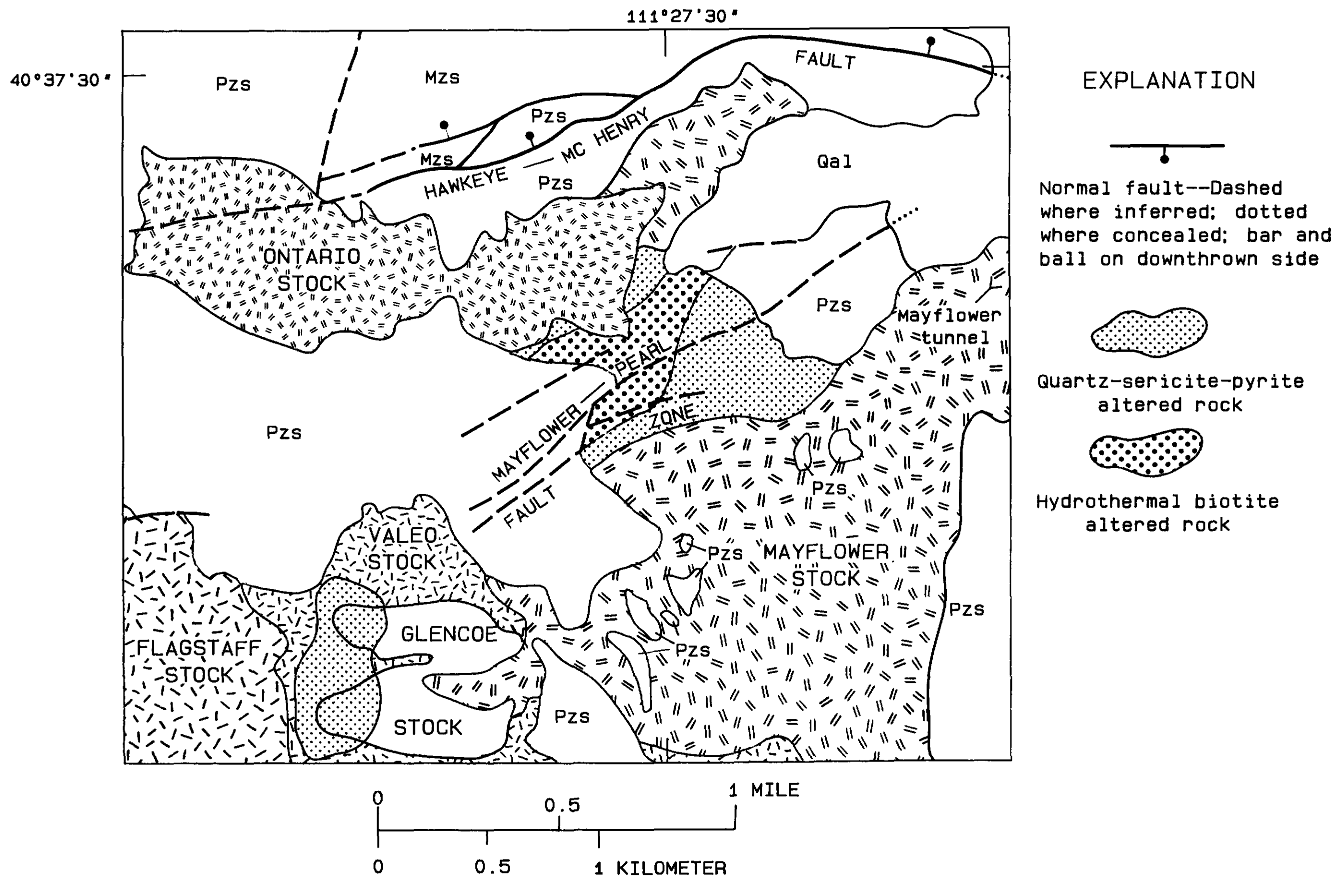


**Figure C4.** Altered rock distribution in the Mayflower mine area (propylitized rock not shown). Qal, Quaternary alluvium; Mzs, Mesozoic sedimentary rocks; Pzs, Paleozoic sedimentary rocks; labelled patterned areas, stocks.

fissures that cut porphyry stocks and thus clearly postdate solidification of the stocks. Although no ore bodies have yet been discovered in the Keetley Volcanics east along the extension of the Wasatch intrusive belt, the volcanic rocks have been extensively altered. Radiometric (K-Ar) ages of hydrothermal minerals range from 36 to 33 Ma, and within the analytical error of the method, are indistinguishable from biotite ages of intrusive and extrusive rocks (Bromfield and others, 1977).

## General Character

The primary ore deposits of the Park City district include deposits in fissure veins and replacement deposits in favorable host rocks. The most favorable host rocks are in the Park City Formation, but favorable host rocks also are in the Thaynes Formation, and as recognized in recent years, in deeper and older units, particularly in the Humbug Formation. The ore bodies have been mined primarily for silver and lead or for silver, lead, and zinc, but small quantities of gold are everywhere present and have been produced. Both fissure and replacement deposits contain gold, generally ranging from about 0.018 to 0.06 oz Au/ton. As a marked exception, the ores from the Mayflower mine averaged about 0.35 oz Au/ton. Veins produced 30 percent of the ore recovered in the Park City mining district, and bedded replacement deposits yielded the remainder. However, of the gold recovered, veins accounted for nearly 80 percent, largely because of the relatively high gold content of the veins in the Mayflower mine and, in particular, the Pearl vein.

## Mineralogy

Hypogene ores below the zone of near-surface oxidation contain chiefly sulfide minerals of lead, zinc, copper, and iron. Galena, sphalerite, and pyrite are the common ore minerals. Tetrahedrite (used here for convenience for members of the tetrahedrite-tennantite series) is widespread and is the main ore mineral for silver; Boutwell (1912, p. 108) stated that this mineral also was the chief source of small amounts of copper produced in the Silver King mine. Chalcopyrite occurs in most veins in small amounts, although in the gold-bearing Pearl vein in the Mayflower mine it was an important sulfide mineral. Enargite, too, was locally abundant in the Mayflower mine. Less common are the sulfosalts jamesonite, bournonite, and boulangerite.

Silver occurs generally in argentiferous tetrahedrite. Argentite ($Ag_2S$) was an important sulfide mineral in the East ore body of the Park Utah mine and also in the veins of the Park City Consolidated mine, where it has been interpreted as a secondary mineral (Bryan, 1935). Nash (1975), in a study of the sulfide mineralogy of the Mayflower mine, determined that silver occurs in coupled atomic substitution with bismuth + antimony in galena, and exsolved in galena as blebs of matildite ($AgBiS_2$), as well as in tetrahedrite-tennantite.

Gold in small amounts occurs in all lode and replacement ores in the district, but it achieves considerable economic importance only in the Pearl vein of the Mayflower mine. There the gold occurs free but is extremely fine grained and is associated with the sulfide minerals, particularly chalcopyrite, but also with hematite (Quinlan and Simos, 1968; Barnes and Simos, 1968).

Quartz and calcite are the most abundant and widespread of the gangue minerals. Rhodochrosite and rhodonite are present in a few veins. In the Mayflower mine, hematite, chlorite, and anhydrite were common in some ore shoots. Manganocalcite was a conspicuous gangue mineral in the Park City Consolidated mine.

At the surface and to varied depths, the primary ores were oxidized to complex silver-rich mixtures of oxides and carbonates of lead, copper, and iron. Zinc tended to be leached from the ores during oxidation (Ashburner and Jenney, 1881), and as a result smithsonite ($ZnCO_3$) was not common. Boutwell (1912, p. 102) noted that although ores of both veins and bedded replacements were in places thoroughly oxidized to depths of 150–245 m, some outcrops contained galena. Minerals of the oxidized zones include massicot, bindheimite, mimetite, cerussite, anglesite, malachite, azurite, and oxides of iron and manganese. Horn silver was common, together with some native silver, in the upper 120 m of the Ontario vein (Ashburner and Jenney, 1881).

## Replacement Deposits

Replacement deposits occur in favorable beds in the Permian Park City Formation and Triassic Thaynes Formation above the Pennsylvanian Weber Quartzite, and in recent years such deposits have been mined from the Mississippian Humbug Formation beneath the Weber Quartzite on the east flank of the Park City anticline. Mining of ore bodies in the Park City and Thaynes has been inactive for many years, and these ore bodies have become largely inaccessible through flooding and caving of mine workings.

Barnes and Simos (1968), Boutwell (1912), Garmoe and Erickson (1968), and Erickson (1968) have given the principal descriptions of these replacement deposits. The most detailed descriptions are by Barnes and Simos (1968). Three of the largest of the replacement ore bodies are described here.

The great Silver King mine contained distinctive replacement ores which formed a series of long, narrow, meandering manto-type bodies (fig. C5) of high-grade lead-silver ore in the lower Park City Formation. The ore bodies occur on the west side of the Park City anticline and extend westward nearly 3,000 m to the adjacent syncline. According to Barnes and Simos (1968, p. 1121), the ore bodies, which are confined almost wholly to the Jenney ore bed, have been mined downdip over a vertical depth of 610 m. In that distance they had little change in grade. In plan (fig. C5), they have an arcuate shape which reflects in part the strike of the Park City Formation as it bends from the flank of the Park City anticline toward the trough of the adjacent syncline to the west. Barnes and Simos (1968, p. 1122) noted that the ore bodies are cut by several minor thrust faults that strike with the beds and cut them at low angles. Later than this thrust faulting, the beds were cut by small-scale normal faults which have little displacement, and which die out rapidly in overlying incompetent shaly limestone. The gold content of the lead-silver ore was about 0.043 oz Au/ton (table C2).

In the Judge–Daly West mine area (fig. C5), bedded replacement ore bodies in the Park City Formation occurred along four principal zones, locally called "vein zones." The largest production came from the Middle vein zone. This zone is characterized by a series of fissures and small faults and several steep south-dipping porphyry dikes. Ore came from the Jenney limestone bed, an informally named economic unit, and from a stratigraphically higher unit (the "920 horizon") located about 30 m below the top of the Park City Formation along the trace of the favorable beds in the strike of the fissure zone. The Jenney bed produced ore along a strike length of more than 1,800 m, a width as much as 50 m, and a thickness ranging from 8 to more than 30 m. The upper ore body was about 1,370 m long (fig. C6) in the strike of the fissure zone, and somewhat narrower than the Jenney ore body (Barnes and Simos, 1968, p. 1120). The ore averaged about 0.019 oz Au/ton.

In recent years, exploration in the Ontario mine at deeper levels, beneath the Pennsylvanian Weber Quartzite, has resulted in discovery and development of

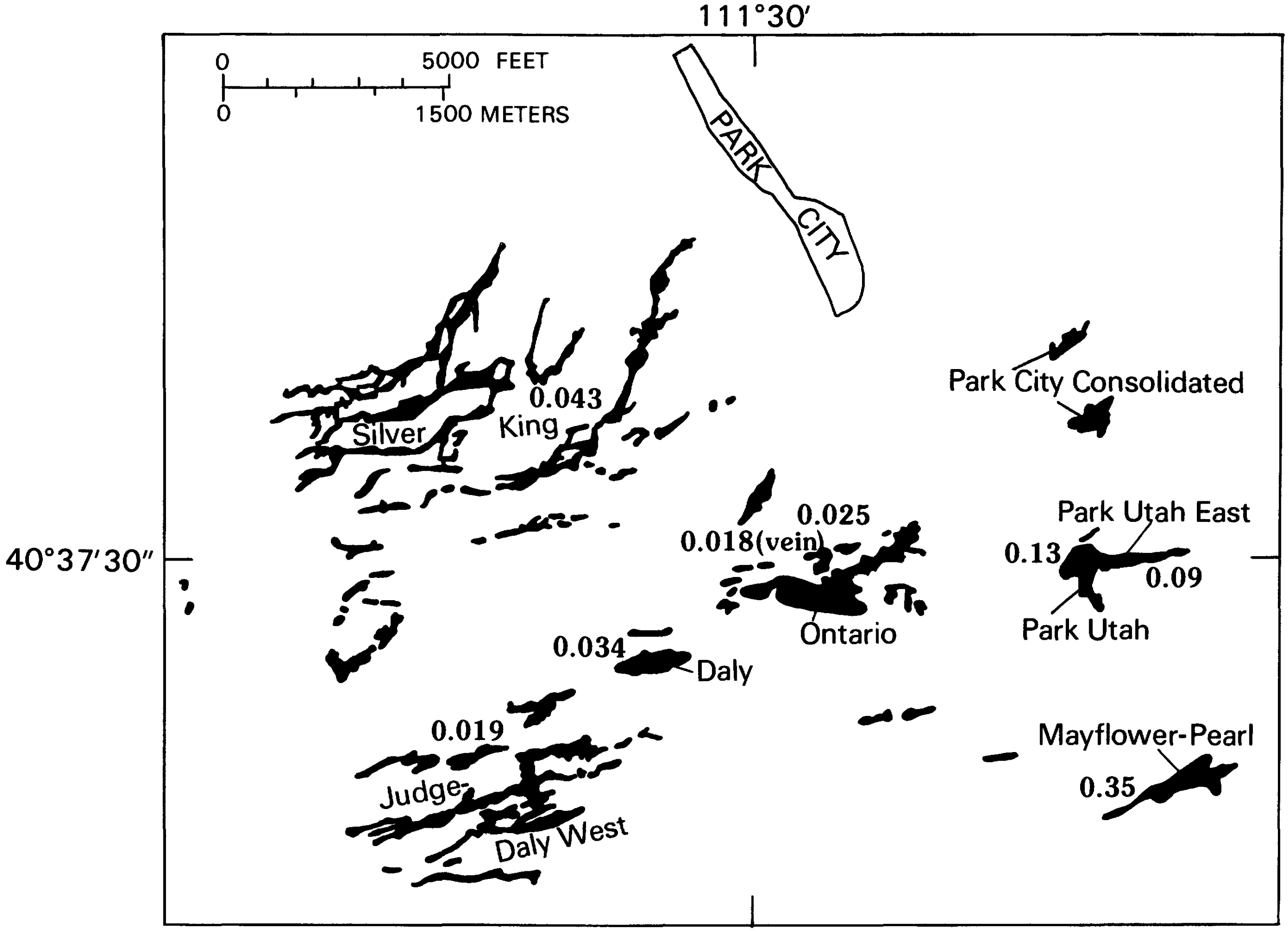


**Figure C5.** Principal ore bodies, Park City district (modified from Hansen, 1981). Figures indicate the average gold content of ore, for example 0.043 oz Au/ton in the Silver King ore deposit.

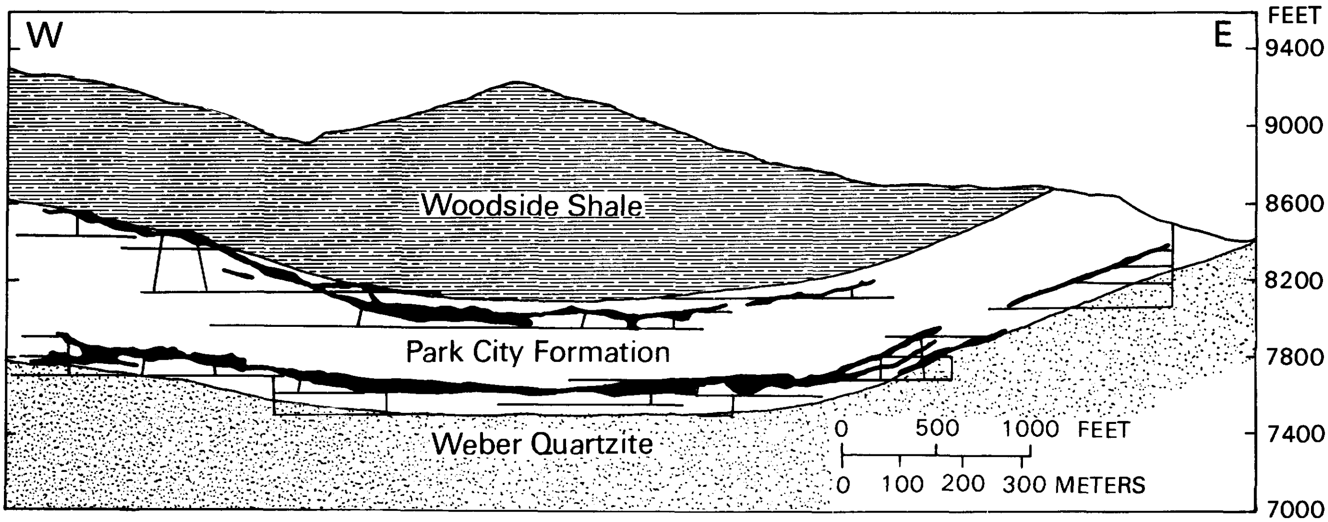


**Figure C6.** Longitudinal section, Middle vein stopes, Judge and Daly West mines (modified from Barnes and Simos, 1968). Upper stopes are along intersection of the Middle vein and the "920 horizon" of the Park City Formation; lower stopes are along the intersection of the Middle vein and the Jenney horizon of the Park City Formation.

replacement ores in the Mississippian Humbug Formation. These ores are near the crest and on the east and west flanks of the Park City anticline. They occur in a block of Humbug between two faults which strike east-northeast and dip about 45° N. These faults are the Hawkeye-McHenry fault (figs. C3, C4), which has a displacement of about 400 m, and the Silver (or Jefferson) fault about 300 m farther north, of unknown displacement. Ore occurs at several horizons in the Humbug and has been followed at least 550 m down dip on the east flank of the anticline; ore averaged 46 m in width and ranged from 2 to 6 m in thickness (Garmoe and Erickson, 1968). It forms tabular to pipelike replacements along several horizons throughout the thickness of the Humbug. Replacements that crosscut bedding tend to be localized by irregular breccia zones (Garmoe, 1958). The ore bodies are galena-sphalerite ores and show an increase of sphalerite with depth (Garmoe and Erickson, 1968). The ore averaged about 0.025 oz Au/ton.

## Fissure Veins

Vein deposits or lodes occur chiefly in east-northeast-trending fault zones. The chief veins were along the Ontario, Daly, Hawkeye-McHenry, and Mayflower-Pearl faults (figs. C3, C4), but many others also were productive. The Ontario vein was discovered the earliest, and for many years the Ontario mine was the chief silver-producing mine in the United States. Ore was produced over a strike length totaling about 1,370 m, and extending from the surface to about the 1500 level (457 m). At its west end, the vein crossed over on three spur veins to the Daly vein and continued to yield ore for another 760 m along the strike. According to Ashburner and Jenney (1881, p. 365), the fissure ranged from 0.6 to 6 m in width, the typical width being 1.2–1.5 m. The ore shoot in the fissure ranged from 0.5 to 0.75 m in width. According to these early authors, primary ore, encountered below the 400 level (122 m), was chiefly argentiferous sphalerite, tetrahedrite, minor galena, and pyrite. In the early years of the district, the product from the vein was chiefly silver, and little base metal was recovered. The Ontario vein in this period averaged 0.018 oz Au/ton. The ore from the Daly lode contained about 0.034 oz Au/ton.

Exploration that began in 1916 east of the Ontario mine, on the east side of the Park City anticline along the Hawkeye-McHenry fault, resulted in the discovery of the Park Utah ore bodies (fig. C5). Two fissure veins occur along the Hawkeye-McHenry fault zone where the fault splits into a classic cymoid loop structure (Garmoe and Erickson, 1968). Displacement on the fault is 200–260 m. The two ore bodies differed markedly in metal content. The values of the primary ore of the East ore body were almost entirely in silver, which was contained in argentite and tetrahedrite, with only minor lead and zinc. Gold content of the ore was 0.09 oz/ton. In contrast, the West ore body was more typical of the district, lower in silver content and higher in lead and zinc content; the gold content was 0.13 oz/ton.

### Mayflower Mine

The ore bodies of the Mayflower mine have several distinctions. They are the most southeasterly ore bodies of the major producing mines in the district; porphyry stocks are the principal wallrock over much of their strike length; they yielded the largest production of the fissure vein deposits; and most important of all, for this discussion, they had a gold content of 0.35 oz Au/ton, far greater than that of other mines in the district. The mine has been described in detail by Quinlan and Simos (1968) and Barnes and Simos (1968). The productive veins lie in a complex fault zone about 60 m wide, made up of parallel, en echelon, interlacing, and braided or branching veins. The displacement across this fault zone is about 30 m, with the north side down. The ore apparently lies at a bend along this fault zone where the fault zone passes from sedimentary rocks on the west into igneous rocks on the east (Quinlan and Simos, 1968, p. 48). The zone strikes N. 60° E. in the sedimentary rocks, and swings more easterly as it passes into the igneous rocks (fig. C7). Ore has been mined from near the surface to nearly the 3000 level (915 m). Within the Mayflower fault zone, the Mayflower vein generally makes up the footwall of the ore zone and was an important producer from the surface to the 2005 level (611 m). The Pearl vein generally makes up the hanging wall of the ore zone and was an important producer from the 1020 level (310 m) to the deepest parts of the mine. The No. 3 vein (not shown on fig. C7), perhaps a linking structure between the Mayflower and Pearl veins, produced ore between the 1380 and 1880 levels (420 m; 573 m), below which it joined the Pearl. Important though smaller replacement ore bodies were found west along the Mayflower fault zone in the sedimentary rocks.

Ore from the Mayflower vein is typical of silver-bearing lead-zinc sulfide ores of the Park City district. Sphalerite and galena are the chief ore minerals, and chalcopyrite occurs in minor amounts. Free gold is present in minor amounts. In contrast, in the Pearl and No. 3 veins gold is of major economic importance, the silver content is higher, chalcopyrite is common, and the content of lead and zinc is less than in the Mayflower vein. Also striking is the common occurrence of hematite and anhydrite, particularly in the No. 3 and Pearl veins. Rhodonite and rhodochrosite also occur from place to place.

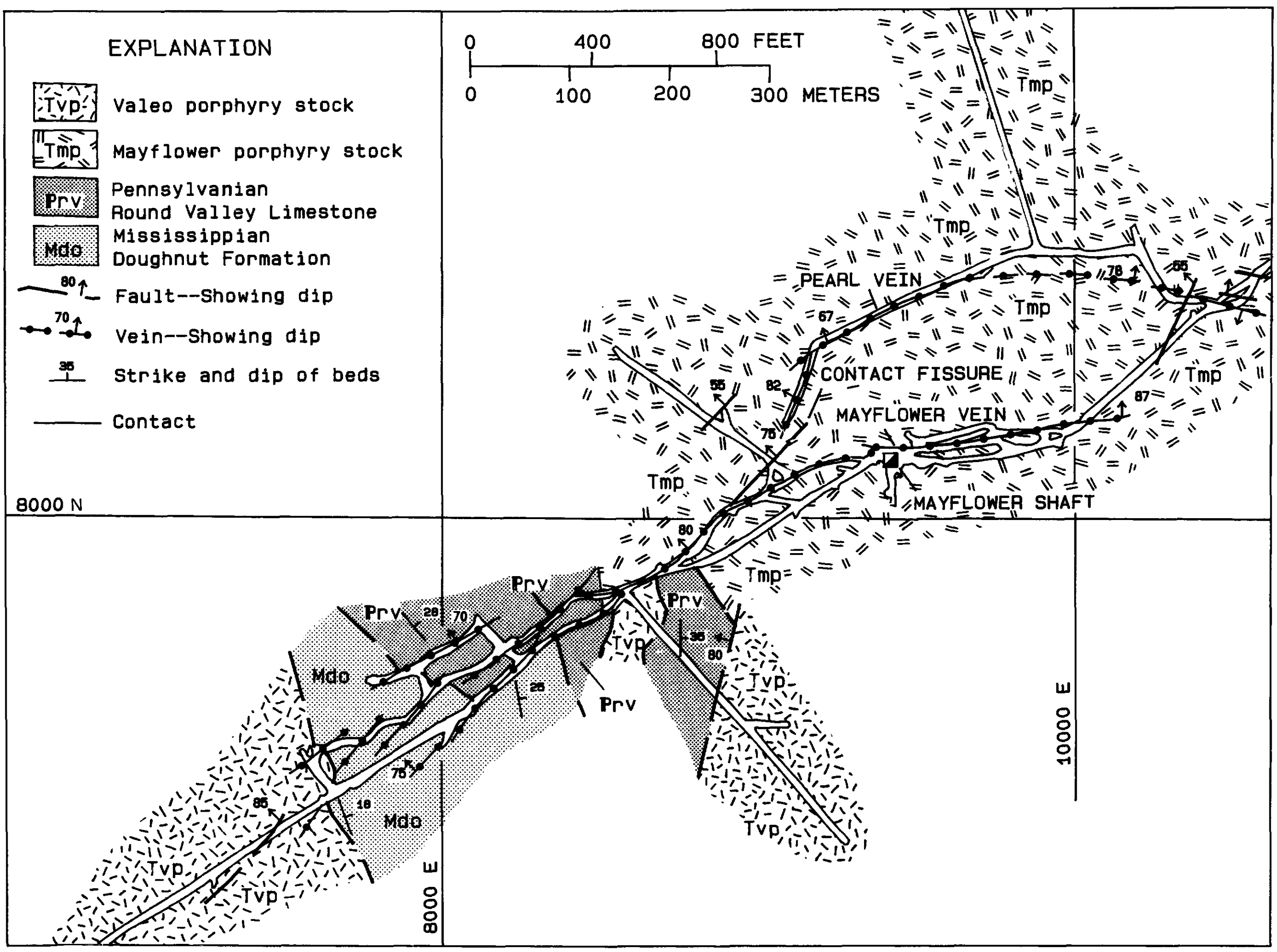


**Figure C7.** Generalized geologic map, Mayflower mine, 800 level (244 m) (modified from Quinlan and Simos, 1968).

According to Simos (in Barnes and Simos, 1968), gold is generally very fine grained and occurs consistently with chalcopyrite, and less consistently with the other sulfide minerals and hematite. Nash (1975, p. 1043) determined that the association frequency of gold was with hematite > chalcopyrite > galena > pyrite > > sphalerite.

## Mineral Zoning

According to Wilson (1959, p. 188) there is a suggestion of zoning in the Park City district—ruby silver minerals to the northeast in the area of the Park City Consolidated mine, silver-lead-zinc ore bodies in a band through the Silver King and Ontario mines, and dominant gold and copper in a core area of the Mayflower mine. Similarly, there are suggestions of vertical zoning. Zinc content of ores increased in depth along some veins. Ashburner and Jenney (1881) noted such an increase of zinc with depth in the Ontario vein. In the Mayflower mine, lead and zinc were more abundant in the upper levels; in the deeper levels, especially in the Pearl vein, copper and gold were economically important. Also in the lower levels, especially in the Pearl vein, anhydrite was a conspicuous gangue mineral.

## Isotope and Fluid-Inclusion Data

Nash (1973) made detailed studies on fluid inclusions in minerals from the Mayflower mine. He determined that fluids in the three veins (Mayflower, Pearl, and No. 3) were similar. Fluid inclusions show that deep early fluids had high salinity and homogenization temperatures of 315–430 °C, and ore-stage fluids had lower salinity and homogenization temperatures of 220–300 °C (probably requiring a minor pressure correction of +10 °C). Salinities were on the order of 0.3–11 wt. percent NaCl equivalent. Samples from near the surface, presumably contemporaneous with the Mayflower ore zone, show evidence of boiling, and about 90 bars pressure is indicated.

Isotope data on Park city ores are not abundant. Jansons (1968) made a sulfur isotope study of minerals in the Park City district. Sulfur isotope ratios showed average $\delta^{34}S$ values for sulfides near 0 per mil, ranging between –0.7 and +4.2 per mil. Comparable though slightly lower values are indicated for Mayflower samples as shown in the work of Rye and Ohmoto (1974, figs. 1, 2).

Stacey and others (1968), in a study of lead isotopes in samples of galena and selected feldspars from mining districts in Utah, determined that the isotopic composition of the lead in feldspars from Tertiary intrusive rocks and from lead deposits associated with them is similar. The isotopic composition of ore lead is best explained as having originated in a two-stage process. Thus, the isotopic ratios of ore leads from Park City indicate that the radiogenic lead component, which was probably obtained from underlying basement rocks, began forming about 2,400 Ma. The ore leads appear to be mixtures of lead derived from intrusive magma, together with a radiogenic lead component derived from upper crustal rocks through which the hydrothermal solutions passed.

# CONCLUSIONS

The mixed sulfide ores of the Park City district have characteristics in common with many similar deposits in the Cordillera of the United States that have long been considered magmatic-hydrothermal in origin. The ore deposits of Park City are associated with an alignment of intrusive rocks that crosses the Wasatch in an east-northeast direction; just west of the Park City district, along this belt, are the Little and Big Cottonwood and American Fork districts. The alignment of intrusives projected westward across the Salt Lake Valley intersects the giant porphyry copper deposit and associated lead-zinc deposits at Bingham, Utah. Radiometric age data have shown that mineralization and the period of intrusion and extrusion occupied a few million years in early Oligocene or, perhaps, late Eocene and early Oligocene. K-Ar ages of hydrothermal minerals cannot be discriminated from the ages of intrusive and extrusive igneous rocks. Nevertheless, veins such as the Mayflower-Pearl that cut the intrusions demonstrate that mineralization was a postintrusive event.

Confirming evidence for a hydrothermal origin is given by fluid inclusions and isotopic data. Evidence for boiling is shown in the early fluids and in near-surface ore-stage fluids. The $\delta^{34}S$ values show a narrow range near 0 per mil, consistent with a magmatic-hydrothermal origin. In addition, lead isotope values appear similar to those in associated igneous rocks, and have been interpreted as mixtures of lead isotopes derived from intrusive magma and radiogenic lead isotopes derived from upper crustal rocks.

The district does not display any simple zonation pattern; nevertheless, the higher gold and copper contents of the Mayflower-Pearl vein system, and the associated alteration, including hydrothermal biotite and quartz-sericite, suggest that this area was nearer the inlet (higher temperature) side of ore-solution channels than was the remainder of the district. Furthermore, rich silver- and lead-mineral replacements of carbonate rocks, relatively low in gold, as in the Silver King mine, or the vein deposits in the Park City Consolidated mine, containing moderate silver values and relatively abundant sulphosalts, suggest deposits on the outlet (lower temperature) side of ore channelways, more remote from the source.

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# Gold in the Eureka Mining District, Nevada

*By* Daniel R. Shawe *and* Thomas B. Nolan

**Abstract**

The Eureka district, Nevada, was discovered in 1864; it has since produced about 1.65 million ounces of gold, mostly during the period 1870-1890. Paleozoic shallow-water marine carbonate formations were extensively folded, thrust faulted, and shattered in late Paleozoic and Mesozoic times. The rocks were mineralized during emplacement of Cretaceous stocks. Mantolike replacement bodies rich in gold, silver, and lead formed along or near faults and fractures. Primary ores consist of pyrite, arsenopyrite, galena, sphalerite, and minor quartz in silicified, bleached, and (or) marmorized dolomite. Grades typically are 0.15–0.2 oz Au/ton, 7.0–9.0 oz Ag/ton, 0.1–0.2 percent Cu, 5–7 percent Pb, 9–12 percent Zn, and 20–30 percent Fe. Rich oxidized bonanza ores mined near the surface contained iron oxides, cerargyrite(?), native gold, anglesite, cerussite, mimetite, plumbojarosite, beudantite(?), bindheimite, and some quartz, halloysite, and calcite. These ores accounted for most of the district's production; they averaged about 1.1 oz Au/ton, 27 oz Ag/ton, and 17 percent Pb. Some of the rich ore mined during the period of peak production also contained about 0.12 percent Cu, 24 percent Fe, 1.9 percent Zn, 4.1 percent As, and 0.25 percent Sb.

Oxidized ores were mined southwest of the northwest-trending Ruby Hill normal fault during the early history of the district. Later, large high-grade primary ore bodies were discovered at depth northeast of the fault, and an attempt to mine them was made in the 1940's. A large flow of underground water stopped the attempt, and the resource remains unmined.

Low-grade disseminated gold ore in "sanded" dolomite at the Windfall mine differs markedly from other ores of the district. It is characterized by abundant jasperoid and realgar; it may be of Tertiary age, perhaps a result of reworking of older base metal ores. Mining has recently exploited these resources.

## INTRODUCTION

The Eureka mining district is in Eureka County in the east-central part of Nevada; the county seat, Eureka, with a population of less than 500, is about 400 km east of Reno, Nev., and 520 km west of Salt Lake City, Utah (fig. C8). The ore deposits in the district are examples of gold-rich mantolike replacement bodies in Paleozoic carbonate rocks near Cretaceous stocks. In addition to gold, the deposits produced substantial lead and silver.

## HISTORY AND PRODUCTION

Ore was discovered in the Eureka district in 1864 during the wave of prospecting that followed the discovery and development of the bonanza ores of the Comstock Lode at Virginia City and, closer at hand, Austin, in what is now the State of Nevada. Discovery of the rich ores resulted in the settlement of the town of Eureka, which at one time in the late 1800's was reported to have a population of some 10,000; similar discoveries elsewhere in the region saw the settlement of such mining camps as Austin, Hamilton, and Pioche. The newly found ores were major factors in the opening of the West through railroad and communication construction.

The initial discovery of ore was made in New York Canyon (fig. C9) south of the present town of Eureka; like most of the ore discovered subsequently, it was oxidized gold-silver-lead ore rich in iron. Initially the ore was not amenable to the beneficiation methods then current, and it was not until 1869, when smelting techniques were improved and when the large rich ore bodies of Ruby Hill (fig. C9) were discovered, that the district became highly productive. The greater part of the district's production took place in the 20 years from 1870 to 1890 and came mostly from the mines on Ruby Hill. Two large smelters, the Richmond, south of Eureka, and the Eureka Consolidated, to the north, produced large quantities of gold, silver, and lead, and their slag piles are still prominent features of the landscape. In addition, several smaller smelters were active during the period.

The production from the Ruby Hill mines decreased after about 1890, but a smaller continuing output was made by lessees from Ruby Hill and from new discoveries in other parts of the district. In 1905, the two major Ruby Hill mines which had been consolidated as the Richmond-Eureka mine were acquired by the U.S. Smelting, Refining, and Mining Co., and considerable

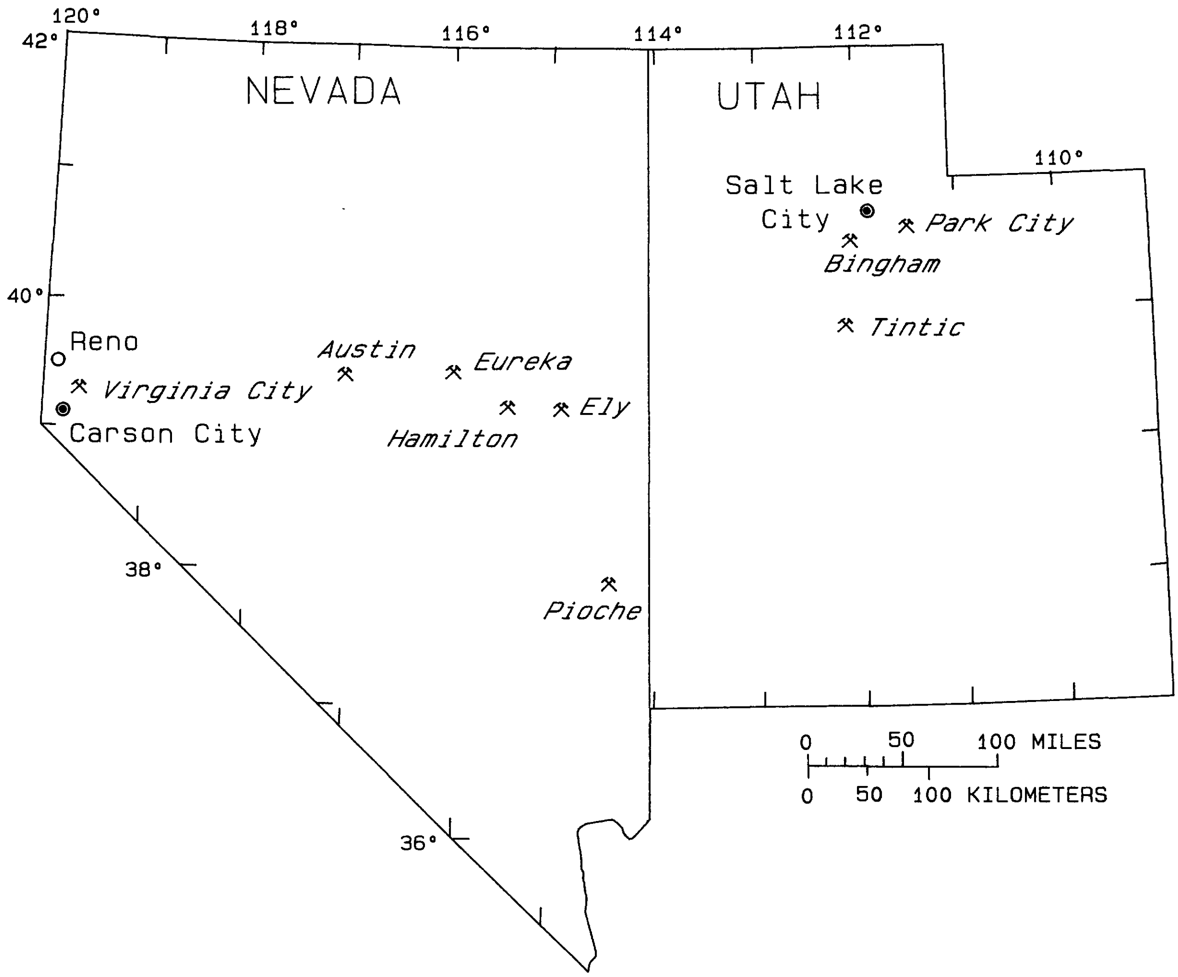



**Figure C8.** Location of the Eureka mining district, Nevada, and some other significant Nevada and Utah mining districts.

amounts of lower grade ore and stope fillings were shipped to Salt Lake Valley smelters.

Beginning in 1919, extensive exploratory drilling was undertaken in search of extensions of the Ruby Hill ore bodies that had been cut off by the northwest-striking Ruby Hill fault. Several drill holes struck ore of good grade, and a new shaft (the Fad) was sunk in 1941–1946 to a depth of 760 m. In crosscutting to the ore intersections from the shaft, however, a large flow of water was tapped, and the shaft was flooded to within a few hundred meters of the surface. Development of the mine then was abandoned, and despite considerable study of methods to accomplish dewatering of the mine to permit access to the ore bodies, the mine has been idle in recent years.

Other mines in the district with significant production include the Diamond mine of the Consolidated Eureka Mining Co., the T.L. shaft of the Eureka Corp., Ltd. (now the Ruby Hill Mining Co.), the Windfall mine, as well as the belt of old mines extending north from the Hamburg to the Dunderberg (fig. C9). All, however, are now idle, although sporadic exploration continues.

Records of production from the Eureka district for the years prior to about 1900 are fragmentary and in many places conflicting. When such information as appears dependable is pieced together, it suggests that in the neighborhood of 2 million tons of ore were mined, containing about 1,650,000 oz of gold, 39,000,000 oz of silver, and 625 million lbs of lead. These metals had a value (at prices existing at the time of production) of somewhat in excess of $120 million. At present-day metal prices, the total value would, of course, be much greater, substantially more than $1 billion.

In addition to the contribution that the production made to the national economy, the Eureka district significantly advanced mineral technology in several respects. Perhaps the most notable was the development of new and improved smelting methods for the oxidized ores of the district; the district has been characterized as the "cradle of modern lead blast furnace smelting." Less well known is the fact that some of the earliest experiments in geochemical and geophysical prospecting were carried out on Ruby Hill. Finally, the Ruby Hill mines constituted one of the earliest districts, if not *the* earliest, in which the leasing or "tribute" system was utilized in mining the ore. Less notable at the time, perhaps, but of major importance to subsequent mining in the United States was litigation to apply mining law to the irregular "limestone replacement" deposits of the district. The dispute between the Richmond and the Eureka Consolidated mines on Ruby Hill resulted in protracted litigation, finally settled in the U.S. Supreme Court.

## GEOLOGY

The Eureka district (fig. C9) was one of the first in the Great Basin to be given detailed geologic study by the newly established U.S. Geological Survey, and the reports on this work by Hague (1892), Walcott (1884), Iddings (in Hague, 1892), and Curtis (1884) were the basis for future work not only in the district but also in adjoining areas in Nevada. Nolan (1962; 1978; Nolan and others, 1956; Nolan and Hunt, 1968) began studies in 1932 in the district; these have continued for a half century, although with decreasing emphasis in recent years.

### Rock Formations

The stratigraphic section initially established in the district has, with relatively minor modifications, continued in use to the present time. The section includes marine strata that represent all the Paleozoic system and that have a total thickness of about 9,000 m; Cambrian formations with a total thickness of about 2,300 m, Devonian units (largely dolomite) totaling about 1,500 m, and Carboniferous and Permian beds totaling about 3,000 m constitute the major part of the section.

A sequence of about 300 m of Lower Cretaceous freshwater sediments was deposited unconformably above these rocks. The Cretaceous sediments were overridden by a series of landslides before lithification; these are now exposed as deeply eroded sheets of megabreccia. A small exposure of quartz diorite that crops out a short distance south of Ruby Hill is of Early Cretaceous age (102–99.5 Ma; Marvin and Cole, 1978, p. 9; Silberman and McKee, 1971, p. 30–31); it is the surface expression of a more extensive mass known from deep drill holes and magnetic anomalies.

Younger rocks include a group of Oligocene intrusive rhyolite plugs, ash-flow and air-fall tuffs, and flows; a number of age determinations on this series of volcanics range from 39 to 34 Ma (Blake and others, 1975; Nolan and others, 1974, p. 6; Jaffe and others, 1959). Other units include Miocene ash-flow tuffs and alkali basalt that are 23–21 Ma (Marvin and Cole, 1978, p. 9; Nolan and others, 1974, p. 6); gravel ranging in age from late Tertiary to Holocene; and locally abundant Pleistocene lakebeds.

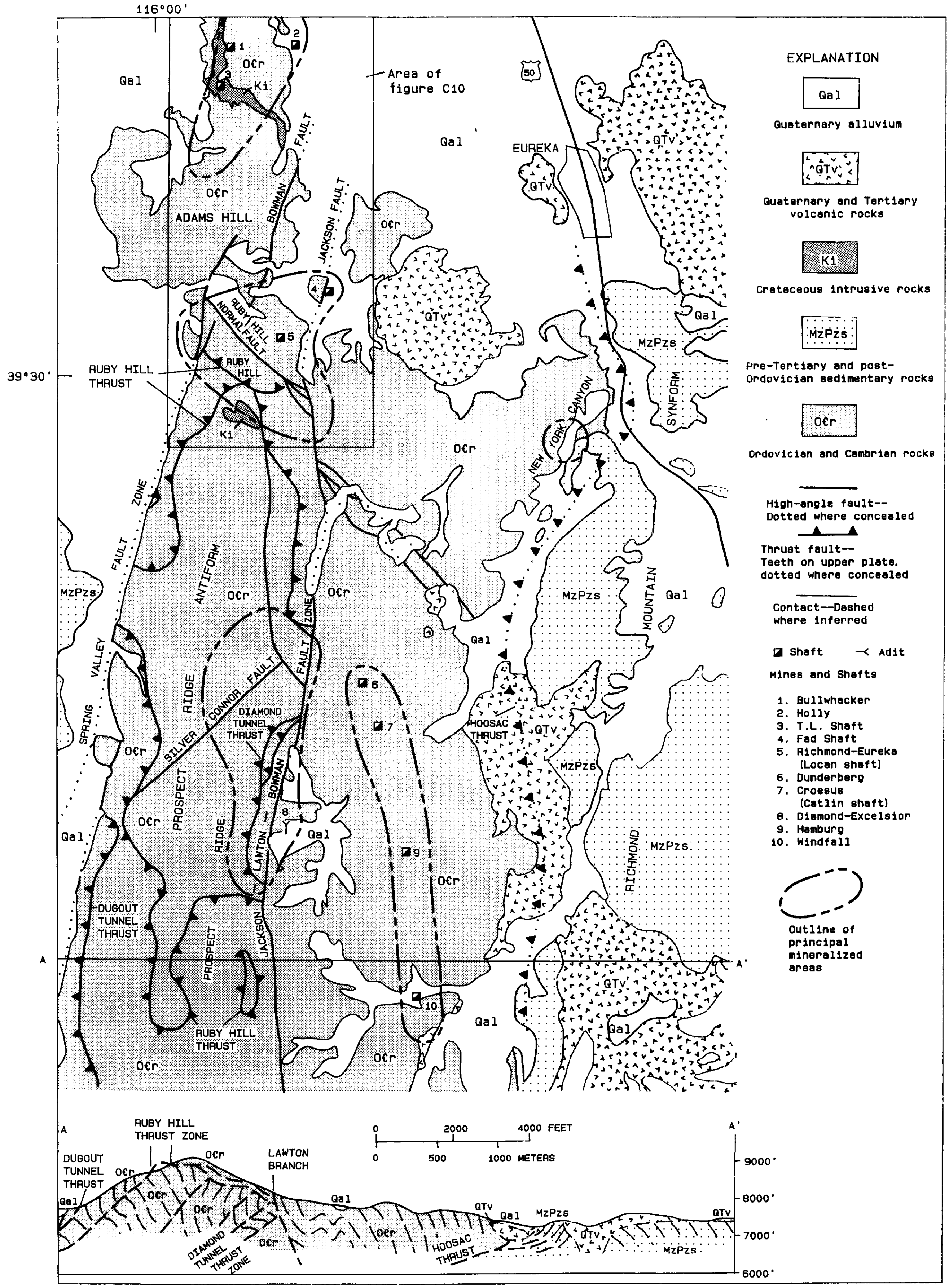
The Cambrian Eldorado Dolomite and Hamburg Dolomite are the host rocks for most of the ores mined in the Eureka district. Limestones in Cambrian and Ordovician formations have also produced some ores, as have calcareous shales in the Secret Canyon and Dunderberg Shales. Characteristically, the ore-bearing dolomites are in part dark gray to black and carbonaceous, although the ores are not known to be directly associated with organic carbon-rich material. The relatively greater brittleness of the dolomitic units is thought to be a more important factor in ore localization than is content of carbonaceous matter. The geologic formations in the Eureka district are summarized in table C4.

### Structure

The Eureka district has been the site of crustal unrest over a long period of time. It lies just east of the probably compound Roberts Mountain thrust system which has brought dominantly clastic lower and middle Paleozoic sedimentary rocks ("western facies") from the west over dominantly carbonate rocks of the same age ("eastern facies"). This zone, which has been dated as of Late Devonian and Early Mississippian age, is not recognized within the Eureka district proper, as there are no marked angular unconformities in the section up to the base of the Permian Carbon Ridge Formation. Disconformities and local clastic horizons, however, indicate nearly continuous regional disturbances during the late Paleozoic.

All of the Paleozoic formations, including the Carbon Ridge Formation of Permian age, have been deformed and cut by thrust faults; these faults have been folded into a series of north-trending antiforms and synforms (fig. C9). Like the Roberts Mountains thrust zone to the west, the structurally lower thrust plates have brought into juxtaposition lithologically different facies of time-equivalent rocks, although the degree of foreshortening is less than that involved in the Roberts Mountains thrust zone. After thrusting ceased, folding persisted into Cretaceous time, as shown by deformation of the Newark Canyon Formation of Cretaceous age northeast of Eureka.

Because the folded Cretaceous rocks were deposited in the developing synforms, the folding is believed to have continued in the Mesozoic and later time. The volcanic rocks were similarly deposited in


116°00'
39°30'
Area of figure C10
EXPLANATION
Qal
Quaternary alluvium
QTv
Quaternary and Tertiary volcanic rocks
Ki
Cretaceous intrusive rocks
MzPzs
Pre-Tertiary and post-Ordovician sedimentary rocks
O€r
Ordovician and Cambrian rocks
High-angle fault--Dotted where concealed
Thrust fault--Teeth on upper plate, dotted where concealed
Contact--Dashed where inferred
Shaft
Adit
Mines and Shafts
1. Bullwhacker
2. Holly
3. T.L. Shaft
4. Fad Shaft
5. Richmond-Eureka (Locan shaft)
6. Dunderberg
7. Croesus (Catlin shaft)
8. Diamond-Excelsior
9. Hamburg
10. Windfall
Outline of principal mineralized areas
EUREKA
50
ADAMS HILL
BOWMAN FAULT
JACKSON FAULT
RUBY HILL NORMAL FAULT
RUBY HILL
RUBY HILL THRUST
NEW YORK CANYON
SYNFORM
SPRING VALLEY FAULT ZONE
ANTIFORM
PROSPECT RIDGE
SILVER CONNOR FAULT
DIAMOND TUNNEL THRUST
FAULT ZONE
BOWMAN
LAWTON
JACKSON
HOOSAC THRUST
RICHMOND MOUNTAIN
DUGOUT TUNNEL THRUST
RUBY HILL THRUST
A
A'
RUBY HILL THRUST ZONE
DUGOUT TUNNEL THRUST
LAWTON BRANCH
DIAMOND TUNNEL THRUST ZONE
HOOSAC THRUST
0 2000 4000 FEET
0 500 1000 METERS
9000'
8000'
7000'
6000'

synforms; in the area east of that of figure C9 they were deposited against a steeply dipping fault that forms the boundary between a synform and an antiform.

Basin-Range normal faults, which were responsible for creating the present mountain ranges, appear to have followed in part the older faults that separate antiforms and synforms. Other faults, such as the Ruby Hill and Silver Connor, transgress the older structures at considerable angles. The topographically expressed faults, such as those that border the Diamond Range northeast of Eureka, branch and die out, and at two localities they clearly have curved traces. They also appear to be offset locally by minor east-trending rifts.

The principal thrust faults in the district proper are, from lowest to highest, the Diamond Tunnel thrust zone, the Ruby Hill thrust zone, and the Dugout Tunnel thrust zone (fig. C9). The Diamond Tunnel thrust zone, which is possibly the oldest of the three, underlies a block of ground in which the ore deposits in and around the Diamond-Excelsior mine occur. The Ruby Hill thrust zone underlies a block of dolomitic rocks at Ruby Hill in which the bulk of the district's productive deposits were formed. Folding occurred during development of the Ruby Hill thrust zone as shown by progressively greater warping of earlier strands of the zone. The Dugout Tunnel thrust zone has no significant ore deposits related to it in the vicinity of Eureka; south of the area of figure C9 there has been some production from the rocks below this thrust.

The Silver Connor transverse fault (fig. C9), representative of several northeast-striking faults, is a steep fault with probable right-lateral strike-slip movement. It formed contemporaneously with the thrusting.

The Jackson-Lawton-Bowman normal fault system (fig. C9) is a north-striking, east-dipping system that had both pre- and post-ore movement, aggregating about 120–900 m. It may have contributed in part to uplift of Prospect Ridge, the high topographic form that extends southward from Ruby Hill and that is bounded on its west side by the north-striking Spring Valley fault zone. The Jackson-Lawton-Bowman fault system probably served as a major channelway for mineralizing solutions in much of the Eureka district.

The Ruby Hill fault (figs. C9, C10, C11), a northwest-striking, northeast-dipping fault with about 600 m of normal displacement, is perhaps the best known fault in the district. It truncates near-surface mineralized ground (oxide ores) on the northeast side of Ruby Hill (fig. C11), and thus it was the object of much interest to early-day miners. It had probably both pre- and post-ore movement on it. The possibility of occurrence of ores on the downdropped northeast side of the fault led to exploration in the 1930's that resulted in discovery of extensive and rich deep sulfide deposits (fig. C11). Because of excessive underground water as well as low metal prices these deposits have not been mined.

**Figure C9** (facing page). Generalized geologic map and section of the Eureka district, Nevada. Modified from Nolan and Hunt (1968, fig. 1).

## Alteration

Carbonate rocks in the vicinity of the ore bodies have been locally bleached and (or) marmorized, but most commonly they are thoroughly fractured. However, at the contact of the Ruby Hill stock (Ki on fig. C9), wallrocks have been converted locally to a hornfels and to a tactite that consists of garnet and diopside and lesser amounts of biotite, chlorite, epidote, pyrite, pyrrhotite, and magnetite. The intrusive rock is locally altered so that biotite has been replaced by chlorite, and feldspars are clouded with alteration minerals. Deep drilling into the stock revealed that the rock contains pyrite and secondary biotite, and it is laced with quartz veinlets that carry sulfides, including molybdenite. Biotite from a sample of such rock has been dated as about 100 Ma (Silberman and McKee, 1971, p. 30–31). The old stopes under Ruby Hill were in many places bordered by jasperoid. Elsewhere, especially along faults, or in other places at the contacts of Dunderberg Shale, irregular podlike bodies of jasperoid have been formed.

The Hamburg Dolomite at the Windfall gold mine was converted to dolomite sand ("sanded") near ore apparently as a result of leaching along dolomite grain boundaries by ore-forming fluids. Small quantities of the arsenic minerals scorodite and realgar are associated with the gold ore. This association suggests that an original Ruby Hill type of arsenic-rich silver-lead ore which replaced the Hamburg Dolomite was altered and leached of its base metals, possibly by hydrothermal fluids derived from the Oligocene dike that cuts through the mineralized zone.

Because of the general spatial association of the Eureka ores with the intrusive rock at Ruby Hill, and the close association of non-economic contact-metasomatic deposits with the Ruby Hill stock, the ores are inferred to be genetically related to the intrusive rocks.

# ORE DEPOSITS

Essentially all the mineralized rocks, as well as the small plug of Cretaceous intrusive rock, are restricted to the antiforms. Probably more than three-quarters of the total production of the Eureka district has come from the mines of Ruby Hill, the summit of which is about 3 km west-southwest of the town of Eureka (fig. C9). The

**Table C4.** Geologic formations present in the Eureka mining district

[Modified from Nolan and Hunt, 1968; leaders (- - -), not applicable]

| Age | Name | | Stratigraphic thickness (in meters) | Lithologic character |
|---|---|---|---|---|
| Quaternary | Alluvium | | 0-150± | Stream and slope alluvium, terrace gravels, and mine and smelter dumps. |
| ----------Unconformity---------- | | | | |
| Miocene | Alkali olivine basalt | | 225+ | Lava flows; a few dikes and small plugs. |
| ----------Tertiary intrusive contact, and unconformity---------- | | | | |
| Oligocene | Rhyolite tuff, rhyolite, and andesite. | | 240± | Welded tuffs; rhyolite flows, plugs, domes, dikes, vent breccias; andesite and rhyodacite flow and dikes; lamprophyre dikes. |
| ----------Tertiary intrusive contact, and unconformity---------- | | | | |
| Late(?) Cretaceous | Quartz porphyry | | --- | Sills and dikes. |
| Early Cretaceous | Quartz diorite | | --- | Intrusive plug south of Ruby Hill. |
| ----------Intrusive contact---------- | | | | |
| Early Cretaceous | Megabreccia | | --- | Landslide sheets. |
| ----------Unconformity---------- | | | | |
| Early Cretaceous | Newark Canyon Formation | | 300± | Fresh-water conglomerate, sandstone, grit, shale, and limestone. |
| ----------Unconformity---------- | | | | |
| Permian | Carbon Ridge Formation | | 300± | Thin-bedded sandy and silty limestone; some included sandstone and dark carbonaceous shale. |
| Unconformity | | | | |
| Early Pennsylvanian-Late Mississippian | Ely Limestone | | 0-500 | Massive-bedded bluish-gray cherty limestone, local chert-pebble conglomerate; brown sandstone beds near base. |
| ----------Unconformity---------- | | | | |
| Late Mississippian | Diamond Peak Formation | | 0-1,200 | Conglomerate, limestone, and sandstone. |
| | Chainman Shale | | 1,100± exposed | Black carbonaceous shale with thin interbedded sandstone. |
| Mississippian | Dale Canyon Formation | | 575 | Grit, sandstone, minor black shale and conglomerate. |
| ----------Break in section---------- | | | | |
| Late and Middle Devonian | Devils Gate Limestone[1] | | 220-500 exposed | Thick-bedded limestone, dolomitized at base. |
| Late Ordovician | Hanson Creek Formation | | 90± exposed | Dark-gray to black carbonaceous dolomite. |
| Late(?) to Middle Ordovician | Eureka Quartzite | | 90 | Thick-bedded vitreous quartzite. |
| Middle and Early Ordovician | Pogonip Group | | 490-560 | Chiefly cherty thick-bedded limestone at top and bottom; thinner bedded shaly limestone in middle. |
| Late Cambrian | Windfall Formation | Bullwhacker Member | 120 | Thin-bedded sandy limestone. |
| | | Catlin Member | 75 | Interbedded massive gray to dark carbonaceous limestone, some cherty, and thin sandy limestone. |
| | Dunderberg Shale | | 80 | Fissile brown shale with interbedded thin nodular limestone. |
| Late and Middle Cambrian | Hamburg Dolomite | | 330 | Massively bedded gray to dark carbonaceous dolomite; some limestone at base. |
| Middle Cambrian | Secret Canyon Shale | Clarks Spring Member | 150± | Thin-bedded platy and silty limestone, with yellow or red argillaceous partings. |
| | | Lower shale member | 60-70 | Fissile shale at surface; green siltstone underground. |
| | Geddes Limestone | | 110 | Dark-blue to black carbonaceous limestone; beds 8-30 cm thick; some black chert. |
| | Eldorado Dolomite | | 800± | Massive gray to dark carbonaceous dolomite; some limestone at or near base. |
| Middle and Early Cambrian | Pioche Shale | | 120-165 | Micaceous khaki-colored shale; some interbedded sandstone and limestone. |
| Early Cambrian and Late Proterozoic | Prospect Mountain Quartzite (base not exposed) | | 560 exposed | Fractured gray quartzite weathering pink or brown; a few thin interbeds of shale. |

[1]Nevada, Lone Mountain, and Roberts Mountains Formations not recognized in mapped area.

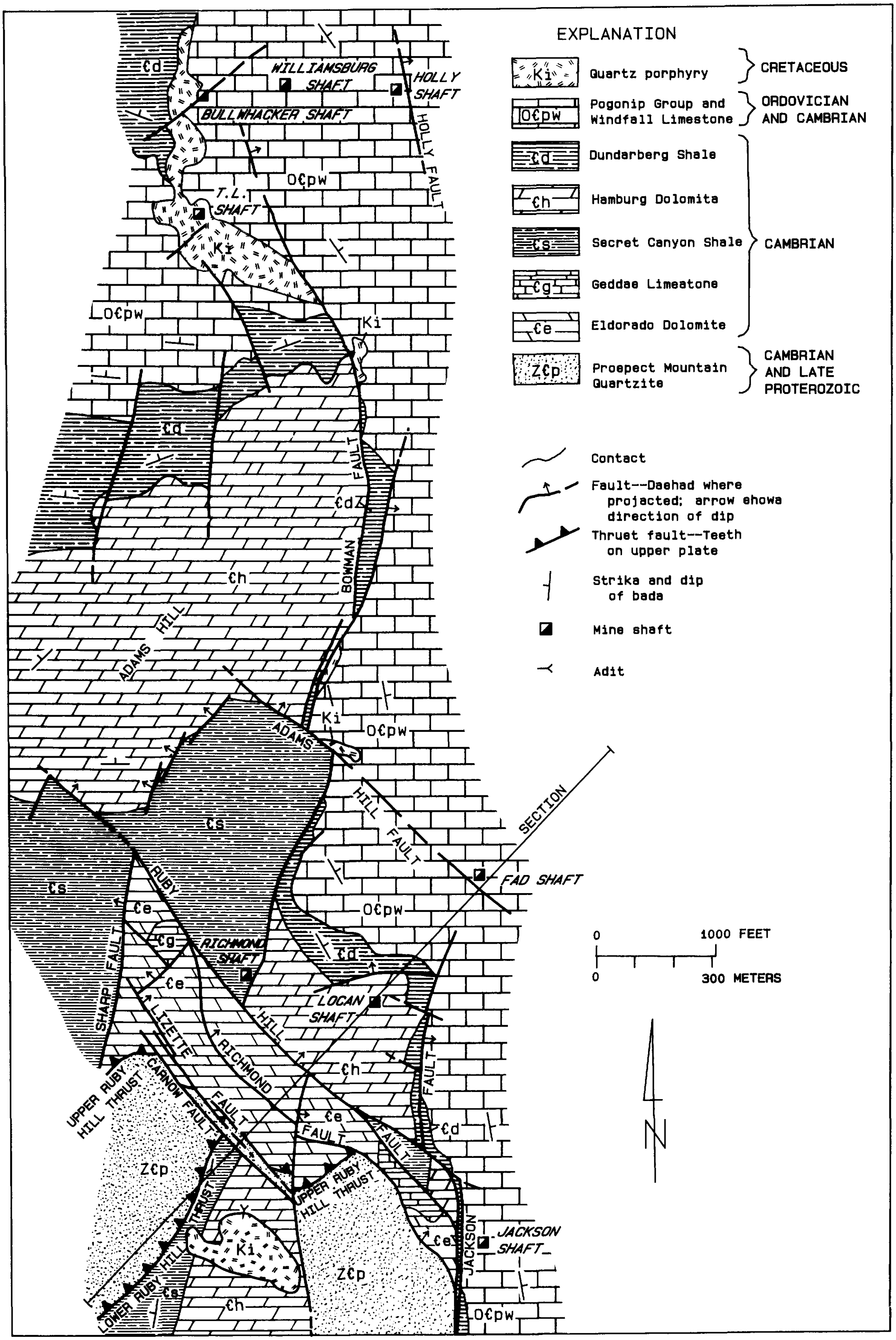



**Figure C10.** Bedrock geology of Ruby and Adams Hills, Eureka district, Nevada. Modified from Nolan and Hunt (1968, fig. 2). Location of area is shown on figure C9. Cross section, figure C11.

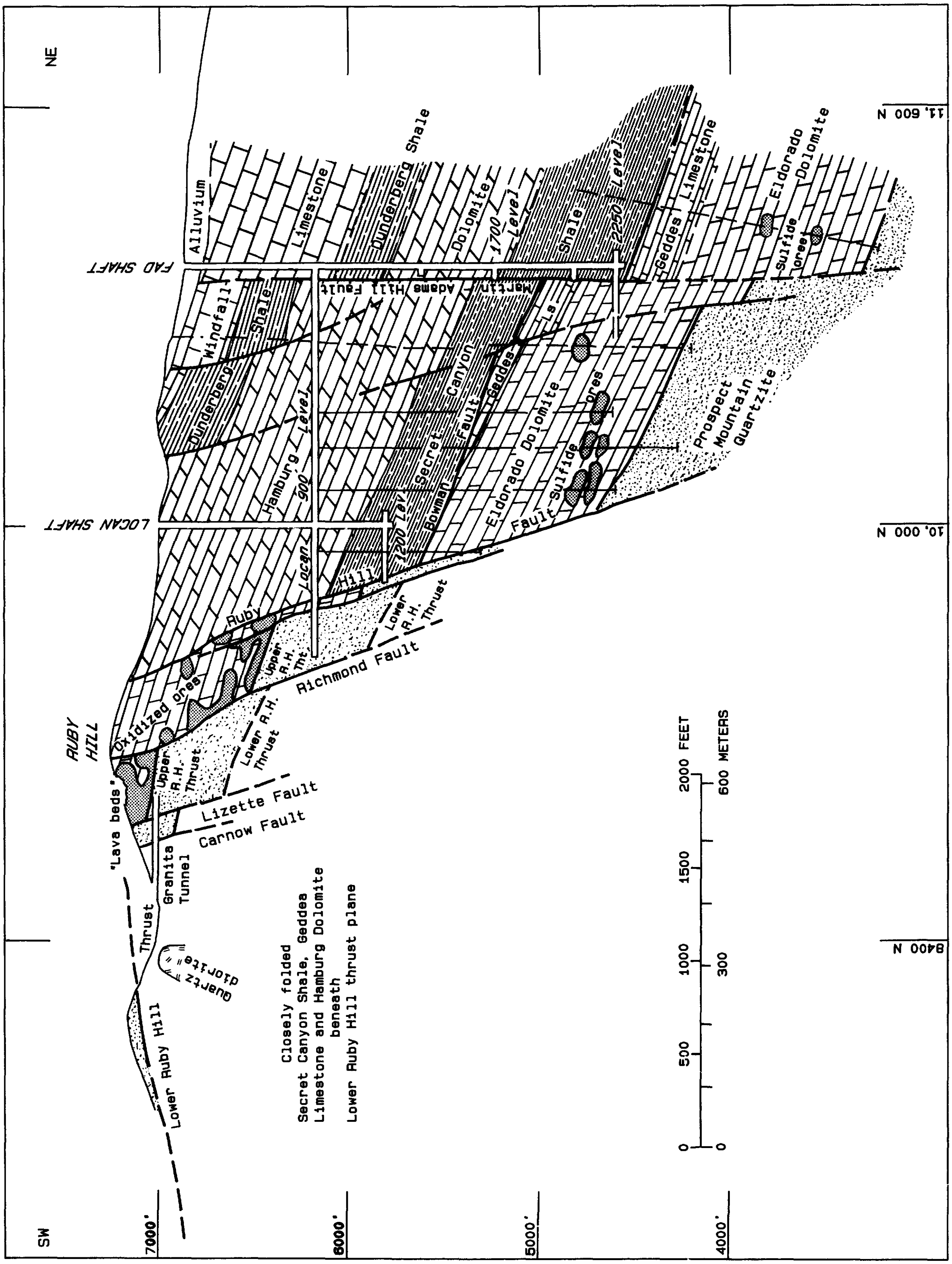



**Figure C11.** Geologic cross section N. 45° E. through Ruby Hill. Modified from Nolan and Hunt (1968, fig. 3). Line of section shown on figure C10. Contacts and faults dashed where inferred. R.H., Ruby Hill. Drill holes shown by vertical or nearly vertical lines (dashed where projected to the plane of section).

Ruby Hill ore deposits form one of five clusters of deposits in the district that are separated by unproductive ground (fig. C9; Nolan, 1962, p. 29).

The Ruby Hill ore bodies were found in a northwest-trending wedge-shaped mass of Eldorado Dolomite (Middle Cambrian). The base of the dolomite mass was truncated by the branching Ruby Hill thrust zone that subsequently was folded into a north-plunging antiform. To the northeast, both the dolomite and the ores were cut off by the more steeply dipping Ruby Hill normal fault (figs. C9–C11); to the west, the ore zone was terminated by a branch of the Basin-Range fault (Spring Valley fault zone) that forms the west boundary of Prospect Ridge (fig. C9).

Individual ore bodies were formed by replacement of the dolomite. Their location, for the most part, was controlled by fractures or faults; the nearly complete oxidation of the original sulfide ores, however, has obscured the important lithologic or structural features. Although some of the ore shoots in the Diamond mine have been characterized as "mantos," most of the Ruby Hill ore was found in irregular replacement bodies, the forms of which were pipelike to more tabular or veinlike. These bodies varied greatly in size, ranging from small podlike bodies a meter or so across to chambers a hundred meters or more in extent. Many of the larger shoots were associated with open caves as much as 50 m high which had formed directly above the large oxidized ore bodies, leading to the speculation that the caves resulted from the leaching action of sulfuric acid formed during supergene oxidation of sulfides. The ground-water table is at various levels in the district, dependent in part at least on impoundment by fault zones, and it almost certainly varied greatly in the past as a result of climatic changes or tectonism.

Most of the ore mined at Eureka was nearly completely oxidized. The oxidized ore in most places contained considerable amounts of iron oxide, anglesite, cerussite, mimetite, plumbojarosite (and probably the arsenic analog, beudantite), bindheimite, and some quartz, halloysite, and calcite. Cerargyrite and native gold were probably present also. Bulk analyses of early-day ore sent to the local smelters suggest that plumbojarosite (and (or) beudantite) may have been abundant constituents.

The oxidized ores on Ruby Hill (fig. C11) were of extremely high grade. Mining during the years 1869–1901 produced 1,317,388 tons of ore that averaged about 1.1 oz Au/ton, 27 oz Ag/ton, and 17 percent Pb. A composite sample of all the Ruby Hill ores treated at the Richmond smelter in 1877 contained 1.59 oz Au/ton, 27.55 oz Ag/ton, and (in percent) 0.12 Cu, 33.12 Pb, 24.07 Fe, 1.89 Zn, 4.13 As, 0.25 Sb, 1.67 S, and 2.95 $SiO_2$. In later years, lower grade ores were produced. For example, about 2,500 tons shipped from Ruby Hill in the years 1920–1925 averaged 0.305 oz Au/ton, 4.21 oz Ag/ton, and (in percent) 0.32 Cu, 6.63 Pb, 34.0 Fe, 5.32 Zn, 2.90 As, 0.51 S, 2.34 CaO, and 12.3 insoluble. (Data are from Nolan and Hunt, 1968, p. 981–982.)

Sulfide ore from the T.L. mine north of Ruby Hill, and from various drill-hole intersections, is probably similar to the original or primary mineralized material. It is made up of pyrite, arsenopyrite, galena, sphalerite, and minor quartz.

Sulfide ores, based on drill-core data from deposits at depth northeast (in the hanging wall) of the Ruby Hill fault (fig. C11), also are of high grade. Large tonnages of mineralized material have a grade-in-place in the range of 0.15–0.2 oz Au/ton, 7.0–9.0 oz Ag/ton, and (in percent), 0.1–0.2 Cu, 5–7 Pb, 9–12 Zn, and 20–30 Fe (Nolan and Hunt, 1968, p. 984). Mineralized material through one diamond drill core interval of 11.1 m assayed 1.33 oz Au/ton, 20.3 oz Ag/ton, 12.6 percent Pb, and 9.37 percent Zn. Mineralized rock through another diamond drill core interval of 20.1 m assayed 0.16 oz Au/ton, 10.5 oz Ag/ton, 7.72 percent Pb, and 9.78 percent Zn. (Data are from Nolan, 1962, pl. 8.)

Gold ore at the Windfall mine differs markedly from the other ores of the district. Windfall ore occurs in altered "sanded" dolomite at the contact of the Hamburg Dolomite with the overlying Dunderberg Shale. The gold ore is relatively low in grade (at the present time about 0.04 oz Au/ton according to A.B. Wallace and J.S. Livermore (written commun., 1983), though grades mined early in the century were higher). Nolan and Hunt (1968, p. 989) indicated that about 65,000 tons of this ore was mined in the years 1908–1916, and A.B. Wallace and J.S. Livermore (written commun., 1983) suggested an overall current tonnage (production and reserves) of about 2.5 million tons of ore. Ore mined in the earlier period was in shoots 15–50 m across that were localized by cross faults that displaced the Hamburg-Dunderberg contact. Gangue minerals, sulfides, and silver are nearly absent. Sparse small pods of jasperoid are present near the Windfall mine and in the ore zone; one mass of jasperoid contains abundant realgar and much fine-grained pyrite.

Low-grade gold ore in the Dunderberg Shale was being mined in 1987 by Eureka Ventures, Inc. at the Lookout Mountain mine in Ratto Canyon south of the area of figure C9 (R.G. Luedke, oral commun., 1987).

Exploration in recent years, cited previously, has demonstrated the presence of relatively unoxidized sulfide ore in the Eldorado Dolomite in the hanging wall of the Ruby Hill fault. This ore, which contains substantial amounts of gold, silver, lead, and zinc, has not as yet been exploited, in large part because of the problems presented by the large quantities of water, and also because of depressed metal prices. Drilling marginal to the lead-silver ore has indicated a considerable area of iron-zinc-mineralized ground that suggests a possible zonal arrangement of the ores relative to the quartz diorite intrusive body.

Other mines productive in the past in the Eureka district include the T.L., Bullwhacker, and Holly to the north, and the Diamond, Silver Connor, Dunderberg, Croesus, Hamburg, and Windfall to the south. Except for the Windfall mine, most of these mines produced oxidized gold-silver-lead ore from replacement bodies in dolomite. However, the host dolomite in most of the southern mines was the younger Hamburg Dolomite rather than the Eldorado Dolomite; most of the production from the mines north of Ruby Hill has come from deposits in the Windfall Formation and Pogonip Group.

## SUMMARY AND CONCLUSIONS

Marine carbonate formations and minor amounts of clastic sediments were deposited in Paleozoic time on an extensive shelf at the west margin of what is now west-central North America. Formations that were to become significantly mineralized at Eureka are characteristically shallow water deposits, now dolomite. Their more westerly correlatives are limestone. During late Paleozoic and Mesozoic time extensive thrust faulting transported plates of carbonate rocks eastward, such that at Eureka three prominent faults juxtaposed previously separated lower Paleozoic formations. Folding accompanied and followed the thrust faulting, and the folded thrust faults (themselves antiforms and synforms) act as bounding faults to the complexly folded sedimentary rocks that also constitute antiforms and synforms, and that are such prominent features of present-day geology. Folding of the antiforms and synforms continued long after the major thrust faulting ceased probably in late Paleozoic or early Mesozoic time. The synforms became the locus of deposition of the non-marine Newark Canyon Formation of Cretaceous age. The Newark Canyon was itself folded, and the Oligocene volcanic rocks were deposited in the continually rejuvenated synforms.

The Ruby Hill stock, following its intrusion, became a center of hydrothermal activity probably in later Cretaceous time. Although it is exposed only in the north part of the district, airborne magnetic measurements indicate that the intrusive mass is a linear body underlying the antiform of Prospect Ridge. The stock has "cupolas," such as the one at Ruby Hill, and it is possible that each cluster of ore deposits in the district (fig. C9) represents a separate mineralized system focused on an individual "cupola." Extensive mineralization took place in such localities, forming the rich gold-silver-lead ores for which Eureka is renowned. Mineralizing fluids were directed to favorable host rocks primarily along the north-trending Jackson-Lawton-Bowman fault system and the Ruby Hill normal fault. The brittle Eldorado and Hamburg Dolomites were extensively fractured and hence favorably permeable for passage of ore fluids, whereas less brittle limestone beds in these formations are in many places marmorized and barren. Galena is more abundant near the Ruby Hill stock and the Ruby Hill fault, and sphalerite is more abundant farther from them, suggesting that the ore-forming solutions may have changed by reaction with the host rock as they flowed outward from the stock and main conduits; decreasing temperature presumably also played a role in the zoning.

The Windfall mine gold ore is quite different from the base metal ores in the other properties on Prospect Ridge. As noted above, it may represent reworking of an original base metal-rich ore by solutions from an Oligocene dike that cuts through the ore body. The presence of realgar in a mass of jasperoid within the ore body suggests that these younger mineralizing solutions may also have been responsible for a gold-rich ore body at the Oswego mine south of Prospect Ridge (south of area of fig. C9). It too contains small amounts of realgar and orpiment; a dike of the Oligocene-Eocene Ratto Spring Rhyodacite is exposed nearby.

Geochemical anomalies suggest that undiscovered ore deposits in the Eldorado Dolomite and the Hamburg Dolomite may occur at moderate depths in the vicinity of the mineralized clusters. Higher metal prices are probably needed to encourage exploration of these anomalies and of other structurally favorable areas.

The presence of widespread jasperoid in areas in the vicinity of the Oligocene rhyodacite, coupled with the speculative correlation of the gold deposits at the Windfall mine and the mines south of Prospect Ridge to these younger rocks, suggests that low-grade gold deposits may exist in formations adjacent to the jasperoids. The inconspicuous character of such deposits could easily hinder their discovery in a district where high-grade ores provided a much more obvious target for mining. Some caution is needed in such exploration, however, as jasperoid also has been formed in the areas of older deposits.

Known sulfide deposits intersected by drilling in the downthrown block north of the Ruby Hill fault remain an attractive target, but their exploitation will depend on solution of both the economic and technical problems that the depth and the large flow of water present.

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# Gold in the Central City Mining District, Colorado

*By* Alan R. Wallace

**Abstract**

The Central City district in central Colorado contains complexly zoned precious and base metal deposits of hydrothermal origin that were directly related to the emplacement of an alkalic rhyolitic magma. The ores are in steeply dipping, mainly northeast trending faults and fractures that cut brittle Proterozoic gneisses; ore shoots are laterally and vertically continuous. The ore deposits are centered around a barren quartz-pyrite core, the periphery of which is marked by gold- and copper-rich veins. These veins grade outward into base metal- and silver-rich veins, which in turn grade into a barren outer zone; the gold:silver ratio decreases outward from the core, from 5:1 to 1:100. Molybdenite occurs in early quartz-pyrite veins and in late fluorite-bearing veins in an area that partly overlaps the southeastern edge of the base metal zonation. Gold telluride veins, which formed during the last stage of mineralization, form an elongate northeast-trending belt in the southeast part of the area.

The mineral deposits were formed largely in Late Cretaceous to Paleocene time, coincident with the emplacement of a complex suite of epizonal stocks and dikes. Temperatures of mineralization were between 300 and 350 °C during the main stage of gold-silver and early molybdenite mineralization; temperatures dropped to 200–280 °C in peripheral zones and during later molybdenite mineralization. Evidence for boiling has not been reported, and reconstructed depths of ore formation range from 1.5 to 3.0 kilometers. Stable isotope data indicate that the hydrothermal fluids responsible for the central quartz-pyrite veins were of primary magmatic origin, whereas the fluids that formed the peripheral or later veins were a mixture of magmatic and evolved meteoric water. Mixing of these two fluids and slight thermal gradients across the district were responsible for much or all of the mineral deposition.

## INTRODUCTION

The Central City district is in the Proterozoic core of the Front Range, approximately 50 km west of Denver, Colo. (fig. C12). The district contains the richest segment of a regionally zoned mineralized area that includes the peripheral Idaho Springs, Chicago Creek, Freeland-Lamartine, and Lawson-Dumont-Fall River districts (fig. C13). These districts lie within the Colorado mineral belt, an elongate belt of mineral deposits and Upper Cretaceous and Tertiary intrusive rocks that extends northeast from the San Juan Mountains to the Jamestown district in the Front Range. The Central City and adjacent districts cover approximately 95 km$^2$ in Clear Creek and Gilpin Counties. They are readily accessible from Interstate 70, U.S. Highway 6, and numerous paved and gravel county and local roads. Towns include Idaho Springs, Central City, Black Hawk, Lawson, and Dumont, of which Idaho Springs is the largest.

Placer gold was discovered along Russell Gulch, southeast of Central City, by W. Green Russell in 1858, and near the future townsite of Idaho Springs by George Jackson in early 1859; the first lode was discovered by John Gregory in 1859 just east of the present site of Central City, igniting a rush to the area. Early mining

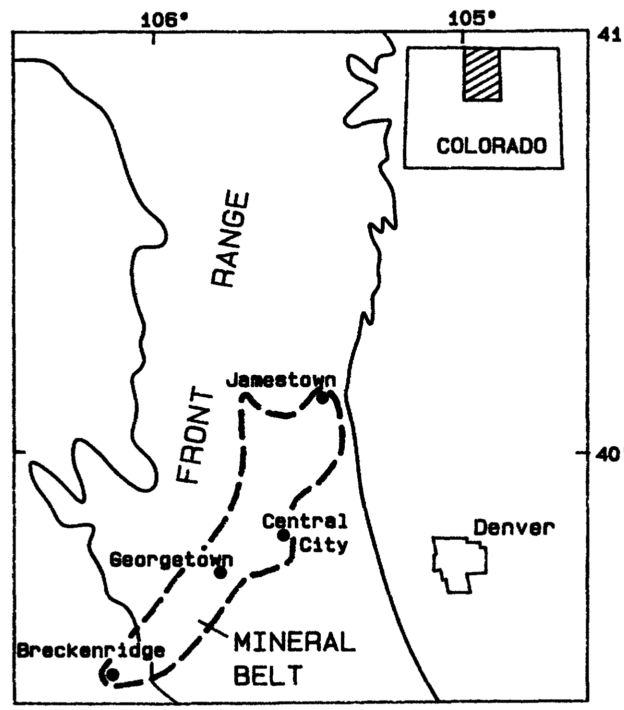


**Figure C12.** Location of the Central City mining district, Colorado.

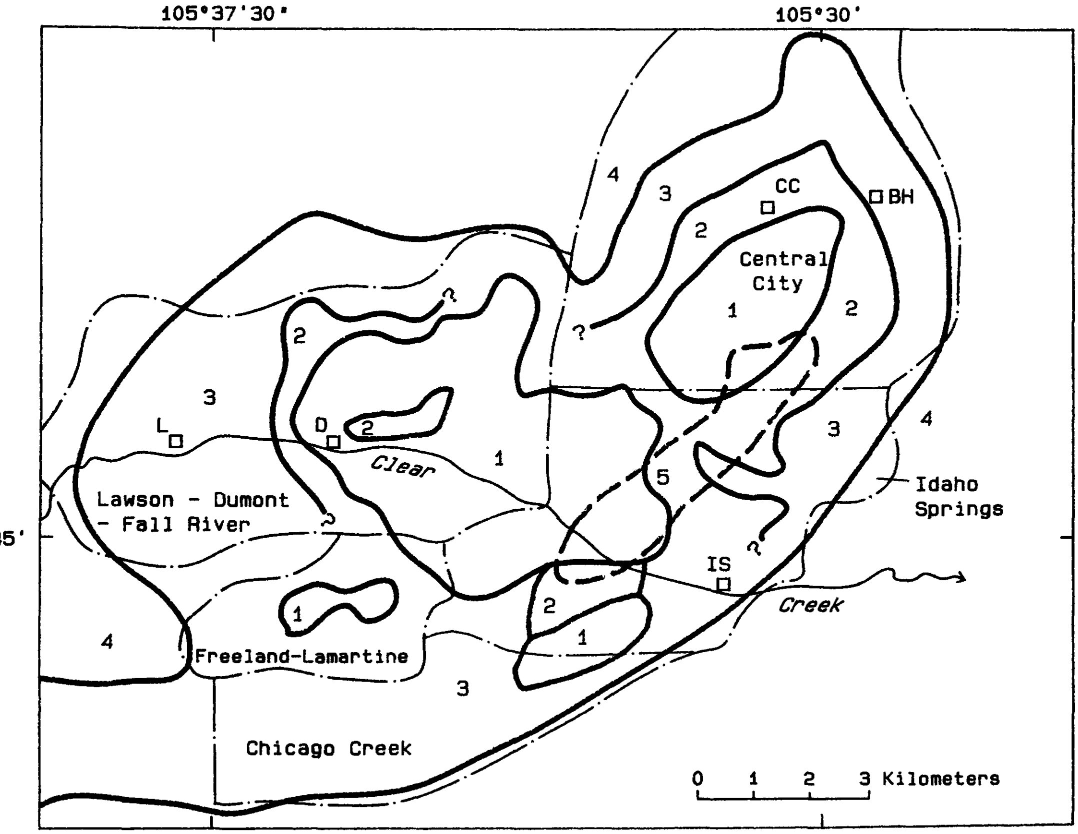


**Figure C13.** Locations of the Central City and surrounding mining districts, Front Range, Colorado, relative to regional hydrothermal mineral zonation: 1, central zone; 2, intermediate zone; 3, peripheral zone; 4, barren outer zone; 5, enargite-bearing zone. Mineral zones from Hawley and Moore (1967); boundaries queried where extent uncertain. IS, Idaho Springs; CC, Central City; L, Lawson; D, Dumont; BH, Black Hawk.

exploited oxidized and readily treated gold ore along the upper 10–40 m of the steeply dipping veins. Within a few years, mining encountered unoxidized pyritic ores, which led to the construction of specialized stamp mills throughout the area and, in 1868, to the development of new amalgamation methods and smelters at Black Hawk, adjacent to Central City. Silver-rich veins also were exploited, but production was largely curtailed during and after the 1873 depression and the 1893 silver panic, when the price of silver plummeted. Mining activity was erratic and generally declined after the turn of the century. Small-scale, short-term lode and placer mining activity has persisted intermittently since World War II. Excellent descriptions of early mining and metallurgy are available in Bastin and Hill (1917) and Sims, Drake, and Tooker (1963).

Production from Gilpin County between 1859 and 1914 totaled 1 million oz of gold, about 55 million oz of silver, 4,777 tons of copper, 77,647 tons of lead, and 9,682 tons of zinc (Bastin and Hill, 1917, p. 174). Total production from the Central City and surrounding districts between 1859 and 1959 exceeded $200 million at prevailing prices, more than half of which came from the Central City district and a third of which was derived from the Idaho Springs district. Production since 1959 has been minimal.

Bastin and Hill (1917) provided the earliest major description of the geology and ores of the Central City district. In the early 1950's, the U.S. Geological Survey began a comprehensive geologic study of the Central City and related districts, resulting in reports and maps for the Central City district (Sims, Drake, and Tooker, 1963; Sims and Gable, 1967; Sims and Barton, 1962), the Idaho Springs district (Moench, 1964; Moench and Drake, 1966), the Chicago Creek district (Harrison and Wells, 1959), the Freeland-Lamartine district (Harrison and Wells, 1956), and the Lawson-Dumont-Fall River district (Hawley and Moore, 1967). Related reports described the alteration (Tooker, 1963), uranium deposits (Sims, Armstrong, and others, 1963), and intrusive rocks (Wells, 1960). More recent studies by C.M. Rice and colleagues have provided additional data on the geochronology of the intrusive rocks and the hydrothermal deposits (Rice and others, 1982), as well as on the source of fluids and the T-P (temperature-pressure) conditions during mineralization (Rice and others, 1982, 1985). These and other reports were used extensively for this summary.

## GEOLOGIC SETTING

The Front Range is a basement-cored uplift that formed during the Late Cretaceous–early Tertiary Laramide orogeny. Phanerozoic sedimentary rocks flank the Proterozoic basement but are absent in the Central City district. The basement rocks consist of complexly deformed metasedimentary and metavolcanic rocks that were intruded by Proterozoic batholiths at 1,700 and 1,400 Ma. Faults and joints formed during both Proterozoic and Tertiary tectonism, and stocks and dikes were emplaced during Laramide time.

### Proterozoic Host Rocks

The principal Proterozoic host rocks for the veins of the Central City and surrounding districts are layered and deformed gneisses. Sillimanite-biotite-quartz gneiss and microcline gneiss are the predominant rock types, although granite gneiss, amphibolite, calc-silicate gneiss, cordierite gneiss, migmatite, and pegmatite are locally abundant. Layering in adjacent units is generally conformable, and some contacts are gradational. Protoliths for the gneisses included interbedded intermediate to basic volcanic flows and volcaniclastic rocks, sandstone and mudstone, arkose, and impure limestone (Moench, 1964). Metamorphism to amphibolite grade took place before and during the emplacement of the older, synkinematic Boulder Creek Granodiorite at about 1,700 Ma (Peterman and Hedge, 1968), achieving P-T conditions of about 3.5 kb and 650–700 °C (Olsen, 1984).

### Laramide Intrusive Rocks

Thirteen suites of epizonal dikes and stocks of Laramide age have been identified in the Central City and related districts (Wells, 1960). They include, in decreasing age, four suites of granodiorite, alkalic syenite, two suites of quartz monzonite, granite, alaskite, bostonite, trachytic granite, quartz bostonite, and biotite-quartz latite. Most of the intrusives are porphyritic and have relatively fine grained groundmasses. According to Wells (1960), quartz monzonite, granite, bostonite, and quartz bostonite are widespread; and the other suites, although locally abundant, are less widespread. All workers recognized that older units formed irregular plutons having associated radiating dikes, whereas younger suites formed long, narrow dikes. The biotite-quartz latite is the only suite that formed after vein mineralization. The others are altered and cut by hydrothermal veins.

Major and trace element analyses of some of the intrusive rocks indicate a progressive increase in $SiO_2$ and alkali contents and a decrease in ferromagnesian minerals and CaO and barium contents with time, during the intrusive sequence (Simmons and Hedge, 1978; Rice and others, 1985). All the intrusive rocks are anomalously radioactive (Wells, 1960), mainly because of high thorium and uranium contents of zircon; whole-rock thorium and uranium concentrations increase with decreasing age through the intrusive sequence.

Both Simmons and Hedge (1978) and Rice and others (1985) concluded that the bostonite was crystallized from highly differentiated magma derived from a leucocratic monzonite parent magma (the leucocratic granodiorite suite of Wells, 1960). High initial Sr ratios in the bostonite suggest some upper crustal contamination. Early biotite granodiorite stocks are exposed in the Fall River area and north of Central City. Trace element studies by Simmons and Hedge (1978) indicate that the biotite granodiorite represents undifferentiated magma. This magma, with varied amounts of contamination, was possibly the parent for the bostonite and other magmas. Alternatively, two isolated magma chambers, one homogeneous and the other differentiated or contaminated, were present at approximately the same time and place. Lead and strontium isotopic data by Stein (1985) and Simmons and Hedge (1978) indicate that the parent magmas in the Front Range were produced by partial melting of the lower crust, with perhaps a small component of mantle-derived magma (Stein, 1985).

Two large intrusion-related breccias are present in the district. The Gold Cup breccia pipe, 1,500 m north of Central City (fig. C14), is an oval-shaped intrusion breccia containing fragments of Proterozoic rocks in a matrix of monzonite porphyry. It cuts quartz monzonite porphyry dikes and in turn is cut by pyrite and galena-sphalerite veins. The Patch, approximately 1 km southwest of Central City, is a steeply dipping breccia pipe containing angular to rounded fragments of Proterozoic rocks set in an "arkose-like matrix" (Sims, Drake, and Tooker, 1963, p. 95) that includes hydrothermal gangue and sulfide minerals.

### Structure

Episodic Proterozoic deformation produced several sets of folds, faults, and joints that were modified by Laramide events. Early folding, accompanied by upper amphibolite grade metamorphism, produced

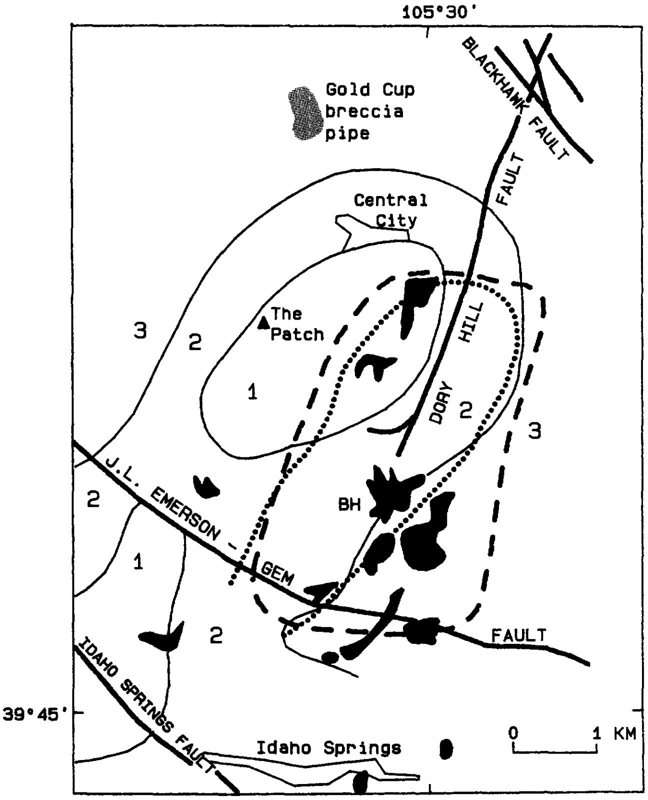


**Figure C14.** Distribution of Laramide stocks (black), major faults, and mineral zones in Central City and adjacent districts. 1, central pyrite-quartz zone; 2, intermediate pyrite+base-metal sulfide zone; 3, peripheral sphalerite-galena zone; short-dash line outlines molybdenite zone; dotted line outlines enargite-bearing zone. BH, Banta Hill pluton. Telluride ores occur along or near Dory Hill fault zone and its projection to the south. Modified from Rice and others (1985), Sims, Drake, and Tooker (1963), and Moench and Drake (1966).

broad west-northwest-trending folds in the metamorphic rocks (Taylor, 1976). Subsequent deformation produced large north-northeast-trending folds, several of which are prominent in the Central City and Idaho Springs districts, superimposed on the early folds. The superimposed folds have wavelengths of a kilometer or more. The Boulder Creek batholith was emplaced during the waning stages of this event. A third major episode of deformation, characterized by cataclasis, shear, and folding, was concentrated in a northeast-trending belt named the Idaho Springs–Ralston shear zone (Tweto and Sims, 1963).

Three major steeply dipping joint sets have been identified in the Proterozoic rocks: N. 70°–80° E., N. 70°–75° W., and N. 12°–30° W. (Sims, Drake, and Tooker, 1963). Proterozoic layering or structures did not influence the joints, and the joints are inferred to be of Laramide age. Significantly, Laramide dikes were intruded preferentially along joints rather than along faults or other structures.

Faults, abundant in the crystalline rocks, were the sites of vein mineralization in all of the districts. Most of these faults are of Laramide age, but at least two sets have a Late Proterozoic ancestry. The latter include the northwest-trending Black Hawk, J.L. Emerson–Gem, and Idaho Springs faults and the north-northeast-trending Wild Wagoner–Apex and Dory Hill faults (Sims, Drake, and Tooker, 1963, p. 16).

Laramide faults are much more abundant than Proterozoic faults and cut all Laramide intrusions except the biotite-quartz latite. Major fault sets dip steeply and trend east, east-northeast, and northeast. East-trending faults are most abundant in the Central City district; they are characterized by small left-lateral displacements. East-northeast-trending faults are widespread, and are the most economically important set in the Central City, Lawson-Dumont-Fall River, and Idaho Springs districts; they have a small right-lateral displacement. The northeast-trending faults are most abundant in the Idaho Springs, Chicago Creek, and Central City districts, and they show a small right-lateral displacement. Although the faults are roughly contemporaneous, detailed mapping shows that the east, east-northeast, and northeast sets formed sequentially (Sims, Drake, and Tooker, 1963). The faults formed in response either to an east-northeast-directed regional compression (Sims, Drake, and Tooker, 1963, p. 25) or to stresses related to a dextral shear system (Lovering and Goddard, 1950).

## MINERAL DEPOSITS

The ores of the Central City and surrounding districts include base and precious metal veins that fill faults and other fractures in Proterozoic and Laramide rocks, as well as a stockwork deposit in a large breccia pipe. The rocks adjacent to the veins are altered to quartz, sericite, and clay minerals. The ore and gangue minerals form a concentric, district-wide zonation that includes an inner central zone, an intermediate zone, and peripheral zones (figs. C13, C14). The general paragenesis of the ores is early pitchblende, followed by molybdenite and base metal sulfide veins and by later molybdenite and telluride ores. The ore deposits were formed during the Late Cretaceous and Paleocene.

### Alteration

Hydrothermal alteration in rocks adjacent to the veins consists of an inner quartz-sericite-pyrite halo and outer argillic haloes. Wall rock quartz, potassium feldspar, and muscovite remained relatively stable during alteration, whereas plagioclase, hornblende, and biotite were variously replaced by quartz, sericite, montmorillonite, chlorite, kaolinite, illite, and mixedlayer clays (Tooker, 1963; Kramer, 1984). Therefore, the proportions of relatively stable versus unstable minerals in the wall rocks partly determined the intensity of alteration and the width of the alteration halo. In the central pyritic core of the district, the width of the alteration halo adjacent to a vein is generally proportional to the width of the vein, whereas in the outer two district-wide zones the widths of vein and alteration haloes are not related (Sims and Barton, 1962). Haloes are generally wider in the center of the district and can exceed 3 m, whereas in the periphery haloes are only a few centimeters to a meter wide. The quartz-sericite-pyrite alteration halo is disproportionately narrower in the periphery of the district.

Alteration largely preceded and accompanied early sulfide vein mineralization. However, alteration around later telluride veins, some of which cut quartz-sulfide veins, must be younger than the alteration around the sulfide veins. Therefore, alteration around any one fracture-filling vein was probably temporally related to mineral deposition in that particular fracture.

## Veins

The ore deposits of the Central City and surrounding districts occur largely as sulfide-quartz veins that filled open fracture zones, but also included is the mineralized breccia of The Patch. Pyrite, galena, sphalerite, chalcopyrite, and tennantite are the dominant sulfide minerals; pitchblende, telluride minerals, and enargite are locally important. Quartz composes most of the gangue, although carbonates and barite are abundant in peripheral zones. Numerous other hypogene ore and gangue minerals have been reported from the various districts, including fluorite, tungstate minerals, molybdenite, electrum, native gold, native silver, pearceite, and marcasite.

The larger ore shoots were localized by fault intersections, dilatant zones, and deflections in strike and dip. Brittle wall rocks such as microcline gneiss tended to form open breccia zones that were subsequently mineralized, whereas less brittle wall rocks, such as mica schist, tended to form gouge zones that impeded the flow of hydrothermal fluids. Ore grades remained relatively constant with increasing depth, but ore shoots in the deeper workings were confined to fault segments with brittle wall rocks (Sims, Drake, and Tooker, 1963). At The Patch, sulfide and gangue minerals were deposited in the interstices between breccia fragments, indicating that the breccia pipe formed prior to mineralization.

The ore and gangue minerals in the Central City–Idaho Springs and nearby districts have a distinct geographic zonation (Sims, Drake, and Tooker, 1963; Sims and Barton, 1962; Hawley and Moore, 1967, pl. 4). In general, the zonation consists of three crudely concentric zones within an area roughly 17 km long and 10 km wide that is elongated northeasterly (Hawley and Moore, 1967, pl. 4; this report, figs. C13, C14).

The central zone is composed of tight quartz-pyrite veins that contain minor amounts of other sulfide minerals. Unlike the surrounding zones, the host fractures in the core of the central zone were not notably reactivated after initial vein mineralization. Accordingly, most of the veins are barren or of very low grade, and production from this zone was relatively small. However, some chalcopyrite-bearing veins in the periphery of the core contained minable grades, and Au:Ag ratios ranged from 5:1 to 1:9.

The intermediate zone contains quartz-pyrite veins having substantial amounts of base metal sulfide and sulfosalt minerals, notably sphalerite, galena, chalcopyrite, tennantite, and locally important enargite. At the Smith mine between Central City and Black Hawk, an early pyrite stage of mineralization was followed by base metal sulfide, galena, chalcopyrite, and late pyrite stages of mineralization (Kramer, 1984). In the Idaho Springs district, Moench and Drake (1966) subdivided the intermediate zone veins into pyritic copper and pyritic lead-zinc veins; at Central City, Sims and Barton (1961) made the distinction between chalcopyrite-tennantite-bearing veins (Type A) and tennantite-enargite-bearing veins (Type B). Native gold, electrum, and various silver-bearing minerals were deposited in this zone, producing high-grade veins having Au:Ag ratios of 1:2 to 1:20.

The peripheral zone is composed of galena-sphalerite veins containing subordinate pyrite and quartz. Pearceite and other silver minerals, chalcopyrite, barite, carbonate minerals, tennantite, and fluorite are also present. Gold is relatively sparse in this zone, and the gold:silver ratio is between 1:20 and 1:100. A zone of barren veins composed of carbonate minerals, barite, and quartz surrounds the major ore-bearing zones.

Other vein assemblages not spatially related to the general district-wide zonation are of less economic importance; these include pitchblende veins, two stages of molybdenite-bearing veins, telluride ores, and Type B enargite ores described by Sims and Barton (1961). Discontinuous pitchblende-pyrite-quartz pods and veins were mined in all the districts, but most notably in the Central City district. The Central City pitchblende ores cut quartz bostonite dikes and are cut by the main quartz-pyrite stage of mineralization (Sims, Armstrong, and others, 1963). In the Fall River district, pitchblende was deposited with pyrite, niccolite, and pararammelsbergite during an early stage of vein mineralization.

Molybdenite has been reported in the Central City, Idaho Springs, and Lawson-Dumont-Fall River districts. The earliest molybdenite-bearing veins contain quartz, pyrite, sericite, and bismuthinite (Moench and Drake, 1966; Rice and others, 1985). Where noted, the molybdenite:pyrite ratio decreases inward in the veins. Most of the early molybdenite veins lie outside the central pyrite-quartz zone (fig. C14), and the temporal relationship between these veins and the early quartz-pyrite stage of mineralization is unknown. In addition, some quartz-pyrite veins contain paragenetically early wolframite, and the relationship of these veins to the early molybdenite veins is also unknown. Molybdenite also occurs in younger veins together with quartz, fluorite, and pyrite in a small area within the larger area of early molybdenite veins; tellurides have been reported from the same veins, but the paragenetic relationship to the molybdenite is equivocal. The molybdenite-bearing veins in the Central City district, both early and late, occur largely in a north-northeast-trending oval area (fig. C14) that overlaps the southeast edge of the district-wide zoning pattern and which is centered around the quartz bostonite Banta Hill pluton (Rice and others, 1985). Those in the Lawson-Dumont-Fall River district are concentrated near the east edge of the district (Hawley and Moore, 1967).

Telluride veins occur in a narrow north-northeast-trending belt in the eastern part of the Central City and Idaho Springs districts, roughly coincident with the Dory Hill fault and its southwestern projection (fig. C14). The grades of the ores were extremely high: telluride ore from the War Dance mine assayed 20 oz Au and 3.5 oz Ag/ton (Bastin and Hill, 1917). The few published descriptions of the veins indicate that they occur along fractures that are parallel to and locally cut the base metal veins. The tellurides, chiefly sylvanite but also hessite and petzite (Rice and others, 1985), are associated with cherty quartz, pyrite, fluorite, and tennantite.

Enargite-bearing base metal veins form a narrow northeast-trending belt, coincident with the zone of molybdenite veins at its north end, which partly overlaps the intermediate zone of the Central City and Idaho Springs districts (figs. C13, C14). The enargite is intergrown with tennantite; in the Idaho Springs district, the veins also contain chalcopyrite, whereas in the Central City area enargite and chalcopyrite are mutually exclusive (Sims, Drake, and Tooker, 1963).

Early mineralizing fluids produced the early molybdenite veins and the central quartz-pyrite vein zone, but the ranges of their occurrence do not coincide. Pitchblende veins are cut by the quartz-pyrite veins, so pitchblende may represent the earliest episode of mineralization in the district. Following a major episode of brecciation along the mineralized structures, newly opened fractures and incompletely mineralized quartz-pyrite veins were filled with the base metal assemblage to form an aureole that overlapped and extended beyond the outer half of the central quartz-pyrite zone. The core of the pyrite-quartz zone was not remineralized. Copper-bearing minerals were deposited nearer the center of the district, whereas carbonate minerals and lead and zinc sulfide minerals were more abundant in the peripheral areas of the district. The gold:silver ratio decreases outward, as does the iron content of sphalerite (Sims and Barton, 1961). Many individual veins graded laterally from a quartz-pyrite assemblage to a base metal assemblage. Bastin and Hill (1917, p. 102) and Moench and Drake (1966) observed that base metal veins became more pyritic with increasing depth, and Harrison and Wells (1956) noted a decrease in galena and sphalerite with increasing depth in the Freeland-Lamartine district. Later mineralization in the vicinity of the Dory Hill fault produced the telluride and late molybdenite veins.

## AGE OF MINERALIZATION

Field relations and isotopic ages from the Central City and surrounding districts indicate that the ores are generally of Late Cretaceous to Paleocene age (table C5). The sulfide-bearing veins cut granodiorite dikes, and they are in turn cut by biotite quartz latite dikes. A biotite potassium-argon age for the granodiorite is 57.3±1.2 Ma (mean of two samples; Rice and others, 1982). For the biotite quartz latite, Rice and others (1982) reported a biotite potassium-argon age of 59.1±1.2 Ma (mean of three samples), whereas C.E. Hedge (written communication in Taylor, 1976) obtained a K-Ar age of 68–69 Ma on biotite from the fresh chilled margin of the same dike. Whole-rock potassium-argon ages for the bostonite dikes, which Wells (1960) and others showed to be among the youngest pre-ore intrusives, ranged from 62.6±1.3 to 63.3±2.2 Ma (Rice and others, 1982). A concern in dating the separate intrusions is the possible inheritance of argon from the Proterozoic metamorphic rocks; such inherited argon could account for the older age reported by Taylor (1976) for the biotite quartz latite.

Field relations demonstrate that the pitchblende veins are the oldest veins in the district (Sims, 1956). Phair (1979) reevaluated previous U-Pb dates from Central City pitchblendes and concluded that the pitchblende was deposited at approximately 58 Ma. However, although he used galena from a post-uranium base metal vein for the common lead correction, he assumed that the galena was cogenetic with the pitchblende. As it was not, the 58 Ma age thus may be incorrect.

Using potassium-argon methods, Rice and others (1982) dated hydrothermal sericites from veins in and near the Central City district. With the exception of two samples that gave ages of 76 and 78 Ma, ten samples of sericite yielded ages ranging from 52.7 to 59.6 Ma with errors of 2.1 Ma or less; the youngest of the sericite ages (52.7 Ma) was from a mine containing telluride minerals,

**Table C5.** Summary of isotopic ages for intrusive rocks and hydrothermal minerals in the Central City area

[Sources of data: (a) Rice and others (1982); (b) Taylor (1976); (c) Cunningham and others (1977). K-Ar, potassium-argon; FT, fission track. Note: each apatite-zircon pair from same sample]

| Rock type | Mineral dated | Method used | Age (Ma) |
|---|---|---|---|
| | Intrusive rocks | | |
| Granodiorite | biotite | K-Ar | 57.0±1.2(a)<br>57.6±1.2(a) |
| Biotite quartz latite | biotite | K-Ar | 57.6±1.2(a)<br>58.4±1.2(a)<br>61.2±1.3(a)<br>68-69(b) |
| Bostonite | whole-rock | K-Ar | 62.6±1.3(a)<br>63.3±2.2(a) |
| Syenite | whole-rock | K-Ar | 61.6±1.3(a)<br>65.2±1.4(a) |
| Syenite | whole-rock | K-Ar | 77.5±2.4(a)<br>84.3±2.2(a) |
| Quartz monzonite (Apex stock) | hornblende | K-Ar | 76.7±3.1(a)<br>79.3±1.9(a) |
| | zircon<br>apatite | FT<br>FT | 61.7±5.5(c)<br>71.7±17.7(c) |
| | zircon<br>apatite | FT<br>FT | 58.8±4.4(c)<br>66.7±6.7(c) |
| | Hydrothermal minerals | | |
| Altered rock (10 samples) | sericite | K-Ar | 52.7±1.6<br>to<br>59.6±1.6(a) |

the youngest ores in the district. With the exception of one sample from The Patch, all the samples having ages between 52 and 60 Ma were from the molybdenite zone. In contrast, only the sample from The Patch produced an age younger than 78 Ma for the base-metal sulfide zones.

Although most of the data from the Central City district indicate a mid-Paleocene age (55–60 Ma) for mineralization, the 10-m.y. spread in the K-Ar ages for sericites and intrusives, the contrast in ages between the later molybdenite and early base metal zones, and the slight disagreement between observed geologic relations and isotopic ages suggest that some of the ages of base metal deposits may have been partly reset by a younger episode of mineralization, perhaps related to the formation of the telluride ores. It might also be argued that the age of the majority of the mineralization at Central City, represented by the base metal sulfide zonation, is closer to 69 Ma, as reported by Taylor (1976), and that the younger molybdenite and telluride mineralization caused partial to complete resetting in mid- to late-Paleocene time.

## FLUID CHEMISTRY

Virtually all of the available light stable isotope data come from the work of Rice and others (1985) in the Central City district. Fluid-inclusion data are from Rice and others (1985), Kramer (1984), and Sims and Barton (1961). Additional data on sphalerite compositions were reported by Sims and Barton (1961) and Moench and Drake (1966).

### Stable Isotopes

The oxygen and hydrogen isotopic data indicate that hydrothermal fluids were confined to fractures and did not significantly affect the country rocks beyond the alteration zones. The deuterium per mil content of 21 hydrothermal sericites ranges from –116 at the periphery of the mineralized area to –41 near the center. Assuming that all the alteration was contemporaneous, a contoured plot of all the data (Rice and others, 1985) shows a north-trending elongate pattern that coincides roughly with the distribution of intrusive breccias and monzonite stocks. However, the plot does not correlate with the mineral zonation of Sims and Barton (1962), nor does it convincingly conform to the distribution of early molybdenite. This might indicate that alteration was not wholly synchronous and (or) that the altering fluids changed composition slightly, due to mixing and water-rock interaction, during the course of mineralization. The $\delta^{18}O$ values of the same samples do not show a consistent pattern, and the $\delta^{18}O$ values of biotite and hornblende from unaltered wall rocks were unaffected by hydrothermal activity.

The $\delta D$ values of water from fluid inclusions show a general increase towards the central part of the zoned pyrite and base metal veins, ranging from –90 per mil near the periphery to –47 per mil in the central zone. The $\delta D$ values from the early and late molybdenite zones range from –87 to –66 per mil and –77 to –57 per mil, respectively, with a general increase along the north-northeast-trending Dory Hill fault zone (fig. C14). The $\delta^{18}O$ values of quartz from all zones range from –0.3 to +11.8 per mil. The central zone fluids are isotopically identical to primary magmatic water, whereas the compositions of the other hydrothermal fluids overlap considerably and likely reflect mixing of magmatic water with isotopically exchanged meteoric water residing in fractures in the country rocks (Rice and others, 1985; Dickin and others, 1986).

Sulfur isotopic data are limited to the data reported by Jensen and others (1960). Isotopic analyses of 23 samples produced a mean of +1.2 per mil, with a range of –0.9 to +2.7 per mil. These values are particularly nondiagnostic, and they permit derivation of sulfur from both metamorphic country rocks and Laramide magmatic sources.

## Fluid Inclusions

Pressure-corrected fluid inclusion homogenization temperatures in quartz from the zoned pyrite and base metal veins range from 350–400 °C in the central zone to 261–400 °C in the intermediate and peripheral zones. Temperatures for inclusions in quartz in the early stage of molybdenite ranged from 320 to 420 °C, and those for inclusions in quartz and fluorite from the late stage molybdenite were 220–320 °C. Late telluride temperatures were 220–320 °C, and the enargite-bearing (Type B) veins formed at 200–300 °C (Rice and others, 1985).

Neither Kramer (1984) nor Rice and others (1985) found evidence for boiling during mineralization, which would require a pressure correction to obtain true trapping temperatures. Geologic reconstructions suggest that the ores formed at a depth somewhere in the range of 1.5–3.0 km (Sims and Barton, 1962), corresponding to lithostatic pressures of 500 to 900 bars, or to hydrostatic pressures of 150 to 300 bars.

Fluid salinities were generally between 2 and 13 equiv. wt. percent NaCl for all stages. Inclusions rich in $CO_2$ were observed in the early molybdenite veins, and inclusions with 36–40 wt. percent NaCl were found in fractures that crosscut the other early molybdenite veinlets (Rice and others, 1985).

## Ore Deposition

Ore and gangue minerals were deposited as a consequence of fluid mixing and partly through a decrease in temperature outward from the center of the district. The fluids responsible for the central quartz-pyrite zone were primarily of magmatic origin (Rice and others, 1985), although their salinities were relatively low in comparison with most magmatic water (Roedder, 1984). The deuterium analyses indicate that the minerals in the intermediate and peripheral zones were deposited from fluids intermediate in composition between magmatic and connate waters, suggesting fluid mixing as a cause of deposition. The connate water could have resided in existing fractures and provided a significant amount of metals (Wallace and Whelan, 1986). At the Smith mine, siderite formed late in the base metal sulfide stage, suggesting an increase in the oxygen and (or) $CO_2$ fugacities that might have resulted from fluid mixing (Kramer, 1984).

Based upon fluid-inclusion data (Rice and others, 1985), the thermal gradient was irregular across the zonation and did not clearly conform to the mineral zones. In contrast, the FeS content of sphalerites decreases outward in the base metal zones; this decrease, in the tennantite stability field, requires a decrease in temperature as well as a slight decrease in sulfur activity (Barton and Skinner, 1979). Sphalerites from the enargite-bearing veins have very low FeS contents, indicating a higher sulfur activity.

Observations by Tooker (1963) and Kramer (1984) indicated that sericite and potassium feldspar were stable in the quartz-sericite-pyrite alteration zone. At 300 °C and a potassium activity of 0.1 (Kramer, 1984), the sericite-potassium feldspar stability field boundary occurs at a pH of 5.2. Rice and others (1985) concluded that alteration was related to the early molybdenite stage of mineralization. However, the wall rocks around many veins, including some base metal sulfide veins whose host fractures demonstrably formed after molybdenite mineralization, are altered as well (Tooker, 1963; Sims, Drake, and Tooker, 1963). Furthermore, veins in a large part of the Central City and surrounding districts are not within the bounds of the molybdenite zone. Therefore, alteration throughout the district probably was related to all stages of mineralization. If so, resetting of the ages of hydrothermal sericites by subsequent mineralizing events cannot be discounted.

The early molybdenite mineralization may have been merely an initial pulse during the quartz-pyrite stage of mineralization, as molybdenite is more abundant along the walls than in the center of some quartz-pyrite veins. However, the distribution of the early molybdenite veins does not coincide with the base metal sulfide zonation seen in the Central City and other districts, and it is conceivable that base metal sulfide and molybdenite-telluride-fluorite mineralization could have occurred at somewhat different times. Contoured plots of deuterium analyses of vein minerals correlate well with the respective base metal sulfide and molybdenite zones, suggesting separate mineralizing centers.

Rice and others (1985), noting the coexistence of $CO_2$-rich and high-salinity fluids in the early molybdenite zone, postulated that an early immiscible $CO_2$-rich fluid coexisted with mixed magmatic-connate waters during early molybdenite mineralization. The later molybdenite and telluride veins, with somewhat lower temperatures and salinities and isotopically more evolved compositions, may have formed during fluid mixing and movement along the Dory Hill fault system (Rice and others, 1985). Oxidation as a result of fluid mixing is an effective method of precipitating telluride minerals in the absence of boiling conditions or drastic cooling (see discussion in Saunders, 1986).

The source of at least some of the magmatic hydrothermal fluids may have been the quartz bostonite magma. In comparison with other intrusive rocks in the district, the quartz bostonite dikes and stocks contain high concentrations of tellurium, silver, gold, lead, zirconium, thorium, uranium, and arsenic (Budge, 1982; Rice and others, 1985). The spatial association of at least the uranium and molybdenite veins with quartz bostonite and bostonite dikes suggests a genetic relation. As noted by Sims, Drake, and Tooker (1963) and Rice and others (1985), mineralization in the Central City district took place during a number of hydrothermal and tectonic pulses, and the various centers of base metal, quartz-pyrite, and early molybdenite mineralization may reflect shifting and variously interacting centers of magmatic, hydrothermal, and tectonic activity. Rice and others (1985) postulated that all the mineralization in the Central City district was related to an alkalic porphyry-molybdenum system, and that the exposed veins represent the upper part of that system. Application of this inference to the other zoned districts nearby would require additional fluid-inclusion, geochronologic, and light stable isotopic data from those areas.

## SUMMARY

The Central City and surrounding mining districts are the products of a large hydrothermal system (or systems) related to the emplacement of a diverse suite of plutonic rocks during Laramide time. The veins formed along faults which developed largely during Laramide tectonic activity. Fault movement continued during mineralization and provided additional conduits and open spaces for fluid movement and ore deposition. Fault segments that cut brittle country rocks were relatively more open and were therefore the favored sites of ore deposition.

The magmas provided a significant amount of hydrothermal fluids and probably much of the metals and sulfur. Connate water residing in fractures in the country rock provided a second source of fluids and perhaps also metals. Mixing of these two fluids was an important mechanism for ore deposition in the fractures. Thermal gradients across the district, in part resulting from fluid mixing, were responsible for the observed lateral and vertical mineral, trace element, and gold:silver ratio zonations in the area. The lack of coincidence between the base metal sulfide zoning pattern and the molybdenite-bearing area is likely the product of two or more mineralizing centers.

The known ores of the Central City district are largely confined to discrete veins, and a modest amount of gold may be produced from these veins and their extensions in the near future. To date (1988), no effort has been made to evaluate the potential for a low-grade, high-tonnage disseminated or stockwork copper-molybdenum or molybdenum deposit at depth.

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