Gold-bearing Polymetallic Veins and Replacement Deposits—Part II

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Chapter F

Gold-bearing Polymetallic Veins and Replacement Deposits—Part II

Gold in the Tintic Mining District, Utah

By HAL T. MORRIS

Gold Deposits in the Sneffels-Telluride and Camp Bird Mining Districts, San Juan Mountains, Colorado

By FREDERICK S. FISHER

Gold in the Alma Mining District, Colorado

By DANIEL R. SHAWE

Precious Metals in the Leadville Mining District, Colorado

By TOMMY B. THOMPSON

Part I is Chapter C

U.S. GEOLOGICAL SURVEY BULLETIN 1857

GEOLOGY AND RESOURCES OF GOLD IN THE UNITED STATES

DANIEL R. SHAWE and ROGER P. ASHLEY, Scientific Editors
L.M.H. CARTER, Technical Editor

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Gold-bearing Polymetallic Veins and Replacement Deposits—Part II

Gold in the Tintic Mining District, Utah

By Hal T. Morris

Abstract

Gold is the fourth most important mineral commodity produced from the Tintic mining district after silver, lead, and zinc. Some of this gold is produced as a byproduct or coproduct of the argentiferous lead and zinc ores, but large amounts also have been produced from gold-bearing fissure veins and lodes in massive quartzite, and from large baritic jasperoid replacement ore bodies in carbonate rocks. Since its discovery in 1869 the Tintic district has produced more than 2.77 million ounces of gold, and the two most recently operating mines in the district—the Mammoth mine in the Main Tintic subdistrict and the Trixie mine in the East Tintic subdistrict—have produced predominantly gold-bearing fluxing ores. Much potentially gold-bearing terrane may remain to be explored and developed in the Tintic district, particularly in the East Tintic subdistrict.

INTRODUCTION

The Tintic mining district of west-central Utah, including its East Tintic subdistrict, is world renowned for its production of silver and lead (Lindgren and Loughlin, 1919; Morris and Mogensen, 1978). This district (fig. F1), however, also has produced important quantities of other metals, including zinc, gold, copper, cadmium, and bismuth. The gold-bearing ores of the district include not only polymetallic base metal ores from which gold is recovered as a byproduct or coproduct, but also replacement ore shoots and quartz veins and lodes that were mined principally for their content of gold. Undeveloped bodies of gold ore are known in the district, and much exploration for gold and silver ore bodies has been undertaken during the past two decades.

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LOCATION, HISTORY, PRODUCTION, AND RESERVES

The Tintic district is in the East Tintic Mountains near the east-central boundary of the Great Basin. It is about 95 km southwest of Salt Lake City (fig. F1), Utah, and is traversed by U.S. Highway 6–50 (fig. F2) and served by the Union Pacific and Denver and Rio Grande Railroads. The district was discovered in 1869, and intermittent new discoveries of concealed ore bodies have kept the district almost continuously productive to the present time (Morris and Lovering, 1979). Through 1987 Tintic has produced somewhat more than 19.1 million tons of ore containing approximately 272 million oz of silver, 1.14 million tons of lead, 225,000 tons of zinc, 127,000 tons of copper, and 2.77 million oz of gold. Reserves of gold-bearing ores in active and inactive mines either are not available for publication or are unknown, but reserves are believed by the author to be small to moderate. Gold resources in unexplored or only partly explored terranes may exceed 650,000 oz, about one-fourth of past production, but they probably do not exceed 2 million oz, about two-thirds of the total historic production.

OTHER SIMILAR DEPOSITS

Magmatic-hydrothermal processes formed the major ore bodies of the Tintic district; some of the ore

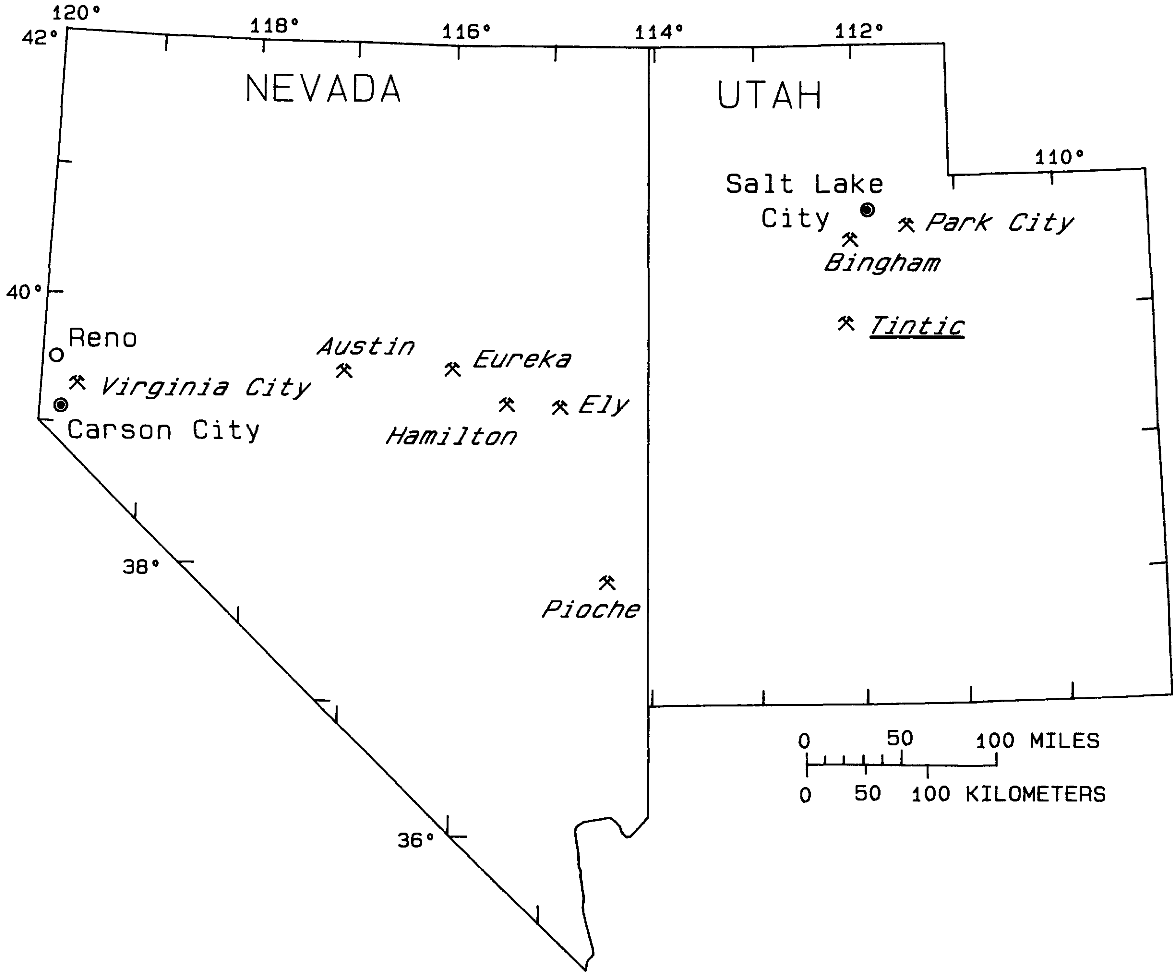


Figure F1. Index map showing location of the Tintic mining district, Utah, and some other significant mining districts in Utah and Nevada.

bodies are classic examples of large interconnected irregularly shaped limestone-replacement deposits (Morris, 1974). As such, they are comparable in many ways to the limestone-replacement ore bodies of Park City and Bingham, Utah, and of Gilman and Leadville, Colo.; and they are also closely similar to limestone-hosted replacement deposits in north-central Mexico and elsewhere in the world. Many of the principal gold ore deposits at Tintic, however, are relatively simple lodes and veins cutting massive refractory rocks, and thus resemble similar tabular deposits throughout the world.

GEOLOGIC SETTING

The East Tintic Mountains are a fault-block range comprising moderately folded and faulted Paleozoic miogeosynclinal sedimentary strata that are partly overlain by Tertiary volcanic deposits (fig. F2). In the mineralized areas in the central part of the range, both the sedimentary and the volcanic rocks are cut by stocks, plugs, dikes, and sills of monzonite and quartz monzonite porphyry and other intrusive rocks of mid-Tertiary age, and locally by numerous dikes of intrusion breccia characterized by abrasion-rounded pebbles of quartzite (Morris and Lovering, 1979). The sedimentary rocks range in age from late Precambrian to Late Mississippian, and are more than 4,400 m thick. The volcanic rocks range from a few meters to more than 1,000 m thick, and probably are thickest within an inferred filled caldera in the central part of the range (Morris, 1975).

In the general proximity of the ore bodies, the sedimentary, volcanic, and intrusive host rocks were weakly to strongly altered by a succession of hydrothermal solutions (Lovering, 1949). Ore bodies within igneous rocks or within sedimentary rocks immediately below volcanic tuffs and flows are wholly or partly surrounded by overlapping halos of altered rocks including phyllic (youngest and closest to ore), argillic, and propylitic (oldest and most widespread) zones. Ore bodies in carbonate rocks also have similar, if less extensive, alteration selvages or halos, including sericitic, silicic, and pyritic zones within and adjacent to the replacement ore bodies (youngest), sanding and severe leaching of carbonate rocks, and widespread dolomitic alteration of limestone (oldest). Ore deposits in quartzite have only minimal or thin halos or selvages of altered rocks, but characteristically show strong phyllic zones; essentially they show no effects of argillic or propylitic alteration except in areas of interbedded shale or phyllite.

The structural features that dominantly localize the ore deposits of the Tintic district include high-angle faults, thrust faults and other low-angle faults, bedding-plane faults, axial zones of folds, and linked and branching fissures. Many of the larger replacement ore bodies appear to selectively replace particular limestone or dolomite formational units: although ore bodies are known to occur in all of the carbonate formations, they are concentrated in those formations that appear to have been somewhat more susceptible to brecciation than others.

The Tintic ore bodies are the terminal products of the Tertiary volcanic episode in the central East Tintic Mountains. Isotopic age dating techniques indicate that volcanism began in the Oligocene about 34.5 Ma and ended about 2 to 2.5 m.y. later. The K-Ar age of secondary foliated biotite in the small concealed Southwest Tintic porphyry copper deposit in the southern part of the district is 31.5 Ma, indicating a geologic age of middle Oligocene.

CHARACTERISTICS OF ORE BODIES

The ore deposits of the Tintic district are classified as: (1) replacement deposits, (2) replacement veins, and (3) fissure veins. Some of the unmined deposits, which are not fully explored, are stockwork or disseminated deposits in brecciated and altered igneous and sedimentary rocks. The replacement deposits, which have accounted for more than 90 percent of the ores produced from the district, occur predominantly in dolomite or limestone and may be described as pods, pipes, columns, and irregular masses. They range in size from small segregations of less than 1 ton to masses containing more than 2,000,000 tons. They are irregular in form and commonly are elongated, and interconnected by narrow stringers and veins of ore (fig. F3). Some of the large replacement ore bodies show pronounced localization by faults and fissures; some others, however, are seemingly unrelated to structures and occur in massive sedimentary rocks (fig. F3).

The replacement veins are much less numerous than the fissure veins but have produced about an equal amount of ore, about 5 percent of total district-wide production. The replacement veins occur chiefly in the contact-pyrometasomatic aureole of the Silver City stock and tend to be tabular in form. They almost completely replace the breccia of the faults in which the ore shoots occur and locally expand outward on some crossing fractures and bedding horizons.

The fissure veins occur in a myriad of short faults that cut massive quartzite, quartz monzonite, monzonite porphyry, latite porphyry, and silicified tuff and agglomerate. The ore shoots commonly are less than 1 m thick and no more than a few hundred meters in breadth and length. Banding and crustification structures are common.

The replacement ore bodies in the Main Tintic subdistrict near Eureka occur in five linear ore zones or ore runs. These include, from west to east, the Gemini ore zone; the Mammoth-Chief ore zone; the small Plutus ore zone; the Godiva ore zone; and the Iron Blossom ore zone (fig. F4). In comparison, the ore bodies of the East Tintic subdistrict, chiefly including the North Lily, Tintic Standard, and Burgin deposits (fig. F4), are localized at the intersections of northeast-trending fissure zones and small thrust faults. However, they are obviously aligned with northeast-trending fissure zones in the igneous centers in the southern part of the district.

ORES

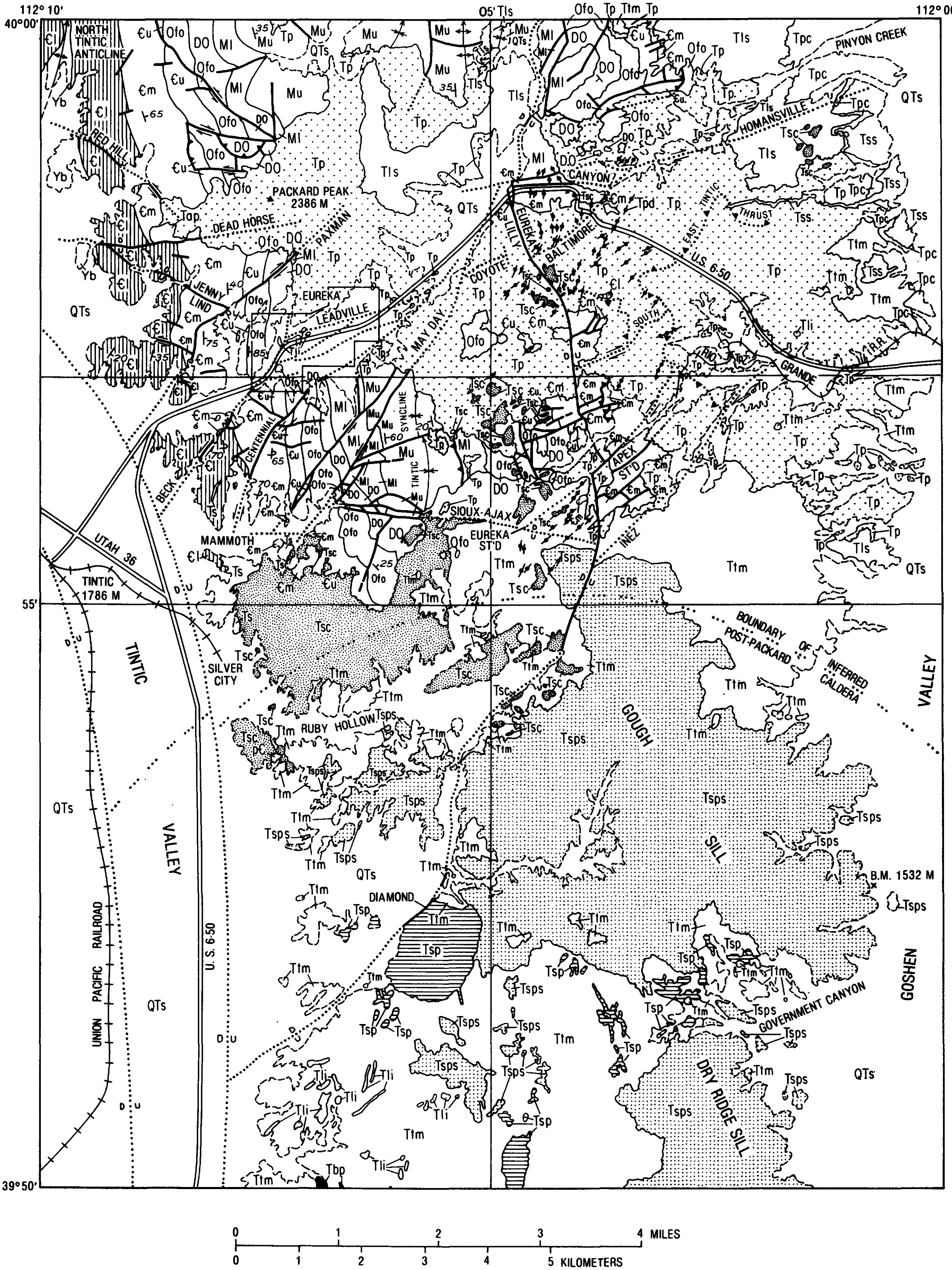
The primary ores of the Tintic district contain galena, sphalerite, acanthite, argentite, tetrahedrite-tennantite, enargite-famatinite, proustite, hessite, calaverite, native gold, native silver, and a wide variety of relatively uncommon copper-, lead-, silver-, and bismuth-bearing sulfosalt minerals. Deep oxidation of these ores has further produced a great variety of sulfates, carbonates, silicates, arsenates, antimonates, and manganates. Some of these oxidized ores also contain native gold.

Although some of the outcropping ores were rich in native gold, their limited distribution and shallow depth of erosion precluded the formation of significant placer deposits.

ZONATION OF ORE BODIES

A prominent feature of the district is a pronounced zonation of the replacement ore bodies and replacement veins of the Main Tintic subdistrict. The deposits south of a line extending from the southern part of the Eureka Hill mine, generally through the Victoria and Northern

Figure F2 (next two pages). Generalized geology of the northern two-thirds of the Tintic mining district.



112° 10'
05'
112° 00'
40°00'
55'
39°50'
NORTH TINTIC ANTICLINE
RED HILL
PACKARD PEAK 2386 M
DEAD HORSE
PAXMAN
JENNY LIND
EUREKA
LEADVILLE
MAY DAY
COYOTE
EUREKA LILLY
BALTIMORE
CANYON
HOMANSVILLE
PINYON CREEK
EAST TINTIC THRUST
U.S. 6-50
SOUTH
RIO GRANDE
R.R.
APEX ST'D
INEZ
CENTENNIAL
BECK
TINTIC SYNCLINE
SIOUX-AJAX
EUREKA ST'D
MAMMOTH
UTAH 36
TINTIC 1786 M
SILVER CITY
RUBY HOLLOW
BOUNDARY OF INFERRED POST-PACKARD CALDERA
GOUGH SILL
DIAMOND
TINTIC VALLEY
UNION PACIFIC RAILROAD
U.S. 6-50
GOVERNMENT CANYON
DRY RIDGE SILL
GOSHEN VALLEY
B.M. 1532 M
0 1 2 3 4 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

TERTIARY AND QUATERNARY

QTs — Surficial and valley-fill deposits

TERTIARY

Tss — Silver Shield Quartz Latite and related feeder dike

Tpc — Pinyon Creek Conglomerate

•—Tbp — Breccia pipe

Tsc — Monzonite porphyry of Silver City stock and related plutons

Tpd — Pebble dikes and related dikes of monzonite porphyry

Tls — Laguna Springs Volcanic Group
(Tintic Delmar Latite, Pinyon Queen Latite, and North Standard Latite)

Tsp / Tsps — Sunrise Peak Monzonite Porphyry and related intrusive rocks
Tsp, crosscutting plutons
Tsps, extensive sills

Tli — Latite intrusive rocks

Ttm — Tintic Mountain Volcanic Group
(Big Canyon Latite, Latite Ridge Latite, and Copperopolis Latite)

Ts — Swansea Quartz Monzonite and related intrusive rocks

Tp — Packard Quartz Latite

Tap — Apex Conglomerate

MISSISSIPPIAN

Mu — Upper Mississippian rocks
(Great Blue Formation, Humbug Formation, and Deseret Limestone)

Ml — Mostly Lower Mississippian rocks
(Gardison Limestone and Fitchville Formation; includes some Devonian strata at base)

ORDOVICIAN TO DEVONIAN

DO — Devonian to Ordovician rocks
(Pinyon Peak Limestone, Victoria Formation, and Bluebell Dolomite)

ORDOVICIAN

Ofo — Ordovician rocks
(Fish Haven Dolomite and Opohonga Limestone)

CAMBRIAN

Єu — Upper Cambrian rocks
(Ajax Dolomite and Opex Formation)

Єm — Middle Cambrian rocks
(Cole Canyon Dolomite, Bluebird Dolomite, Herkimer Limestone, Dagmar Dolomite, Teutonic Limestone, and Ophir Formation)

Єl — Lower Cambrian rocks
(Tintic Quartzite)

MIDDLE PROTEROZOIC

Yb — Big Cottonwood Formation

Contact—Dashed where approximately located

Fault—Dotted where concealed; U, upthrown side; D, downthrown side; arrows show direction of relative movemont. In figure F3: A, relative movement away from observer; T, toward observer. Significant faults are named

Thrust fault—Dotted where concealed; Sawteeth on side of upper plate

Syncline—Showing trace of axial plane and plunge of axis

Anticline—Showing trace of axial plane and plunge of axis

50 — Strike and dip of beds

70 — Strike and dip of overturned beds

Ore bodies

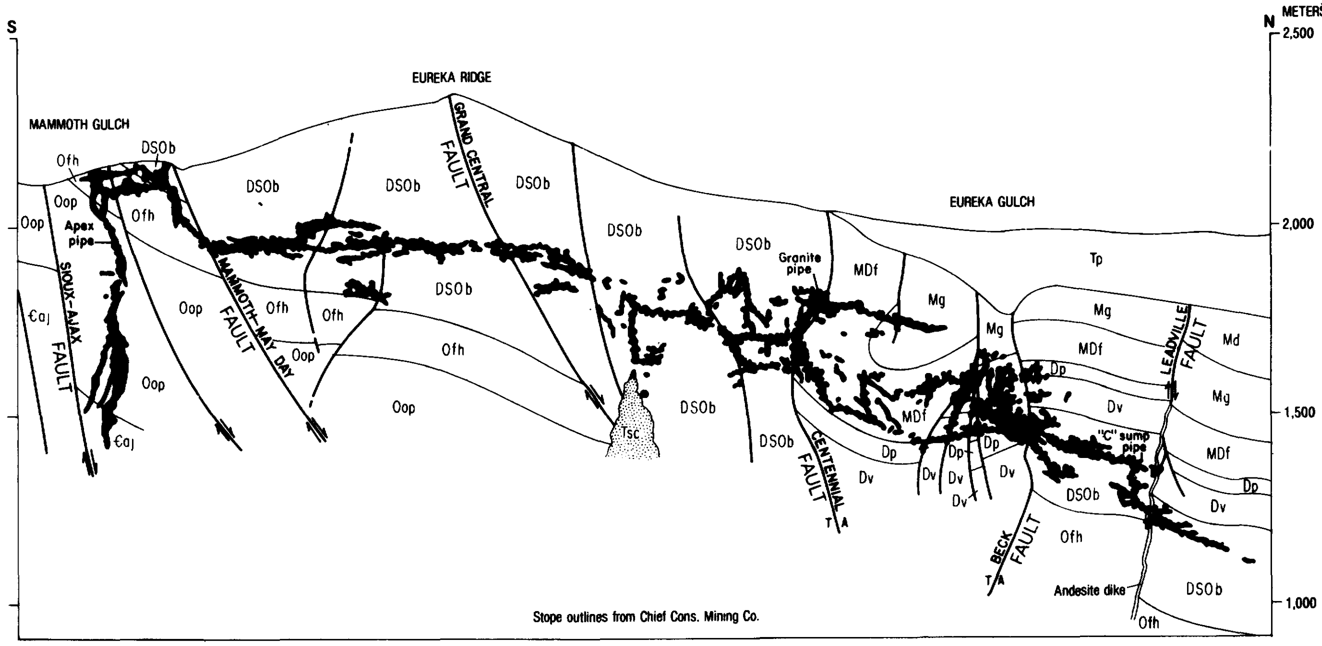


Figure F3. Geologic cross section in northern part of Mammoth-Chief ore zone in Main Tintic subdistrict showing known ore bodies projected horizontally to plane of section. Cross section extends from Mammoth mine northward through Victoria mine and about 1 km beyond Chief No. 1 mine shown on figure F4. €aj, Cambrian Ajax Dolomite; Oop, Ordovician Opohonga Limestone; Ofh, Ordovician Fish Haven Dolomite; DSOb, Devonian, Silurian, and Ordovician Bluebell Dolomite; Dv, Devonian Victoria Formation; Dp, Devonian Pinyon Peak Limestone; MDf, Mississippian and Devonian Fitchville Formation; Mg, Mississippian Gardison Limestone; Md, Mississippian Deseret Formation; Tp, Tertiary Packard Quartz Latite; Tsc, Tertiary Silver City monzonite porphyry stock. Ore bodies are in black (based on stope outlines from Chief Consolidated Mining Co.). Additional explanation accompanies figure F2.

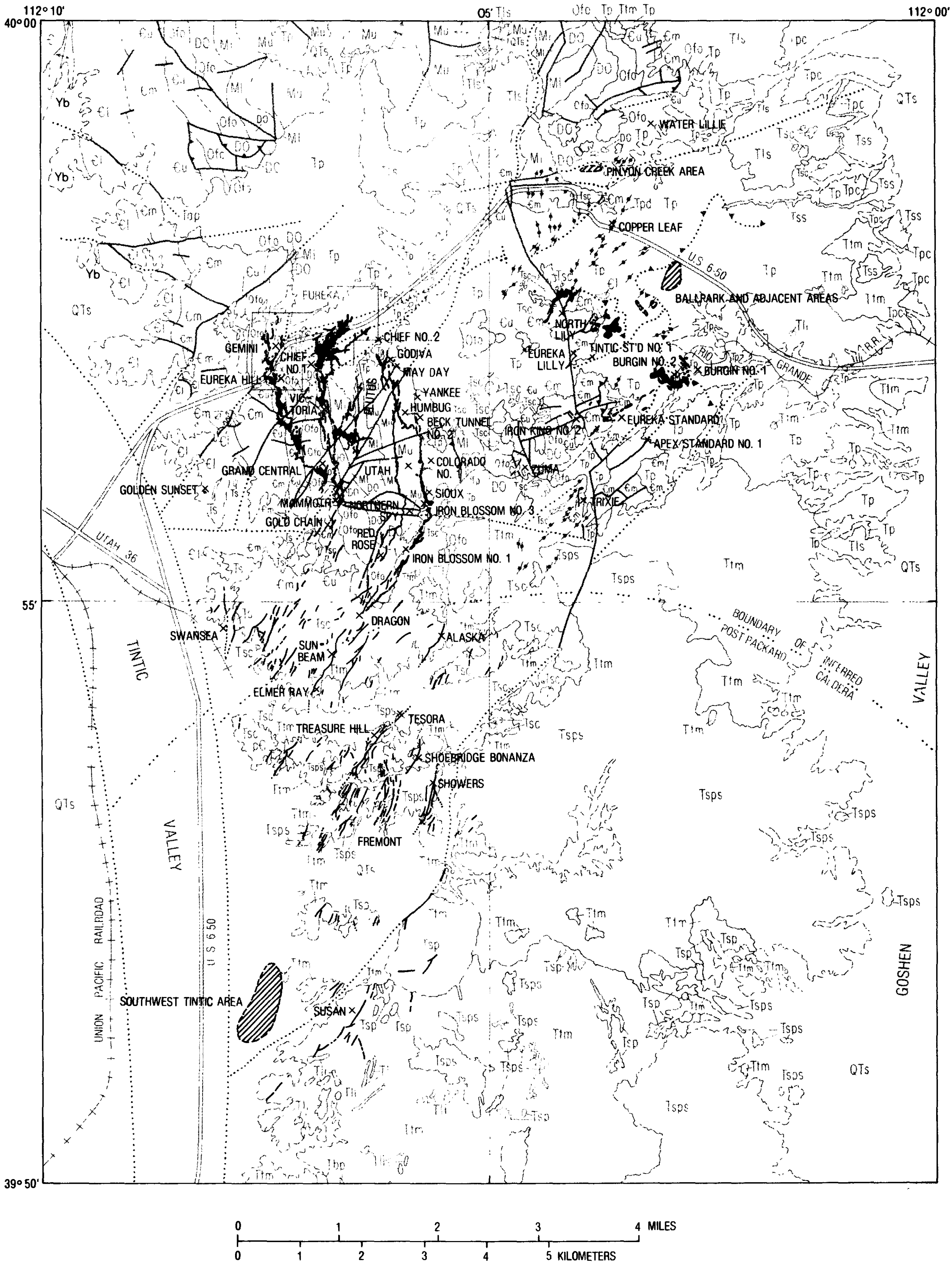
Spy mines to the Iron Blossom No. 3 mine, were chiefly valuable for copper and gold, although lead and silver ores were common. In a middle zone, lying between this line and a line drawn through the northern part of the Eureka Hill mine, the southern part of the Chief No. 1 mine, and the Yankee mine, the ore bodies produced chiefly lead and silver ores, some of which were exceptionally high grade. North of this middle zone, in the Gemini, Chief No. 1, Godiva, and May Day mines in the northernmost part of the Main Tintic subdistrict, the ore bodies carry as much zinc as lead. These zinc-rich ores contain only moderate amounts of silver and only traces of gold, and virtually no copper. In general the gangue minerals also are horizontally zoned. In the southern, or copper-gold zone, large crystals of quartz and barite are abundant in vugs in coarse-grained jasperoid. In the middle, or lead-silver zone, the jasperoid is medium grained, and crystals of quartz and barite are small. In the zinc-rich northern zone much of the jasperoid is flinty, and most of the barite can be recognized only under the microscope.

In the more compact ore centers of the East Tintic subdistrict, zonation of the individual ore bodies also is recognizable, but it is not obvious; in several of the mines it appears somewhat telescoped. In this subdistrict, the North Lily mine produced rich gold and copper ores from the lower levels of the southwestern part of the mine and moderate-grade lead and silver ores from the central and northeastern parts of the mine. The Tintic Standard mine also produced small quantities of gold-copper ore from the lower southwestern levels of the mine, great amounts of silver and lead ore from the central part of the mine, and some zincian manganese ores from the upper northeastern levels of the mine. In contrast, most of the ores of the Burgin mine contain zinc, only moderate quantities of silver, and insignificant amounts of copper and gold. The Burgin ores are distinguished, however, by abundant rhodochrosite, which is rare in other East Tintic ore bodies.

ISOTOPIC AND FLUID-INCLUSION DATA

Fluid-inclusion and light stable isotope studies have been made on selected samples of quartz, barite, sphalerite, and galena from both fissure and replacement

Figure F4 (facing page). Map of the northern two-thirds of the Tintic mining district showing mine locations (X) and names, vertical projection of known ore bodies (solid black), and mineralized areas (cross lined). Additional explanation, figure F2.


112° 10'
05'
112° 00'
40° 00'
55'
39° 50'
WATER LILLIE
PINYON CREEK AREA
COPPER LEAF
U.S. 6-50
BALLPARK AND ADJACENT AREAS
EUREKA
CHIEF NO. 2
GODIVA
MAY DAY
GEMINI
CHIEF NO. 1
EUREKA HILL
VICTORIA
YANKEE
HUMBUG
BECK TUNNEL NO. 2
NORTH LILY
TINTIC ST'D NO. 1
EUREKA LILLY
BURGIN NO. 2
BURGIN NO. 1
RIO GRANDE
EUREKA STANDARD
APEX STANDARD NO. 1
IRON KING NO. 2
COLORADO NO. 1
UTAH
GRAND CENTRAL
ZUMA
GOLDEN SUNSET
SIOUX
MAMMOTH
NORTHERN
IRON BLOSSOM NO. 3
TRIXIE
GOLD CHAIN
RED ROSE
IRON BLOSSOM NO. 1
UTAH 36
DRAGON
SWANSEA
ALASKA
SUN-BEAM
BOUNDARY OF POST PACKARD INFERRED CALDERA
TINTIC
VALLEY
ELMER RAY
TESORA
TREASURE HILL
SHOEBRIDGE BONANZA
SHOWERS
FREMONT
UNION PACIFIC RAILROAD
U.S. 6-50
SOUTHWEST TINTIC AREA
SUSAN
GOSHEN
VALLEY
0 1 2 3 4 MILES
0 1 2 3 4 5 KILOMETERS

ore bodies, particularly in the East Tintic subdistrict and the southern part of the Main Tintic subdistrict (Batchelder and others, 1978; Reed, 1981; Ames, 1962; Jensen, 1967). Batchelder and his coworkers determined that filling temperatures of fluid inclusions in the quartz and barite range from 150 to 300 °C, and that salinities range from <0.1 to 3.1 equivalent weight percent NaCl. Present-day hot-spring waters in the East Tintic subdistrict have a δD of approximately –120 per mil and a $\delta^{18}O$ of –15 per mil. Water liberated from fluid inclusions in quartz yield δD values ranging from –121 to –118 per mil. In sulfide samples, water liberated from fluid inclusions have δD values ranging from –114 to –101, and in a coarse galena sample a value of –84 per mil. Calculated $\delta^{18}O$ values for water in equilibrium with quartz range from –5.1 to 0.0 per mil. These data seem to indicate a hydrothermal system dominated by meteoric waters in which the oxygen in the waters reequilibrated with oxygen in the altered sedimentary rocks. In contrast, the data from the sulfides suggest substantial amounts of magmatic water present during ore deposition.

Reed's (1981) study generally confirms the fluid-inclusion investigations of Batchelder and others (1978). Reed determined the homogenization temperatures of 322 fluid inclusions, 85 percent of which were in quartz and sphalerite and the remainder in barite and calcite. These temperatures, corrected for pressure, ranged from 140 to 344 °C. Most of the homogenization temperatures, however, were between 200 and 300 °C. In general the fissure-vein ores from the southern part of the Main Tintic subdistrict had the highest temperatures, averaging about 285 °C. Fluid inclusions in ores from the central and northern parts of the Main Tintic subdistrict and the central part of the East Tintic subdistrict had slightly cooler homogenization temperatures, averaging 257 °C.

Ames (1962) investigated the isotopic compositions of sulfur in the sulfide ores of Tintic. He determined that the $\delta^{34}S$ values of Tintic ore sulfides have a very narrow range, extending from –10 per mil to +4 per mil and averaging –1.4 per mil, and are typical of unquestioned hydrothermal ore deposits. The significance of the narrow range of the $\delta^{34}S$ values of the Tintic sulfides has also been discussed by Jensen (1967), who drew comparisons with primordial sulfur from meteorites, and suggested a mantle origin.

Stacey and others (1968) examined the isotopic compositions of lead in galena and feldspar from the Tintic area. They concluded that the leads of the feldspars from the main Tertiary intrusive bodies are isotopically similar to the lead deposits closely associated with them, and that the ore leads show little more than 1 percent variation in the $^{206}Pb/^{204}Pb$ ratios of 14 deposits sampled. Stacey and his coworkers also concluded that the ore leads appear to be mixtures in various proportions of lead derived from the intrusive magma and a radiogenic lead component derived from upper crustal rocks through which the mineralizing fluids passed. In general, for 10 large and small ore deposits in the Main Tintic and East Tintic subdistricts, the $^{206}Pb/^{204}Pb$ ratios range from 18.487 to 18.711, and average 18.607; the $^{207}Pb/^{204}Pb$ ratios range from 15.715 to 15.741 and average 15.728; and the $^{208}Pb/^{204}Pb$ ratios range from 38.986 to 39.080 and average 39.036. Other studies of the isotopic composition of Tintic lead ores have also been carried out by Bruce R. Doe and his coworkers (oral commun., 1975–1985).

SELECTED GOLD-PRODUCING MINES

Mammoth Mine

The second largest gold-producing mine in the Tintic district, after the less well known Centennial Eureka mine, is the Mammoth mine, which has yielded approximately 425,000 oz of gold from about 1.28 million tons of ore and dump material, along with approximately 13.6 million oz of silver, 18,000 tons of copper, and 20,000 tons of lead. The mine has produced intermittently since 1872 and recently was operated by Kennecott Copper Corporation for the production of gold-bearing siliceous fluxing ores. The deposit is located in the west-central part of the Main Tintic subdistrict about 2.5 km south of Eureka. The principal ore body of the mine is the Apex shoot, an irregular but nearly vertical columnar mass of ore about 30 m in diameter that extends from the surface to a point below the 2700 level. Other ore bodies connect the Apex shoot with adjacent runs of ore. The Apex shoot is localized at or near the intersection of the Gold Chain fissure with the Sioux-Ajax fault and lies almost entirely in carbonate rocks in the hanging wall of the Sioux-Ajax. The ore is predominantly medium grained baritic jasperoid; it is highly oxidized and has a cellular appearance, containing much iron and manganese oxide. The dominant ore minerals are galena, commonly converted to cerussite and anglesite, enargite and famatinite (both partly oxidized to malachite), azurite, clinoclasite, olivenite, tyrolite, and other secondary minerals, and bismuthinite, almost entirely oxidized to arsenobismite. Silver, mostly in the form of cerargyrite derived from argentite or acanthite, has been the source of greatest revenue from the mine. Gold was next in value to silver; its ores chiefly are masses of limonitic and manganiferous jasperoid containing fine-grained native gold as well as minerals of silver, copper, and other metals. The original form of the gold is unknown, but chemical tests on some ores have indicated the presence of tellurium, suggesting possible telluride progenitors. In general, the richest gold ores are associated with the copper ores; but not all copper ores are auriferous, and some lead ores are not without gold. Other mines that have produced important amounts of gold from polymetallic replacement ore bodies in the Tintic district are the Centennial Eureka (near the Eureka Hill mine on fig. F3), Grand Central, Chief No. 1, and Iron Blossom No. 1 mines.

Eureka Standard Mine

The first mine in the Tintic district whose principal revenues derived from the gold content of its ores was the Eureka Standard mine in the East Tintic subdistrict. Ore was discovered in 1928, and the mine continued to operate until 1939; since that time considerable amounts of gold- and silver-bearing dump material also have been sold as siliceous fluxing ores. From 1928 through 1970 the Eureka Standard produced about 363,000 tons of ore and dump material, containing approximately 243,000 oz of gold in addition to considerable quantities of silver, copper, lead, and zinc. The mine lies in the southern part of the East Tintic subdistrict about 5 km east-southeast of Eureka. The shaft, about 435 m deep, is collared in alluvium a short distance above the Oligocene Packard Quartz Latite; it penetrates volcanic rock to a depth of about 180 m and then enters a sequence of Middle Cambrian carbonate rocks and shale. At the 900 level, about 260 m below the surface, the shaft penetrates the Eureka Standard fault and passes into the Lower Cambrian Tintic Quartzite. Workings from the shaft are mainly along the northeast-trending Eureka Standard fault at a point where it is cut or joined by a series of north-northeast-trending fissures or faults of small displacement. The principal gold ore bodies consist of masses of brecciated quartzite that lie in sheeted zones between branches of the main fault; some gold ore bodies also occur in zones of closely spaced nearly vertical minor fissures in the quartzite footwall of the fault. The principal hypogene metallic minerals include pyrite, marcasite, luzonite, tetrahedrite, galena, sphalerite, petzite, hessite, and native gold. Less abundant metallic minerals include chalcopyrite, proustite, and sylvanite (or krennerite). The dominant gangue minerals are quartz, barite, and kaolinite. The average grade of the greater part of the fissure ores that were produced from the mine was 0.7 oz Au/ton, 9.85 oz Ag/ton, 0.37 percent Cu, and 1.02 percent Pb. In comparison, the minor replacement ore bodies in the mine averaged 0.1 oz Au/ton, 14 oz Ag/ton, 0.37 percent Cu, 12.13 percent Pb, and 9.11 percent Zn. Other mines that are similar to the Eureka Standard mine include the adjacent Apex Standard No. 2, and the Iron King No. 2 mines.

North Lily Mine

The North Lily mine has produced gold ores from fissure and breccia zones in the Tintic Quartzite, as well as argentiferous lead ores in much greater abundance from Cambrian carbonate rocks and shale that lie in thrust-fault contact with the quartzite. This mine lies about 3.6 km east-northeast of Eureka in the central part of the East Tintic subdistrict. The silver-lead replacement ore bodies in the North Lily are overlain and concealed by 250–400 m of altered but barren quartz latite and hydrothermal dolomite; they were discovered in 1927, but the rich gold ore-shoots in the lower levels were not developed until about 1933. The mine ceased operation in 1949, and at that time the underground ore bodies had produced a total of about 377,000 tons of ore containing approximately 151,000 oz of gold, 3.48 million oz of silver, 1,325 tons of copper, 50,000 tons of lead, and 2,600 tons of zinc (Cook, 1957, pl. 3). The best of the gold-bearing ores came from the so-called Endline Dike fissure zone in the southeastern part of the mine, which produced about 65,000 tons of ore averaging about 1.33 oz Au/ton, 4.75 oz Ag/ton, and about 1.37 percent Cu (Kildale, 1957, p. 105). The main gold ore bodies occur in fissure zones a few centimeters to several meters wide in the Tintic Quartzite down-rake from the silver-lead replacement ore bodies in the overlying carbonate rocks. The fissure zones apparently were conduits for the solutions that deposited the replacement ore bodies, and a genetically late age for the gold ore deposition is indicated by the occurrence of a tabular zone of gold-enriched replacement ore directly up-rake from the gold-bearing fissures. This feature was known as the "gold shadow." The metallic minerals of the gold ore bodies of the North Lily mine include pyrite, galena, sphalerite, auriferous luzonite, tetrahedrite, hessite, krennerite, petzite(?), and native gold. The nonmetallic gangue minerals include crystalline and fine-grained quartz, large and small platy crystals of barite, and some kaolinite. Some parts of the Endline Dike fissure zone contained exceptionally rich ores; Kildale (1957) reported a selected rich sample that assayed 9.25 percent Au (2,221 oz Au/ton), 0.72 percent Ag (173 oz Ag/ton), 44.14 percent Cu, 27.43 percent S, 13.98 percent As, 3.81 percent Sb, and 0.63 percent Fe. Tellurium was present only as a trace. Similar ore shoots in fissures in quartzite down-rake or adjacent to large replacement ore bodies, although not as high in grade, also were mined or explored in the Tintic Standard and Burgin mines, both in the East Tintic subdistrict.

Trixie Mine

The most recent discovery of a concealed gold deposit in the Tintic district was the Trixie ore center, about 1.5 km southwest of the Eureka Standard mine. As described by Mogensen, Morris, and Smith (in Morris and Lovering, 1979, p. 182–188), lead-silver ore was cut in several diamond core holes drilled in the Trixie area in 1954–1956 to evaluate a geochemical and hydrothermal alteration anomaly overlying a concealed geologic target similar to other mineralized areas in the district. The Trixie shaft was sunk in 1968–1969, and shortly after its completion to the 750 level, gold ore was encountered in a steeply dipping fissure west of the shaft. The mine began sustained production in 1970. Through July 1985, the Trixie produced approximately 600,000 tons of ore, containing about 113,000 oz of gold and 3,980,000 oz of silver along with significant quantities of copper, and minor but mostly unrecovered quantities of lead and zinc. From August 1985 to November 1987, operations were suspended; but production resumed in December 1987, and by February 1988, a production level of 1,500 tons per month had been achieved.

The Trixie is located in the southernmost part of the East Tintic subdistrict about 5 km southeast of Eureka. The shaft is currently (1988) about 436 m deep and bottoms at the top of the permanent water table. It is collared in the lower part of the Middle Cambrian Teutonic Limestone and within a short distance enters the Middle Cambrian Ophir Formation. At a depth of about 127 m, it enters the Lower Cambrian Tintic Quartzite and remains in this unit to the bottom. The Cambrian strata in the vicinity of the mine are overlain by hydrothermally altered tuffs and flow rocks of middle Oligocene age, and all these units are cut by dikes of injected pebble breccias and by tabular bodies and small irregular plutons of monzonite porphyry.

The dominant geologic structures exposed in the mine workings are the northeast-trending Eureka Standard wrench fault in the northernmost part of the property, and the related east-northeast-trending Trixie fault zone. Both these faults originated during movement on the deeply underlying north-trending East Tintic thrust fault (Morris and Lovering, 1979, p. 75). Both the footwall and hanging wall rocks of the Trixie fault zone are cut by north- to northeast-trending faults and fissures that locally were invaded by monzonite porphyry dikes and intrusion breccias. At the Eureka Standard fault the movement on many of these young fractures appears to have been deflected along this older northeasterly structure.

The principal ore bodies in the mine consist of three, generally en echelon, veinlike structures consisting of mineralized quartzite breccia that cut the footwall rocks of the Trixie fault zone. The largest of these mineralized bodies is the north-plunging "756" ore shoot, which lies about 46 m west of the shaft. At the 900 level it is about 260 m in slope breadth, narrowing upward to the top at about the 500 level and downward to 100 m or less in slope breadth at the 1350 level. Below this level the shoot appears to merge downward into the Trixie fault zone. It has been mined over widths of 0.3 to 12 m. The south-plunging "75–85" ore shoot, about 500 m south of the shaft at the 900 level, is somewhat smaller, averaging about 100 m in breadth and 5 m in width; and it extends from about the 600 level to an unknown depth below the water table. The "Survey" or "1050" ore shoot lies south and west of the 75–85 ore body and has been mined through a horizontal distance of about 300 m and a width of about 5 m between the 900 and 1200 levels. Its full dimensions are unknown.

Within the multi-stranded Trixie fault zone, a small siliceous lead-silver ore body lies between the 750 and 900 levels. It is about 40 m in breadth and 25 m in width. In the triangular block of ground between the intersecting Trixie and Eureka Standard faults, the limestone beds between the 750 and 1050 levels also are largely replaced by weakly mineralized jasperoid; but all this material is considerably below ore grade.

The primary ore minerals of the tabular ore shoots in the Tintic Quartzite include argentian and bismuthian tetrahedrite-tennantite, enargite, chalcopyrite, bornite, proustite, polybasite, stromeyerite, sylvanite, and native gold along with locally abundant galena and sphalerite. The predominant gangue minerals are pyrite, crystalline quartz, barite, chalcedony, sericite, chlorite group minerals, and illite. Inasmuch as the ores occur in highly porous breccia above the water table, they are considerably oxidized, and locally contain chalcocite, covellite, azurite, malachite, cerussite, hemimorphite, hematite, scorodite, and other secondary minerals.

The overall grade of ore produced from the Trixie is approximately 0.19 oz Au/ton, 6.7 oz Ag/ton, and about 1.2 percent or less Cu. Much of the ore from the "756" shoot contained 0.15 oz Au/ton and 8–10 oz Ag/ton. The grade of ore mined from the "75–85" fissure was considerably higher in gold and lower in silver, the first 7,000 tons mined averaging 0.626 oz Au/ton, 4.30 oz Ag/ton, and 0.15 percent Cu.

The announced drilled reserves in the mine in 1987 consisted of about 64,000 short tons of ore containing 0.11 oz Au/ton, 7.8 oz Ag/ton, and 0.014 percent Cu. Much favorable ground remains to be explored below the water table and in the southern part of the mine.

SUMMARY

Although the Tintic district has produced mainly silver, lead, and zinc ores from complex replacement ore bodies in carbonate rocks, it has also been the source of important quantities of gold ore. The richest gold ores occur in fissure veins and lodes in a thick sequence of generally massive quartzite, but large volumes of lower grade gold ores also were mined from siliceous replacement ore bodies within the thick sequence of younger carbonate rocks. At Tintic, most of the gold ores are important also for their copper content, but contain only small to moderate amounts of lead and zinc. The dominant gangue minerals of the gold ore bodies are crystalline quartz and barite, and coarse- to fine-grained jasperoid. Much possible gold-bearing terrane remains to be explored.

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Gold Deposits in the Sneffels-Telluride and Camp Bird Mining Districts, San Juan Mountains, Colorado

By Frederick S. Fisher

Abstract

The Sneffels-Telluride and Camp Bird mining districts have produced base and precious metals valued at more than $300 million at the time of production. The production included about 6,200,000 ounces of gold. The ores were mined from veins and replacement deposits developed on the northwest side of the Tertiary Silverton caldera. West-dipping Paleozoic and Mesozoic sedimentary rocks rest unconformably on Precambrian quartzite and are unconformably overlain by the Tertiary Telluride Conglomerate, an important host of base metal replacement deposits. Overlying the Telluride Conglomerate are more than 1,000 meters of volcanic flows, breccias, and tuffs that are the major hosts for most of the precious metal deposits in the district. Throughout the entire district the volcanic rocks have been propylitically altered. Near the veins sericitic, argillic, and calc-silicate altered zones are extensively developed.

The district is dominated by a northwest-trending swarm of dikes, fissures, and veins radiating from the Silverton caldera. Many of the faults have been mineralized and commonly contain both veins and dikes. The veins may be divided into a southern group that has produced base and precious metals and a northern group that has produced predominantly precious metals. Age data indicate that the northwest-trending fracture system formed during caldera collapse about 25 Ma and that it was initially barren. Mineralization of the fracture system occurred later during at least two stages, at 17 Ma and 13 Ma. Fluid-inclusion studies of the veins in the district indicate filling temperatures of about 280–290 °C and very low salinities. Important controls of ore deposition were types of wall rock, vein intersections, character of fault movements, presence of intersecting dikes and faults, and abrupt changes in strike or dip. The suggested hypothesis for the origin of the ore deposits is that the metals (copper, zinc, gold, and silver, and perhaps some of the lead) were derived directly from magmatic sources and mixed with a large volume of meteoric water circulating within caldera-related fracture systems. Some of the lead was derived from nearby wall rocks traversed by the meteoric waters. This ore-forming process may have been repeated at least once within the district.

INTRODUCTION

The Sneffels-Telluride and Camp Bird mining districts are located in the western San Juan Mountains, Colo. (fig. F5). For purposes of this report, the two districts will be treated as one and will be referred to simply as the "district." Both districts were developed within the extensive radial vein-dike-fault system on the northwest side of the Silverton caldera (fig. F5).

Approximately 22 million tons of ore exceeding $300 million in value at the time of production has been mined from the district. Of this about 1.8 million tons of ore containing 0.8 oz Au/ton, 2.5 oz Ag/ton, and 2–3 percent Cu, Pb, and Zn combined, has been produced from the Camp Bird vein (U.S. Bureau of Mines records). Early production (pre-1900 to 1950) from these radial veins was of the precious metals, and the ores averaged about 0.3 oz Au/ton and 3.5 oz Ag/ton. Parts of some lodes were much richer; for example, about 800,000 tons of ore from the Camp Bird vein contained 1.0 oz Au/ton and 2 oz Ag/ton; approximately 100,000 tons of ore from the Virginius vein contained 0.9 oz Au/ton and more than 100 oz Ag/ton; and about 5,000 tons of ore from the Mt. Top mine contained 0.1 oz Au/ton and more than 200 oz Ag/ton (U.S. Bureau of Mines records). Later production (1950–1975) was from the deeper parts of the veins where the ores typically contained 0.07 oz Au/ton and 1.95 oz Ag/ton and approximately 2.33 percent Pb, 0.72 percent Cu, and 3.62 percent Zn (Mayor, 1978). Total amount of gold produced from the district is about 6,200,000 oz.

Prospecting in the San Juan region commenced in the late 1860's, and in 1870 the district was prospected by R.C. Darling (Silver, 1957). Indian hostilities prevented extensive exploration, and few claims were filed until a new treaty with the Ute Tribe was negotiated in 1874, after which prospecting flourished. The original discovery on the Camp Bird property was made in 1877: early interest was directed at silver mining, but in 1896,

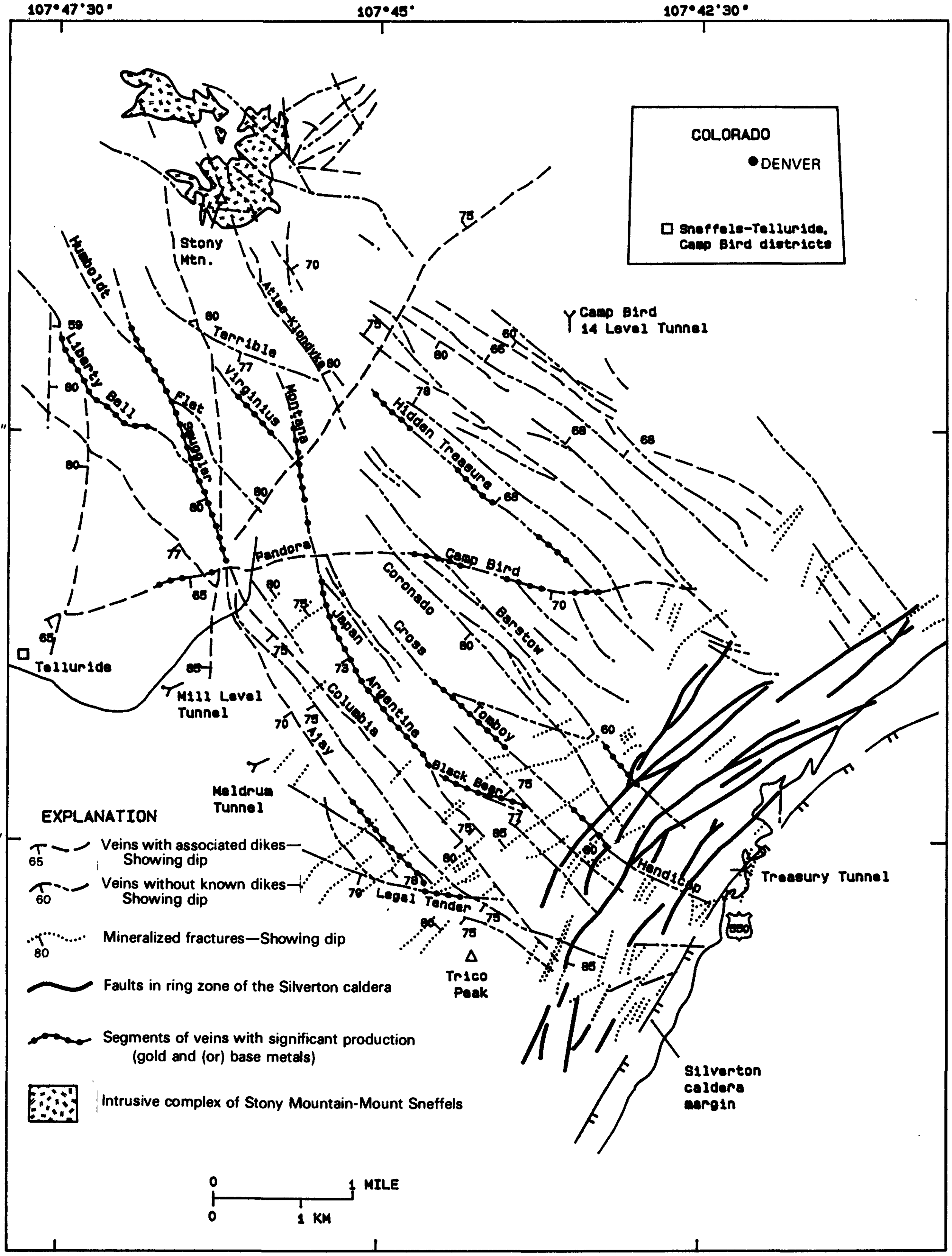

Figure F5. Principal veins, showing names, and structures on the northwest side of the Silverton caldera, Sneffels-Telluride and Camp Bird mining districts, Colorado.

Thomas Walsh purchased most of the claims in the Camp Bird group and developed the property into a highly successful gold mine. Since the turn of the century, mining in the district has waxed and waned following this pattern: (1) discovery of promising ore in several structures and the attempt to produce from numerous individual mines, (2) consolidation of properties and more efficient mining leading to successful production, until declining grade and increasing costs (and (or) fluctuating metal prices) ended operations, (3) new discoveries and a repeat of (1) and (2) above.

Deposits similar to those in the district occur elsewhere in the San Juan Mountains at Silverton (Burbank and Luedke, 1969), Creede (Steven and Ratté, 1965), and Sunnyside (Casadevall and Ohmoto, 1977). Deposits at the Mayflower mine in Utah (Nash, 1973; Bromfield, 1989) are similar to those in the Argentine–Black Bear vein system in the district; all are base and precious metal deposits that formed in extensive structural systems exhibiting similar ores, temperatures of formation, salinity of fluids, and wall rock alteration.

In a broad sense the ore deposits in the district may be compared to those in volcanic areas in Japan (Hattori, 1975), Sumatra (Emmons, 1937), and Fiji (Denholm, 1967).

GEOLOGY

Stratigraphic relations in the district are relatively simple. West-dipping Paleozoic and Mesozoic sandstone, siltstone, limestone, shale, and conglomerate rest unconformably on quartzite of the Early and Middle Proterozoic Uncompahgre Formation. Unconformably overlying the Paleozoic and Mesozoic sedimentary rocks is the Tertiary Telluride Conglomerate, an important host of base metal replacement deposits. Overlying the Telluride is more than 1,000 m of volcanic flows, breccias, and tuffs. The lowermost volcanic unit, the 35–30 Ma San Juan Formation, is approximately 700 m thick and consists of intermediate-composition mudflows, volcaniclastic sedimentary rocks, lava flows, and flow breccias. The San Juan Formation is the major host for most of the precious metal deposits in the district. Overlying the San Juan Formation, in the highest peaks in the district, are ash-flow sheets whose eruption led to the collapse of the clustered calderas in the western San Juan caldera complex (Steven and Lipman, 1976; Burbank and Luedke, 1968). These siliceous ash-flow sheets did not in general provide favorable hosts for major ore deposits in the district.

The largest intrusive body in the district is the intrusive complex of Stony Mountain–Mt. Sneffels (fig. F5). This is a composite stock and ring dike composed of diorite, gabbro, quartz monzonite, and rhyolite (Forester and Taylor, 1980; Dings, 1941). Dioritic phases of the complex have been dated at 32 Ma and crosscutting rhyolites at 15 Ma (Lipman and others, 1976). Andesite dikes radiate from the complex and are cut by younger veins and dikes related to the formation of the Silverton caldera. The younger dikes are mostly intermediate in composition (commonly andesite) and generally are extensively altered where they are adjacent to parallel veins. Crosscutting the northwest structural grain of the district are scattered rhyolite and quartz porphyry dikes, one of which has been dated at 11 Ma (Lipman and others, 1976). Within and near the ring fault zone of the Silverton caldera, small plugs of quartz latite are common. In the Red Mountain mining district, immediately southeast of the district and within the Silverton caldera, these quartz latite plugs are commonly associated with mineralized breccia pipes (Fisher and Leedy, 1973; Burbank, 1941), but in the district these plugs are barren.

Throughout the district, the volcanic rocks have been propylitically altered to epidote, calcite, chlorite, and pyrite. The propylitization resulted from the release of water and carbon dioxide during the later phases of volcanic activity in the area and preceded the vein-related mineralization and alteration (Burbank and Luedke, 1961). Regionally the propylitization increased in intensity towards the southeast (towards the Silverton caldera). Within the volcanic rocks adjacent to the veins, a sericitic zone of quartz-pyrite-sericite may extend outward as much as 1 m. Farther outward (to 8 m) an argillic zone may be present that is characterized by the presence of kaolinite in addition to the quartz, sericite, and pyrite. In deeper zones adjacent to the veins, epidote-rich calc-silicate skarns are extensively developed in calcareous beds of the Telluride Conglomerate, Cutler Formation (Permian), and Dolores Formation (Triassic) (Mayor and Fisher, 1972).

The structure of the district is dominated by a northwest-trending swarm of dikes, fissures, and veins radiating from the Silverton caldera. This fracture system forms a belt that extends N. 45° W. for about 12 km outward from the caldera. The belt is 3,000 m wide at the southeast end near the ring faults of the Silverton caldera and 1,200 m wide on the northwest end near Stony Mountain. Structures within this belt formed as a result of a complex sequence of stress systems generated during the collapse and resurgence of the San Juan and Uncompahgre calderas, the collapse of the Silverton caldera, and the emplacement of the intrusive complex at Stony Mountain–Mt. Sneffels. Diverse structures present within this belt include sheeted fractured zones, joints, faults, dikes, veins, ring faults and dikes, cone sheets, and radial dike swarms. The faults mainly have normal displacements ranging from slight to as much as 50 m; those northeast of the central axis of the belt of radial structures dip to the northeast and those southwest of the central axis dip southwest. Many faults have been mineralized and commonly contain both veins and dikes; some contain only one or the other. In most of the faults, the veins or dikes are not continuous over the entire strike length of the structure (Burbank, 1941; Dings, 1941; Steven and Lipman, 1976).

The veins can be divided into a group north of the Pandora–Camp Bird structure and a probably correlative group south of that structure. The southern group includes the Ajax, Legal Tender, Columbia, Argentine, Black Bear, Japan, Cross, Tomboy, Handicap, Coronado, and Barstow (fig. F5). Gold and base metal ore deposits both occur in this group, and some veins are zoned and contain precious metals near the surface and base metals at depth. Veins north of the Pandora structure have produced predominantly precious metals, silver being more abundant toward the north end and gold more abundant toward the Pandora structure. Veins of this group include the Liberty Bell, Smuggler, Flat, Humboldt, Virginius, Montana, Terrible, Atlas-Klondyke, and Hidden Treasure (Mayor, 1978).

The anomalously east-trending Camp Bird vein has been interpreted (Burbank, 1941) as an older structural weakness that was formed as a cone or spiral fracture early in the development history of the calderas, following which the structure reactivated during some of the latest faulting and mineralization in the district. An early ancestry for the vein is supported by the presence of an andesite dike along parts of the Camp Bird structure similar to the dikes along both the Argentine and Ajax veins. But both the Argentine and the Ajax veins have been offset by the Camp Bird–Pandora structure. Also, material from the Camp Bird vein has been dated at about 10 Ma (Lipman and others, 1976). Thus, Burbank's (1941) suggestion that the Camp Bird vein was structurally active during at least two separate times is correct.

Age data (Lipman and others, 1976) indicate that the northwest-trending fracture zone in the district formed during the collapse of the Silverton caldera and emplacement of part of the Stony Mountain–Mt. Sneffels stocks at 27.5 Ma. These fractures were reopened and mineralized at about 17 Ma and again at about 10.5 Ma. Adularia from the gold-quartz stage in the upper levels of the Camp Bird vein yielded a K-Ar age of 10.5±0.5 Ma, and fine-grained sericite from the Orphan base metal replacement ore in the Camp Bird mine gave a K-Ar age of 10.2±0.3 Ma. Fission-track ages on apatites in granodiorite intrusives in the vicinity of the Camp Bird vein gave apparent ages of a heating event at 6.98±4.8 Ma (Billings, 1980). Potassium feldspar from the base metal replacement ores adjacent to the Argentine vein yielded a K-Ar age of 17.0±0.6 Ma and an impure sericite from the same sample an age of 13.1±0.4 Ma. Thus age data indicate that the northwest-trending fracture system formed during caldera collapse at about 25 Ma and that it was initially barren. Mineralization of the fracture system occurred later, during at least two stages, at 17 Ma and 13 Ma.

CHARACTERISTICS OF ORE BODIES

Veins in the district were formed by both open-space filling and replacement processes; they range in width from less than 30 cm to more than 6 m, but most are 1.5–2 m wide. Veins in structures that contain pre-mineral dikes may occur either within the dike or adjacent to one of the walls of the dike. Most of the veins are compound and have been reopened several times. In detail a wide variety of vein structures and textures, including massive, banded, colloform, brecciated, and sheeted zones, can be observed in sections a few meters in length (Mayor, 1978; Hillebrand, 1957; Burbank, 1941). Many veins have been mined for several thousand meters along strike and as much as 900 m vertically.

In the veins north of the Pandora–Camp Bird structure (the northern group), the major metallic minerals are galena, sphalerite, pyrite, tetrahedrite, tennantite, arsenopyrite, marcasite, native gold, and minor amounts of covellite and chalcopyrite. The tetrahedrite and galena both are argentiferous. Gangue minerals are quartz, barite, sericite, beidellite, calcite, and rhodochrosite. In the upper gold-rich part of the Camp Bird vein, the major metallic minerals are pyrite, sphalerite, galena, native gold, hessite, specularite, chalcopyrite, and magnetite. Gangue minerals are quartz, carbonates, adularia, epidote, zoisite, chlorite, fluorite, kaolinite, sericite, and barite (Moehlman, 1936a, 1936b; Burbank, 1941). Paragenetic relationships of these veins in the northwest group are poorly known, though Burbank (1941, p. 210) suggested three main stages: early quartz veins with base metal sulfides; gold- and silver-bearing quartz and (or) quartz carbonate veins; and late, relatively barren quartz and quartz-carbonate veins.

South of the Pandora–Camp Bird structure, the major metallic minerals in the veins are sphalerite, galena, chalcopyrite, pyrite, and native gold, along with minor specularite and gold-silver tellurides. Gangue minerals are quartz, rhodonite, chlorite, sericite, clay minerals, epidote, calcite, adularia, rhodochrosite, fluorite, and barite (Mayor, 1978; Hillebrand, 1957). Paragenetic relationships are as follows: an early sulfide stage consisting of abundant sphalerite and galena, lesser chalcopyrite and pyrite, and small amounts of quartz; a middle sulfide stage with abundant gangue and smaller amounts of metallic minerals; a late sulfide stage characterized by chalcopyrite and pyrite; and a postsulfide stage characterized by quartz, fluorite, carbonate, and native gold (Nash, 1975).

Metal distribution in the district is zoned: complex base metal ores predominate in the southeastern part of the district (south of the Pandora–Camp Bird structure, near the caldera), and silver-gold and silver-lead ores dominate in the northwestern part of the district (north of the Pandora–Camp Bird structure). This overall general pattern commonly is complicated by the compound nature of the ores. Gold-bearing quartz is found throughout the district, but its concentration may be erratic.

In the Montana–Argentine–Black Bear vein system (fig. F5), copper, zinc, and silver content of the ores increases with depth and also toward the southeast. Lead values also increase with depth but not as significantly as those of copper and zinc. In the Black Bear vein the overall gold values decrease 45 percent between the 600 and 1200 levels. The upper parts of the Argentine vein were characterized by gold values of one-third to several ounces per ton, whereas at lower levels, the gold values decrease to one-tenth or less of those on the upper levels. North of the Pandora–Camp Bird structure, the gold values in the Montana vein are consistently two to four times greater than those in veins south of that structure (Hillebrand, 1957).

Productive gold ore shoots in the Camp Bird vein were restricted to the upper parts of the San Juan Formation. The tops of these ore shoots are all near an elevation of 11,900 ft (3,620 m), and the shoots extend downward a maximum of 180–210 m. Ore grades in the shoots averaged 1 oz Au/ton or more. At deeper levels the gold content diminished rapidly with the increase of the base metals (Burbank, 1941).

Lead-bearing ores from the Argentine, Black Bear, and Camp Bird veins range widely in their isotopic composition ($^{206}Pb/^{204}Pb = 18.6–18.9$ and $^{208}Pb/^{204}Pb = 38.2–38.4$), indicating little or no interchange of lead between mineralizing solutions and the adjacent wall rocks at the sample levels (Doe and others, 1979). To explain the range of the values, Doe and others (1979, p. 20) suggested an ore deposition model wherein deeply circulating convective cells of meteoric water leached lead from a variety of upper crustal rocks including Mesozoic and Paleozoic sedimentary rocks, Precambrian crystalline rocks, and Tertiary volcanic rocks, and then deposited the mixed leads in the veins.

Fluid-inclusion studies of gangue minerals (Nash, 1975) from the main ore stage of the Argentine, Black Bear, Camp Bird, and other veins in the district indicate filling temperatures of about 280–290 °C and very low salinities. No systematic variations in temperature or salinities were noted over a vertical range of 1,100 m and a lateral range of 3,400 m, including both ore-bearing and barren veins, suggesting physically homogeneous ore fluids. Filling temperatures in postsulfide quartz and fluorite are as low as 153 °C with salinities generally less than 0.5 wt. percent. A pressure correction of +25 °C should be added to all of the filling temperatures. Fluid inclusions from calc-silicate altered rocks associated with base metal replacement deposits deep in the Argentine, Black Bear, and Camp Bird veins suggest filling temperatures 50–100 °C hotter than inclusions in gangue associated with the base metal minerals higher in these structures (Nash, 1975, p. 1460).

Material collected from several veins north of the Pandora structure (northwestern vein set) near Stony Mountain yielded $\delta^{18}O$ values ranging from –1.8 to 5.1, clearly suggesting a meteoric water composition of the ore-forming hydrothermal fluids (Forester and Taylor, 1980).

CONCLUSIONS

Many of the veins in the district have been mined for several thousand meters along strike and as much as 900 m vertically. Several factors either separately or in combination controlled the location of the richer ore shoots. The most important of these factors are:

1. Wall rock type in the volcanic rocks: the San Juan Formation overall is the most favorable host for the vein deposits, followed in order by the overlying andesite and then by the capping rhyolite flows (which are generally poor hosts). Burbank (1941) suggested that the San Juan Formation fractured in ways that created larger open spaces, thus providing better channelways for the mineralizing solutions, and that the rhyolites tended to fracture in more numerous but smaller, tighter breaks. The basal and middle parts of the Telluride Conglomerate below the volcanics in the deeper parts of some of the veins, notably the Argentine, Black Bear, Ajax, Cross-Tomboy, Basin (no surface expression), and Japan, are hosts for important base metal replacement deposits (Mayor and Fisher, 1971). Similar replacement deposits occur adjacent to the Orphan vein (no surface expression) in the Dolores Formation in the Camp Bird mine. These replacement deposits are associated with parts of the host formation that are more permeable and calcareous.

2. Vein intersections: vein intersections have provided considerable control over ore deposition in some places (Mayor and Fisher, 1972, p. 222-223; Hillebrand, 1957, p. 187; Burbank, 1941); however, not all intersections are significantly productive.

3. Character of fault movement: faults with a relatively large horizontal component of movement created a greater amount of open space along the structure for the mineralizing solutions. This relation appears to have obtained in the upper gold-rich parts of the Camp Bird vein (Burbank, 1941, p. 234).

4. Presence of dikes and faults that intersect the veins: locally dikes and faults that intersect the veins

have controlled the deposition of ore by acting as dams to the mineralizing solutions, thus creating either richer or poorer values for varied distances along a given structure.

5. Abrupt changes in strike or dip: in places attitude change in the veins has been an important control (for example, the Terrible vein as described by Burbank, 1941, p. 235); however, Hillebrand (1957, p. 187) stated that in general the ore controls caused by changes in strike or dip are erratic and specifically that they have little individual significance for the overall grade of the ore in the Argentine, Black Bear, and Montana veins.

Oxygen, hydrogen, and carbon isotope compositions coupled with temperatures and salinities determined from fluid-inclusion studies indicate that meteoric water was probably the major constituent of the ore fluids in the district. Lead isotope compositions suggest that the meteoric water circulated deeply enough to scavenge lead from upper crustal Proterozoic rocks and then rose in relatively restricted channelways within the district to form the ore bodies. Based on extensive oxygen, hydrogen, sulfur, carbon, lead, and strontium isotope studies and also fluid-inclusion data, Casadevall and Ohmoto (1977) suggested that the source of metals in the Sunnyside hydrothermal system (located in the Eureka district; T. Casadevall, written commun., 1984) was leached rocks adjacent to and within the Silverton caldera.

An alternative hypothesis for the origin of the ore deposits in the district is that the metals (at least the copper, zinc, gold, and silver, and perhaps some of the lead) were derived directly from magmatic sources and mixed with a large volume of circulating meteoric water. Support for this hypothesis comes from:

1. The close temporal and spatial association of mineralization and the emplacement of quartz porphyry intrusives in the San Juan region (Lipman and others, 1976).

2. Mineralogical zoning and chemical zoning in the district that suggest higher temperatures to the southeast and at depth (Hillebrand, 1957). Reality of these higher temperatures is supported by the data from the calc-silicate skarns in the southeastern part of the district (Nash, 1975) indicating temperatures 50–100 °C higher than those in the upper parts of the veins.

3. The locations of the replacement ores and associated calc-silicate skarns that suggest a closer proximity to a heat source.

4. The zone within the Argentine vein (immediately north of its intersection with the Black Bear vein) that contains greater than 1 percent copper, suggesting higher temperatures in this area (Mayor and Fisher, 1972).

The ore genesis model suggested here thus incorporates convective cells of meteoric water associated with the emplacement of metal-bearing magmas. I infer that some of the lead in the ore bodies was derived from nearby wall rocks traversed by these meteoric waters (compare with Doe and others, 1979) but that most of the other metals were derived from the metal-bearing magmatic water and mixed with a large volume of circulating meteoric water. Early caldera-related fracture systems provided ready access for these metal-enriched fluids, dominantly meteoric, to migrate upward and form the rich ore bodies in the district, the ores being generally zoned outward from central sources. The different ages of the ores from the Argentine–Black Bear system (about 17 Ma) and the Camp Bird system (about 10 Ma) suggest that this model of ore formation repeated at least once within the district. Such repetition of mineralization is compatible with the data presented by Lipman and others (1976) for the igneous and mineralizing events within the district.

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Gold in the Alma Mining District, Colorado

By Daniel R. Shawe

Abstract

The Alma district, discovered in 1860, has produced more than 1.3 million ounces of gold and substantial silver, lead, zinc, and copper. The district lies on the east flank of the north-trending Sawatch uplift. Precambrian gneisses, schists, and granites, and overlying Paleozoic marine sedimentary rocks have been intruded by Laramide intermediate to silicic porphyry dikes, sills, and a stock. The porphyries were strongly altered, mostly before ore deposition. Major north-northwesterly reverse faults with associated drag folds, such as the prominent London fault, were major controls on localization of ore deposits.

Three principal types of gold ores formed following emplacement of the porphyries. (1) Gold-bearing quartz veins produced most of the value of the Alma district. The greatest vein production came from the "London ore zone," in shattered porphyry sills beneath west-dipping shale on the limb of a drag syncline adjacent to the London fault. The veins contain pyrite, dark-colored sphalerite, galena, chalcopyrite, and free gold. During early mining, gold grades averaged 1.86 oz Au/ton. (2) Next in importance are silver-lead replacement mantos formed in dolomitic limestone host rocks adjacent to fissures. The replacement deposits are characterized by a gangue of ferroan dolomite, barite, jasperoid, and quartz, and by ore minerals including light-colored sphalerite, galena, pyrite, chalcopyrite, and locally tennantite, luzonite, argentite, freibergite, tetrahedrite, covellite, and chalcocite. The replacement deposits are somewhat similar to mantos in the nearby Leadville district. Numerous secondary minerals formed from the manto ores in the weathered zone. Ores mined from the replacement deposits contained 0.04–0.26 oz Au/ton. (3) The third ore type is gold deposits in quartzite; the deposits consist of pyrite-sphalerite-galena-chalcopyrite replacements of certain beds adjacent to minor faults, and of small veins. Gold content of mined quartzite ores was 0.05–0.30 oz Au/ton.

District-scale mineral zoning is poorly developed, but some smaller clusters of deposits are zoned. Highest gold values along the London fault are near the center of the district. Groups of silver-lead replacement deposits are rich in silver centrally, and rich in barite peripherally. Some gold- and pyrite-bearing quartz veins in Precambrian rocks grade upward into silver-lead-manganese veins, which in turn merge upward into silver-lead replacement ore bodies in overlying Paleozoic carbonate rocks.

The principal ores of the district probably formed about 35 Ma from heated solutions driven by porphyry intrusion. The Alma district appears to have high potential for new gold discoveries.

INTRODUCTION

The Alma mining district is in the central part of the Colorado mineral belt, about 105 km southwest of Denver and 10 km east of Leadville (fig. F6). It lies in Park County at the northwest edge of South Park, on the east flank of the Mosquito Range.

Gold was discovered at the Phillips lode and other nearby deposits in the upper reaches of Buckskin Gulch (along Buckskin Creek, fig. F7) in the headwaters of the middle fork of the South Platte River in 1860 (Henderson, 1926, p. 36–38). By 1863 mining had exhausted the oxidized ores near the surface, and deeper sulfide ores, some of large volume as at the Phillips mine (Patton and others, 1912, p. 234), could not be treated successfully and were abandoned. Silver ore was discovered on Mount Lincoln and Mount Bross, northwest of the town of Alma (fig. F7), in 1871, resulting in substantial silver production that continued until 1892 when the price of silver dropped. Silver ore was discovered in the London vein west of Alma (fig. F7) in 1873 (Singewald and Butler, 1941, p. 36), and silver and gold production from these deposits was almost continuous until 1942 (Koschmann and Bergendahl, 1968, p. 109). Gold placer deposits along the South Platte River east of Alma (fig. F7) were first mined in the 1870's, although greatest production occurred during the period 1904–1942. Only small and sporadic gold production has occurred in the Alma district following World War II. Cobb Resources and Boulder Gold announced the start of new production in the London mine in May 1988 (Mining Journal, 1988).

Production of gold from the Alma district through 1959 amounted to about 1,350,000 oz, of which about 1,320,000 oz came from lode deposits (Koschmann and Bergendahl, 1968, p. 109). In the period 1859–1951 the district also produced 7,636,045 oz of silver, 58,892,775 lbs of lead, 3,103,485 lbs of copper, and 8,263,500 lbs of

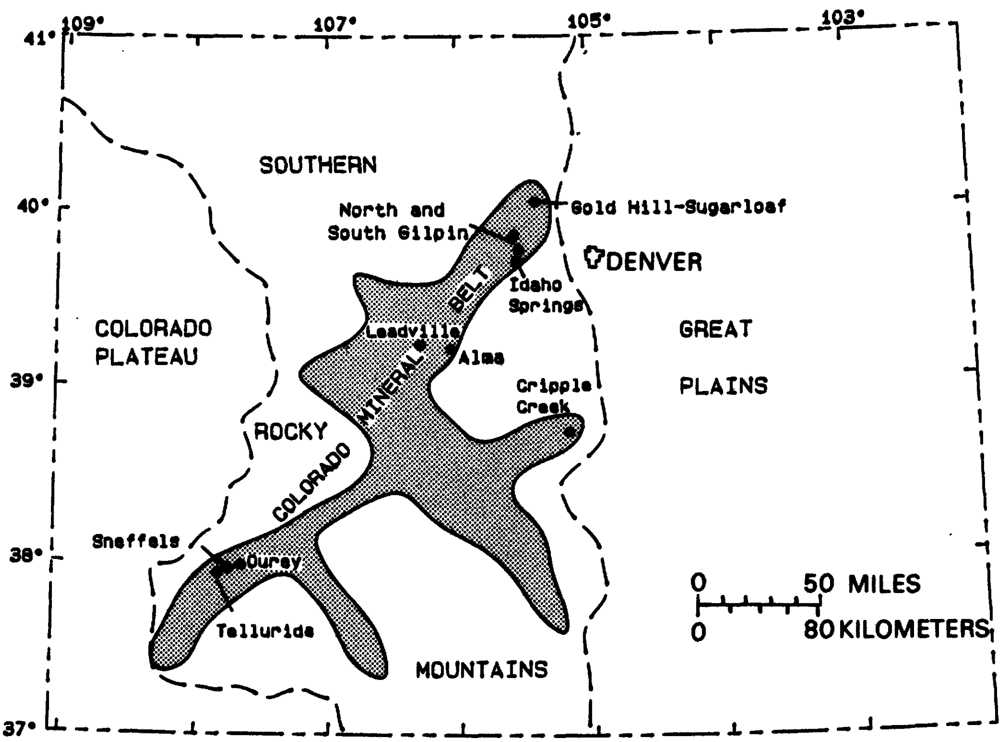

Figure F6. Map of Colorado showing location of the Alma district and other major gold-producing districts. Shaded area shows the principal mineralized region in Colorado (Shawe and others, 1978).

zinc (U.S. Bureau of Mines, 1943, p. 5; U.S. Bureau of Mines Minerals Yearbooks 1933–1951). Zinc recovery did not begin until 1937, and consistent zinc recovery started in 1940. Minable reserves in the London mine of 400,000 tons of gold ore averaging about 0.4 oz Au/ton (12.3 g Au/ton) were reported in May 1988 (Mining Journal, 1988).

Much of the geologic information for this report was derived from earlier publications, particularly those of Singewald and Butler (1930, 1931, 1933, 1941). Moore (1913) and Patton and others (1912) made early studies in the district.

GEOLOGIC SETTING

In the Alma district Paleozoic marine sedimentary rocks overlie gneisses, schists, and granites of an uplifted Precambrian basement. The Precambrian and Paleozoic rocks are intruded by numerous dikes and sills and a stock of Cretaceous-Tertiary porphyry (fig. F7). The gold deposits occur mostly in porphyry sills, in limestone, and in quartzite near the London fault and at the Phillips mine in Buckskin Gulch. Much of the earliest production in the district came from high-angle fissure veins in Cambrian quartzite and the underlying Precambrian rocks in Buckskin Gulch.

Precambrian Rocks

Quartz-mica schists and migmatitic gneisses (Singewald and Butler, 1941, p. 7) that date at 1,700–1,800 Ma (Tweto, 1977) are the oldest rocks exposed in the Mosquito Range near Alma. The schists are probably in the most part metamorphosed sandy marine shales from which the felsic components of the migmatites were "sweated-out" during metamorphism. The schists and gneisses were invaded by granitic rocks of two ages, about 1,700 Ma and about 1,400 Ma (Tweto, 1977; 1979). The older granite is foliated coarse-grained, somewhat porphyritic, pink biotite-muscovite granite, and the younger granite is fine- to medium-grained light-gray biotite-muscovite granite. Pegmatites are associated with both younger and older granites.

The dominant strike of foliation in the Precambrian gneisses and schists in the district is northwest, but locally foliation strikes northeast to east. A broad zone of northeast-striking foliation in Precambrian rocks passes north of London Mountain (Singewald and Butler, 1941, pl. 1).

Figure F7 (facing page). Generalized geology of the Alma district, showing locations of principal mines (modified from Singewald and Butler, 1941, plate 1).

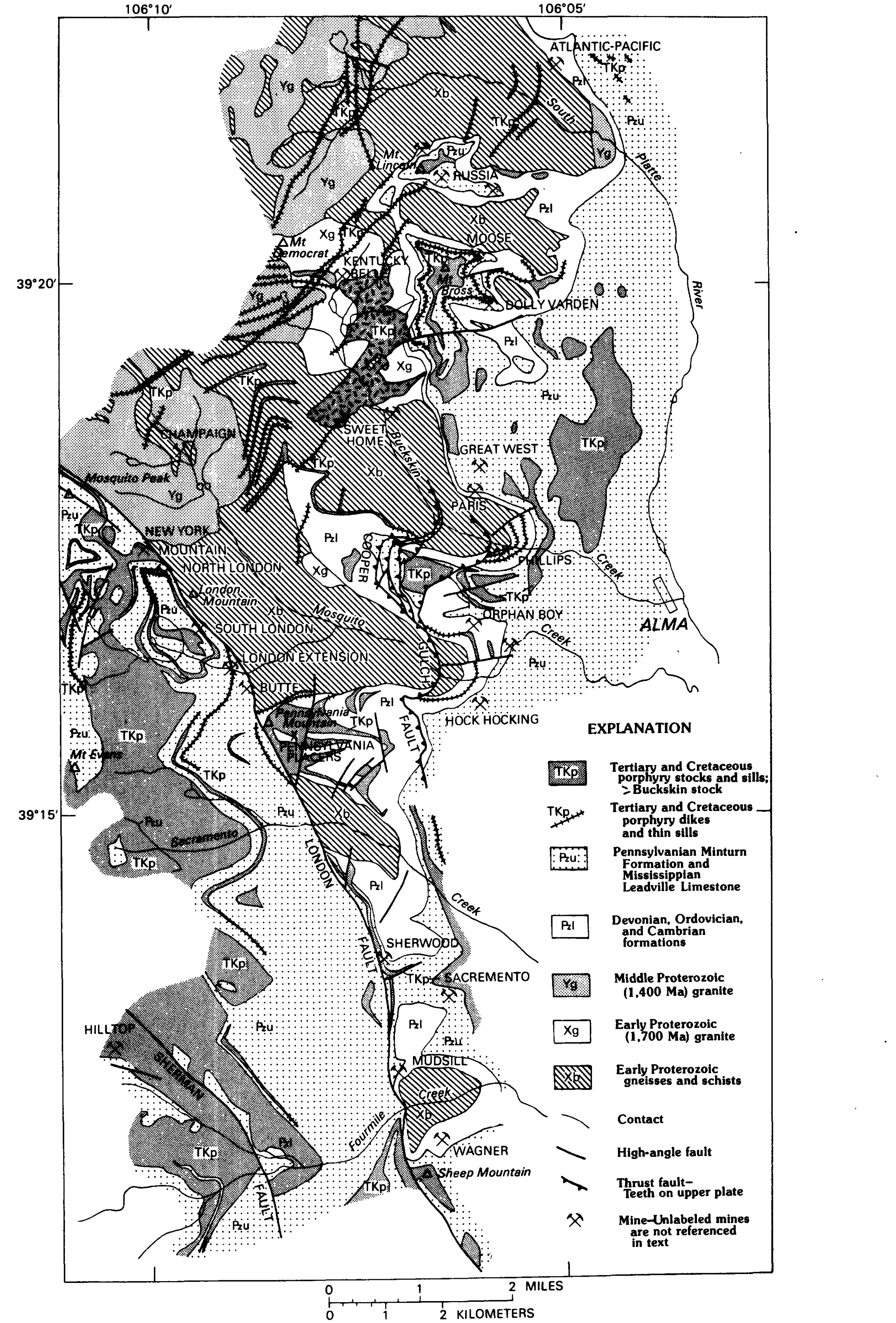
106°10′
106°05′
39°20′
39°15′
ATLANTIC-PACIFIC
South
Platte
River
Mt Lincoln
RUSSIA
Mt Democrat
KENTUCKY BELLE
MOOSE
Mt Bross
DOLLY VARDEN
CHAMPAIGN
Mosquito Peak
SWEET HOME
Buckskin
GREAT WEST
PARIS
NEW YORK MOUNTAIN
NORTH LONDON
London Mountain
COOPER
PHILLIPS
Creek
SOUTH LONDON
Mosquito
ORPHAN BOY
ALMA
LONDON EXTENSION
GULCH
BUTTE
Pennsylvania Mountain
PENNSYLVANIA PLACERS
HOCK HOCKING
FAULT
Mt Evans
Sacramento
LONDON
FAULT
SHERWOOD
SACREMENTO
HILLTOP
SHERMAN
MUDSILL
Fourmile
WAGNER
Sheep Mountain
TKp
Pzu
Pzl
Yg
Xg
Xb
EXPLANATION
TKp Tertiary and Cretaceous porphyry stocks and sills; >Buckskin stock
TKp Tertiary and Cretaceous porphyry dikes and thin sills
Pzu Pennsylvanian Minturn Formation and Mississippian Leadville Limestone
Pzl Devonian, Ordovician, and Cambrian formations
Yg Middle Proterozoic (1,400 Ma) granite
Xg Early Proterozoic (1,700 Ma) granite
Xb Early Proterozoic gneisses and schists
Contact
High-angle fault
Thrust fault—Teeth on upper plate
Mine—Unlabeled mines are not referenced in text
0 1 2 MILES
0 1 2 KILOMETERS

Table F1. Stratigraphic section in the Alma district, Colorado

[Modified from Singewald and Butler, 1941, p. 8–9; and Tweto, 1960]

Age	Stratigraphic unit		Thickness	Lithologic character
Pennsylvanian	Minturn Formation		1,200 m	Interbedded quartzite, conglomerate, arkose, shale (in part carbonaceous), and sparse limestone.
Mississippian	Leadville Limestone		0–50 m	Bluish-gray to dark-gray dense, massive-bedded dolomitic limestone. Contains "zebra rock", chert, and breccia.
Mississippian? and Late Devonian	Chaffee Group	Gilman Sandstone	0–3 m	Lenticular dense white quartzite.
		Dyer Dolomite	12–24 m	Whitish- and bluish-gray, buff-weathering, dense, thin-bedded dolomitic limestone.
		Parting Formation	0–17 m	Light- to dark-brownish-gray weathering, crossbedded and conglomeratic quartzite, sandy limestone, and minor shale.
Early Ordovician	Manitou Limestone		0–40 m	Whitish- and bluish-gray crystalline limestone, locally slightly shaly.
Late Cambrian	Peerless Formation	"Upper shaly beds"	4–8 m	Interbedded brown- and green-weathering dolomitic limestone, shaly limestone, and shale.
		"Upper limy beds"	5–9 m	Brown-weathering somewhat sandy dolomitic limestone with limy-shale partings.
		"Lower shaly beds"	6–9 m	Brown- and green-weathering thin-bedded dolomitic limestone and shale.
		"Middle limy beds"	5–9 m	Brown-weathering dolomitic limestone with shale partings.
	Sawatch Quartzite	"Purple quartzite"	1–5 m	Purple to nearly black quartzite.
		"Upper white quartzite"	2–4 m	White, fine-grained thick-bedded quartzite.
		"Lower limy beds"	3–4 m	Brown-weathering thin-bedded quartzite, limy quartzite, sandy limestone, shale, and rare limestone.
		"Lower white quartzite"	14–27 m	White fine-grained thick-bedded quartzite, conglomeratic at base.

Paleozoic Sedimentary Rocks

The Paleozoic stratigraphic section in the Alma district is summarized in table F1. It is about 1,400 m in maximum thickness. A more detailed description of the Paleozoic rocks can be found in Singewald and Butler (1941). The basal part of the Pennsylvanian Minturn Formation and the Mississippian Leadville Limestone are significant as the host rocks of the largest gold deposits in the district.

Cretaceous and Tertiary Igneous Rocks

Late Cretaceous and early Tertiary porphyry dikes and sills have abundantly intruded the Precambrian gneisses, schists, and granites, and the Paleozoic sedimentary rocks. The ores in the district appear to be genetically related to the porphyries. Although the porphyries are generally hydrothermally altered and apparently mostly pre-ore, residual magmas in deeper source zones of the porphyries may have provided sufficient heat to cause circulation of mineralizing fluids, following emplacement of the porphyries. Sills are most abundant in the basal part of the Minturn Formation, though they have invaded all of the sedimentary formations; dikes occur mostly in the Precambrian rocks. At the London mine (North and South London, and London Extension) the basal part of the Minturn Formation is extensively intruded by porphyry sills, and this interval is called the "porphyry zone" or the "London ore zone" (fig. F8). A Cretaceous porphyry stock called the Buckskin stock intruded Precambrian rocks northwest of Alma (fig. F7). The porphyries are all part of a regional northeast-trending belt of Laramide porphyries that coincides with the Colorado mineral belt.

The porphyries in the Alma district have been classified generally in three groups, an earlier "White porphyry" equivalent to the White porphyry of the nearby Leadville district (Emmons and others, 1927, p. 43–46), intermediate "Gray porphyry" in part equivalent to the Lincoln Porphyry of the Leadville district (Emmons and others, 1927, p. 46–48), and a later white porphyry. The following descriptions of the porphyries, from oldest to youngest, are based on Singewald and Butler (1941, p. 17–22).

The White porphyry is a whitish-gray rock with sparse small- to medium-sized quartz and muscovite phenocrysts scattered through a homogeneous strongly altered groundmass. Some of the White porphyry contains altered feldspar prisms. Rocks of the Gray porphyry are divided into three types, monzonite-diorite porphyry, quartz monzonite porphyry, and the Lincoln Porphyry. The monzonite-diorite porphyry is a dark-gray rock with small- to medium-sized abundant hornblende and sparse quartz phenocrysts in a dense greenish-gray groundmass. The rock has been moderately altered in places. The quartz monzonite porphyry, the most abundant type in the Alma district, is a medium-greenish-gray rock that contains generally numerous small to large (to 1 cm) phenocrysts of plagioclase, quartz, and biotite in a dense groundmass. Locally, the rock has been moderately to intensely altered and is light colored. The Lincoln Porphyry is a distinctive rock, similar to the quartz monzonite porphyry except that it contains large euhedral pink orthoclase phenocrysts 2.5–10 cm long. In places quartz phenocrysts are as large as 2.5 cm. Locally, the rock has been intensely altered and is light gray in color. The White porphyry and the Gray porphyry constitute the bulk of the sills in the district, as well as of the Buckskin stock. The later white porphyry, not abundant in the Alma district, is a whitish-gray rock that contains sparse to abundant small- to medium-sized phenocrysts of albite, orthoclase, quartz, and muscovite. The rock has been strongly altered generally. It was emplaced mostly as northeast-trending dikes.

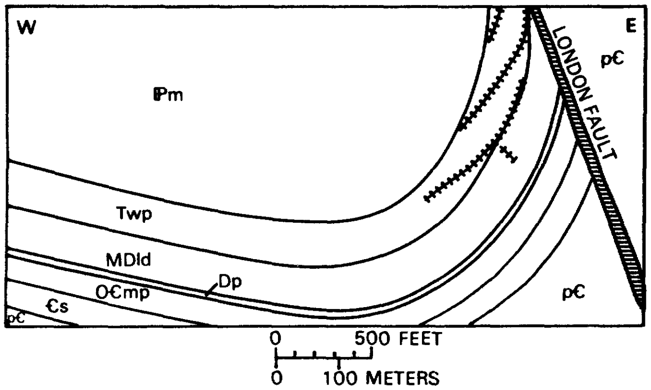

Figure F8. Diagrammatic west-east cross section at the London mine depicting ore bodies before postmineral faulting. Veins are crosshatched; p-C, Precambrian rocks; -Cs, Cambrian Sawatch Quartzite; O-Cmp, Cambrian Peerless Formation and Ordovician Manitou Limestone; Dp, Devonian Parting Formation; MDld, Devonian Dyer Dolomite and Mississippian Leadville Dolomite; IPm, Pennsylvanian Minturn Formation with sills of quartz monzonite porphyry; Twp, Tertiary White porphyry and quartz monzonite porphyry with lenses of Minturn Formation (London ore zone). Modified from Singewald and Butler (1941, fig. 5).

The age of melagranodiorite of the Buckskin stock is 71.2±1.7 Ma, and a dike of the Lincoln Porphyry that intrudes the stock dates at 66.7±1.6 Ma, according to Marvin and Dobson (1979, p. 12–13). Bookstrom and others (1987, p. 18) reported an age of 63.6±2.3 Ma for an aplitic rhyolite porphyry dike that cuts Lincoln Porphyry in Buckskin Gulch. The period of major porphyry intrusion in the Alma district thus was in the Late Cretaceous–early Tertiary between about 71 and 64 Ma. Bookstrom and others (1987, p. 18) reported a K-Ar age of 34.9±4.0 Ma for a dike of the later white porphyry, but they indicated the dike was mineralized. The age may represent age of mineralization rather than of dike emplacement. This age and fission-track ages reported by Bookstrom and others (1987, p. 18–19) that range from about 44 to 27 Ma may represent either intrusion or mineralizing events related to formation of quartz-pyrite-molybdenite veins northwest of the Buckskin stock. K-Ar ages of some other younger porphyries in the area surrounding the Alma district are about 40–45 Ma (for example, Bryant and others, 1981). T.B. Thompson (written commun., 1987) suggested that the age of nearby Leadville ores, similar in many ways to gold-bearing ores at Alma, is about 34 Ma. Probably more than one mineralizing event occurred in the Alma district, and the age of the gold-bearing ores remains uncertain.

The Mosquito Range was uplifted during the Laramide episode of porphyry intrusion (Tweto, 1975), and probably again in middle to late Tertiary time.

Effects of Glaciation

The topography of the Mosquito Range before the Pleistocene was that of a mature upland. Pleistocene glaciation caused extensive deepening of the major drainages, and widespread deposition of glacial debris. Deep oxidation and supergene enrichment of the ore deposits in the Alma district took place before glaciation, and these zones largely were destroyed where the glaciers existed. Also, debris spread by the glaciers, and talus that formed at the oversteepened margins of the glaciers, cover much of the surface of the district, and these surficial deposits have inhibited exploration for new ore deposits.

Structure

The Alma district lies on the east flank of the north-trending anticlinal Sawatch uplift. The regional easterly dip of the stratified rocks in the district has been modified locally by faults and minor folds. Emplacement of the Late Cretaceous–early Tertiary sills has expanded the stratigraphic section of Paleozoic rocks and modified their attitudes significantly in places. The most important structures in regard to localization of the ores are the north-northwest-trending London reverse fault zone, an associated south-southeast-plunging anticlinal nose on the east side of the London fault, and a complementary south-southeast-plunging syncline on the west side of the fault. Other faults, including the Sherman fault and the Cooper Gulch fault system, were important in localizing ore deposits. Folds associated with some of the faults also influenced the positions of some ore deposits.

The London fault, more than 30 km long, extends through the Alma district from near Mosquito Peak south-southeastward and beyond, to where it is truncated by an east-trending fault. It extends northwestward to the Leadville district, where it is truncated by the north-trending Mosquito fault. The fault dips steeply (60°–80°) to the east, and drag related to reverse movement on the fault has resulted in the formation of the anticlinal nose on the east side of the fault, and the slightly plunging syncline on the west side of the fault (fig. F8). The fault and fold zone is a disturbed belt in which are numerous auxiliary faults that localized the principal gold-bearing veins of the district.

The main strand of the London fault is characterized by a strongly sheared zone as much as 30 m wide of alternating layers and lenses of coarse breccia, clay gouge, and clay gouge that contains breccia fragments. Breccia lenses are silicified to varied degrees, as well as unsilicified.

Total apparent throw on the London fault is about 900 m, about half of which is attributable to folding and about half to actual vertical fault displacement. Singewald and Butler (1941, p. 26) suggested that the London fault had a horizontal as well as vertical component of displacement, but of unknown magnitude.

As illustrated by Singewald and Butler (1941, pl. 8), the London fault flattens where it encounters the porphyry zone at the base of the Minturn Formation, as though "refracted" by the more brittle igneous rocks. Reverse movement on the London thus would tend to open the fault where it intersects the porphyry zone. The resultant locally increased permeability of the London fault, together with increased permeability in the igneous rocks owing to auxiliary fracturing related to movement on the London, may help account for the extensive mineralization of the porphyry zone (London ore zone; see fig. F8).

Numerous auxiliary faults in the London fault zone are poorly known except where mapped in underground workings, particularly at London Mountain (Singewald and Butler, 1941, p. 26). There, most auxiliary faults strike parallel to the London fault and dip to the southwest, whereas others have similar strike but dip to the northeast. The principal gold veins formed near the London fault in southwest-dipping faults that intersect the London fault (fig. F8). Some transverse faults terminate against the London fault and others displace it, perhaps as much as 100 m. The largest apparent offset of the London fault along transverse faults is just south of the main zone of gold deposits at London Mountain.

The Sherman fault 2–3 km southwest of the London fault is a northwest-striking, steeply northeast dipping reverse fault that appears similar in character and origin to the London fault; an associated southeast-plunging anticlinal nose is located on the northeast side of the Sherman fault. Ore bodies near the Sherman fault lie farther into its footwall than do those near the London fault.

The Cooper Gulch fault system between London Mountain and the town of Alma also localized ore deposits. The system consists of a north-striking thrust fault with flat dip to the east that splays into several strands in the north half of the system. A zone of ore deposits was formed in the hanging wall of the Cooper Gulch system west of Alma (fig. F7).

A southeast-plunging anticlinal nose in the north part of the district appears to have localized a group of ore deposits. This anticlinal nose, however, unlike those farther south, is not associated with a northwest-striking reverse fault at the surface.

Numerous small faults of northeast strike and steep dip have been mapped throughout the district (Singewald and Butler, 1941, pl. 1; Singewald, 1947, p. 338). Some of the northeast-trending faults were intruded by the younger dikes of Tertiary porphyry, and the northeast-trending set of faults is parallel to the strike of the porphyry belt that controlled the Colorado mineral belt. Many of the northeast-trending faults show evidence of significant late horizontal (strike-slip) displacement (Singewald and Butler, 1930, p. 307), and several of them offset the London fault.

According to Singewald and Butler (1930, p. 307; 1931, p. 398–399), movement on the major reverse and thrust faults took place after intrusion of all of the Cretaceous-Tertiary(?) porphyries except the later white porphyry, and minor displacements continued after mineralization. An episode of minor faulting characterized by formation of the northeast-trending set began before intrusion of the Gray porphyry and lasted until after mineralization.

Most of the numerous minor faults associated with the London fault, though of greatly diverse orientations, strike subparallel with the London and are in its footwall, extending no farther west than the axis of the drag syncline on the west side of the London fault. Generally these faults dip to the southwest at angles slightly less than the dip of sedimentary strata and of the porphyry sills intruded into the strata. The southwest-dipping faults, though commonly flatter than the dip of sedimentary strata and of the enclosed porphyry sills, follow contacts of the strata and sills in many places, having taken advantage locally of existing planes of weakness. The auxiliary faults as indicated by their close proximity to the London fault undoubtedly formed as a result of movement along the London fault. Also, because the faults contain both unbrecciated and brecciated veins, it is evident that different faults of the system were active both before and after ore deposition, as was the London fault. The southwest-dipping faults are the most productive set on London Mountain. Some minor faults that dip northeast are reverse faults, and are sympathetic to the London fault. They are of premineral origin, as they contain ore, but most movement on them occurred following ore deposition. Also, some of the northeast-dipping faults displace southwest-dipping veins, showing that they are generally younger than the more productive southwest-dipping fissure veins, and in fact the London fault itself is offset by a minor northeast-dipping fault.

Alteration

Rocks in which the ore deposits formed were strongly and widely altered by hydrothermal solutions. The altered porphyries show varied degrees of silicification and clay-alteration of feldspars, ferromagnesian minerals, and groundmass; Paleozoic sedimentary rocks generally show less conspicuous effects of alteration, though shale of the Minturn Formation locally is bleached strongly. Fragments and horses of shale from the lower part of the Minturn in the fault gouge of many fissures are black with carbonaceous material apparently concentrated from the original sedimentary rock by hydrothermal fluids (Singewald and Butler, 1941, p. 37–39). The common association of carbonaceous material with the ores suggests the influence of chemical reduction on precipitation of the ores. Jasperoid (chert) is abundant near the London fault from the Mudsill mine to a point 1–2 km south of Sheep Mountain (fig. F7).

Near veins the porphyries are exceedingly altered. Though retaining original textures, they now are made up entirely of quartz, sericite, and minor original accessory minerals. Farther from veins, to as much as 100 m or so, carbonate (Fe-dolomite or ankerite?—Singewald and Butler, 1931, p. 406) occurs with quartz and sericite. Some altered porphyry is so intensely iron mineralized as to have a deep-red color (Singewald and Butler, 1931, p. 400). Shale of the Minturn Formation in and near fissure veins consists of a yellowish mat of sericite locally enclosing rounded fragments of carbon-rich shale that contains angular quartz grains, sericite, carbonate, and pyrite. The shale wallrock may also contain abundant sericite veinlets. Quartzite of the Minturn near veins has been mildly sericitized. Except where replaced by ore, limestone of the Leadville exhibits little effect of alteration near veins. However, "zebra rock" and chert (Singewald and Butler, 1931, p. 392), possibly related to mineralization, are locally common in the Leadville.

ORE DEPOSITS

Ore deposits in the Alma district are part of the northeast-trending Colorado mineral belt (fig. F6). Within the district they form clusters that appear to be related to major structures. For example, near London Mountain, the most productive mines of the district lie in a narrow zone in the footwall of the London fault; farther south the Sherwood and nearby mines are in the hanging wall of the London fault; about 3 km west of Alma a north-trending zone of mines is in the hanging wall of the Cooper Gulch fault; and mines farther north near Mount Lincoln and Mount Bross lie on a structural terrace that, according to Singewald and Butler (1941, p. 28), is part of the same "tectonic unit" as the Cooper Gulch fault (fig. F7). Despite the fact that major faults exercise rough structural control of ore distribution, individual ore bodies have been localized exclusively on minor structures, some of which are en echelon zones of minor high-angle fissures.

The most important deposits fall into three classes: (1) gold-bearing quartz veins in or against porphyry sills near the base of the Minturn Formation, (2) silver-lead replacement deposits in carbonate formations, and (3) gold deposits in quartzite of the Sawatch Quartzite. Quartz-pyrite-molybdenite veins in Precambrian rocks just northwest of the Buckskin stock have not been mined, and a vuggy quartz-tetrahedrite-fluorite-rhodochrosite vein in Precambrian rocks at the

Sweet Home mine southeast of the Buckskin stock has been mined mostly for mineral specimens (Kosnar, 1979).

Gold-bearing Quartz Veins

The gold-bearing quartz veins near London Mountain that have produced most of the value of the Alma district are thin tabular fissure fillings (Singewald and Butler, 1941). Moore (1913) reported that an ore body on the London vein was stoped continuously for a distance of 560 m horizontally, and to a height ranging between 45 and 200 m. Other stopes are smaller, and the smaller ore bodies mined from them were perhaps the result of disruption of the original vein by postmineral faults. Maximum width of veins was only a few meters. The principal ore shoot on the London vein pitched gently to the south following the intersection of the London vein and a west strand of the London fault. Locally the vein terminated where the fissure passes downward (but up section) from the porphyry zone into the Minturn Formation.

The London vein dips about 65° SW. in its lower mined part, and it steepens upward and is locally overturned adjacent to the London fault. The McDonald vein, similar to the London and subparallel with it, lies in the porphyry zone about 30 m farther east and below the London. Minor subparallel veins of southwest and northeast dip, as well as of other attitudes in the porphyry zone in the footwall of the London fault, have produced small amounts of locally rich ore.

The hypogene ore throughout the London system is of generally uniform character. The relatively simple mineral assemblage consists of early quartz and sulfides cut by late veinlets of milky-white quartz, minor sericite, and local but rarely abundant calcite. The sulfides are pyrite, dark sphalerite, galena, and chalcopyrite, commonly in that order of abundance. Sulfides are found as tiny veinlets, small clusters, and large irregularly shaped masses intergrown with small quartz grains and interstitial to the large quartz crystals. Crude "banding" and comb structure are evident locally in the veins. Free gold, visible in places in rich ore, occurs as ragged flakes and tiny veinlets, most commonly with sphalerite, galena, and chalcopyrite. Gold is not visible in most of the ore.

Fragments, thin layers, and filaments of wallrock are common in the veins, generally in amounts inversely related to tenor of the ore.

Polished- and thin-section studies of ore and gangue minerals by Singewald and Butler (1941, pls. 14–17; p. 49–55) showed a paragenetic sequence of initial quartz, early pyrite followed in succession by sphalerite, chalcopyrite, galena, and gold, and then late calcite. Probably some overlap occurred in the sequence of deposition of ore minerals. Brecciation followed initial emplacement of barren quartz veins, after which pyrite was deposited.

Pyrite occurs commonly as subhedral cubes; it also has been fractured, corroded, and embayed during younger brecciation and mineralization. A second stage of quartz commonly fills fractures in pyrite. Sphalerite, chalcopyrite, and galena occur in irregular masses; these minerals appear to have been deposited during a single stage as suggested by their commonly intergrown habit. They were deposited preferentially in zones of shattered quartz, probably by replacement of quartz. Sphalerite in the veins is dark and has a high iron content, and it contains abundant small (exsolution?) blebs of chalcopyrite. The sphalerite, chalcopyrite, and galena aggregates may or may not be associated with pyrite, suggesting that the second stage of quartz mineralization may have sealed off parts of the pyrite-bearing zones from later sulfide mineralization.

"Native gold occurs in small grains with smoothly curved margins or in short, hackly stringers some of which form networks" (Singewald and Butler, 1941, p. 53). The description of stringers is reminiscent of the common occurrence of gold as tiny chains of connected imperfect octahedral crystals. Blebs of gold occur mostly at grain boundaries between two sulfide minerals or between two quartz crystals, suggesting the gold's late age. It also forms tiny veinlets in quartz.

At the small Hard-to-Beat mine (not shown on fig. F7) a few hundred meters northwest of the North London mine, a small amount of gold was produced from an irregular limonitic quartz ore body and from nearby small quartz veins in quartzite of the Minturn Formation. The quartz veins contained abundant carbonate and lesser amounts of simple sulfides. The Oliver Twist tunnel (not shown on fig. F7), driven to intersect the porphyry zone about 300 m northwest of the Hard-to-Beat mine, encountered two quartz-sulfide veins, but of too low gold tenor to be profitably worked.

Oxidation of pyrite and chalcopyrite, resulting from near-surface weathering of the ore bodies, formed abundant limonite. Small amounts of malachite, azurite, and anglesite have been recognized near the surface, and leaching has left the ores somewhat porous. Throughout most of the London system no secondary enrichment of gold has been recognized. However, oxidized ore at the Hard-to-Beat mine contained small pockets especially rich in gold.

Grade of the ore mined in the London system generally has been high. According to Moore (1913, p. 415–427), about 52,500 tons of ore that was produced from the London mine in the period 1895–1910 averaged about 1.86 oz Au/ton. Of this, a 2,000 ton lot assayed 2.895 oz Au/ton, 2.585 oz Ag/ton, 4.13 percent Pb, 2.66 percent Zn, 4.85 percent Fe, and 6.11 percent S. Cobb

Resources Corp., the operator of the London mine, has reported drilling a vein that assays 3.75 oz Au/ton through a thickness as much as 2.5 m (The Mining Record, Dec. 12, 1984). Current (May 1988) reserves in the mine of 400,000 tons average about 0.4 oz Au/ton.

The gold-mineralized fissure veins in the London mine in the period 1901–1931 produced 263,273 oz of gold, 237,178 oz of silver, 5,879,725 lbs of lead, and 165,520 lbs of copper. No zinc was recovered (Singewald and Butler, 1941, p. 36–37). The Champaign mine in the headwaters of Mosquito Creek was the most productive of several small mines that worked gold-mineralized fissures in the Precambrian rocks. Other strongly gold-mineralized, nearly vertical fissures occur in Sawatch Quartzite and Precambrian rocks in Buckskin Gulch. Most are of northeast trend. They have not been very productive because of their abundant pyrite content, although many are large and of good grade. They almost certainly acted as feeders for higher ore bodies in the carbonate rocks on Mount Bross and London Mountain.

Silver-Lead Deposits in Carbonate Rocks

In addition to gold-bearing quartz veins, the London mine had some ore along mineralized fissures in the Leadville Limestone, where limestone near the fissures was replaced by ore just below the top of the formation. One ore body was mined for about 180 m on strike and through a maximum vertical interval of about 60 m and as much as 6–7 m outward from the fissure. In one place ore was continuous from the Leadville upward into the porphyry zone and to the McDonald vein.

At New York Mountain (fig. F7) small silver-lead replacement deposits were mined in limestone of the Leadville Limestone. A gangue of unreplaced limestone contained small, irregular, somewhat rounded clusters of sulfide minerals as large as 5 cm. Sphalerite was the chief ore mineral and was accompanied by less abundant galena and minor pyrite and chalcopyrite. Sphalerite in the limestone replacement deposits is lighter colored than in the gold-bearing quartz veins in the London mines, it has a low iron content, and it contains virtually no exsolved chalcopyrite. Singewald and Butler (1941, p. 60) suggested the presence of small amounts of tetrahedrite-tennantite at the New York Mountain mine. Iron-bearing dolomite in amounts similar to the sulfides formed vuggy masses some of which enclosed sulfide clusters. Minor amounts of calcite and quartz were present in ore; in places near ore the limestone has been silicified.

The American mine (not shown on fig. F7) lies between the South London and London Extension mines near the London fault. Since its discovery in 1931, it produced 60,000 tons from a limestone replacement ore body that contained 0.40–2 oz Au/ton, 1–2 oz Ag/ton, 6–10 percent Pb, and 7–16 percent Zn (the zinc was not recovered; U.S. Bureau of Mines, 1943, p. 19).

At the Sacremento mine in the hanging wall of the London fault, about 6 km south-southeast of Pennsylvania Mountain and about 8 km southwest of the town of Alma (fig. F7), a small replacement deposit was mined in limestone of the Leadville. The tabular deposit, an irregular oval-shaped body about 30×40 m in plan dimension, produced ore that contained about 0.75 oz Au/ton, 300 oz Ag/ton, and 10 percent Pb. Gangue consisted of iron-bearing dolomite, barite, and jasperoid, with minor coarse quartz. Galena and pyrite were the dominant sulfides.

The Mudsill mine, about 1.6 km southwest of the Sacremento (fig. F7), also produced only a small amount of ore. The ore occurred beneath a jasperoid layer in the Dyer Dolomite. Mineralized material from prospect dumps near the mine contained white dolomite, barite (much less abundant than at the Sacremento mine), and calcite gangue, along with galena, sphalerite, pyrite, and minor tennantite, chalcopyrite, and luzonite. Typical oxide minerals were present in the partly oxidized material.

At the Sherwood mine about 1 km northwest of the Sacremento mine (fig. F7), replacement veins near the top of the Leadville Limestone yielded a small amount of ore typical of the silver-lead ores of the district, and in which argentite was identified.

The Russia mine lies close to the axis of a gentle southeast-plunging anticlinal nose near the top of Mount Lincoln (fig. F7). One of the largest silver mines in the Alma district, it is developed mostly in the Leadville Limestone. The ore bodies, similar to those at New York Mountain, formed along fissures, or more commonly as blanketlike replacement bodies in shattered limestone of the Leadville near fissures. Less extensive mineralization similar to that in the Leadville took place at greater depth in the Manitou Limestone. The replacement ore bodies are a few meters to perhaps 100 m long, and aligned on faults that have shattered and slightly displaced the limestone. Gangue minerals in the Leadville ore bodies are ankerite, barite, and milky-white quartz. Large masses of the limestone near ore have been completely silicified (jasperized). Ore minerals are sphalerite, galena, pyrite, chalcopyrite, freibergite, tetrahedrite, covellite, and chalcocite. The sulfides are intimately intergrown in small clusters (maximum size about 2.5 cm). Covellite, chalcocite, and minor native silver probably are of supergene origin, and many secondary minerals such as cerussite, anglesite, malachite, smithsonite, hemimorphite, cerargyrite, and jarosite occur near the surface (Heyl, 1964, p. C67-C68). The paragenetic sequence is consistent: pyrite is the earliest sulfide formed, and is followed successively by sphalerite, freibergite, chalcopyrite, and galena. Silver-free tetrahedrite occurs locally where freibergite is absent.

Silver content of the Russia ore was generally somewhat less than 100 oz Ag/ton, though some ore assayed more than 700 oz Ag/ton. Freibergite carried a high content of silver but the galena carried very little, indicating that virtually all the silver in primary ore was in freibergite. Gold content was relatively low.

A northwest-striking fault fissure in the Russia mine localized a vein called the "gold vein." The small ore body extended about 30 m along the fault, was about 15 m high, and locally replaced wallrock no more than 5 m from the fissure. Its mineralogy was similar to that of the blanketlike replacement ores, except that it had higher gold content, as much as 0.5 oz Au/ton.

In 1922 the Russia mine produced ore that averaged about 0.05 oz Au/ton and 14–18 oz Ag/ton (U.S. Bureau of Mines, 1943, p. 24). The Moose mine, 1.5 km southeast of the Russia and similar to it, in 1942 exposed an ore layer about 1 m thick that assayed 5.2 oz Ag/ton, 0.6 percent Pb, 28.3 percent Zn, and 1.5 percent Fe (U.S. Bureau of Mines, 1943, p. 22). The Alma Syndicate shaft (not shown on fig. F7), about 2 km east of the Dolly Varden mine in the Russia-Moose group, in 1942 had blocked out a lens of ore about 60 m long and 2 m thick much of which averaged 0.26 oz Au/ton, 2.2 oz Ag/ton, 16.1 percent Pb, 7.8 percent Zn, and 1.2 percent Fe (U.S. Bureau of Mines, 1943, p. 17).

The Hill Top mine near the Sherman fault (fig. F7) in 1923 worked a limestone-replacement deposit in the Leadville Limestone. In 1923 an ore shipment to a lead smelter assayed 0.042 oz Au/ton, 15.69 oz Ag/ton, 15.72 percent Pb, and 5.16 percent Zn. The same year a shipment to a zinc smelter assayed 33.25 percent zinc (U.S. Bureau of Mines, 1943, p. 26).

The silver-lead replacement deposits in carbonate host rocks in the Alma district are quite similar to such deposits as described by Emmons and others (1927) in the nearby Leadville district, and they probably had a similar genesis.

Gold Deposits in Quartzite

According to Singewald and Butler (1933, p. 108–109), gold-silver deposits occur in the Sawatch Quartzite in the lower reaches of Mosquito and Buckskin Creeks about 3 km west of Alma (fig. F7). There the Brownlow (not shown on fig. F7), Orphan Boy, Phillips, Paris, and Excelsior (not shown on fig. F7) mines have worked ore shoots characterized by pyrite, sphalerite, galena, and chalcopyrite in certain beds along minor faults in the middle and upper parts of the Sawatch, as well as similarly mineralized beds that have been replaced for a meter or so from minor faults. The Atlantic-Pacific mine about 9 km north of Alma (fig. F7) worked similar ores in the Sawatch. Replacement apparently took place in beds that contained calcareous cement. Proportions of gold and silver varied among different veins in the same mine, although gold was significant in all. A vein about 0.5 m wide exposed in the Orphan Boy mine in 1942 averaged 0.30 oz Au/ton, 10 oz Ag/ton, 10 percent Pb, and 35 percent Zn (U.S. Bureau of Mines, 1943, p. 15). In the same mine a tabular deposit about 1 m thick averaged 0.05 oz Au/ton, 6 oz Ag/ton, and 3 percent Zn, whereas another layer 0.3–2.3 m thick averaged 0.15 oz Au/ton, 6 oz Ag/ton, 5 percent Pb, and 17 percent Zn (U.S. Bureau of Mines, 1943, p. 15–16). Although copper content is not reported in these assays, production data for the years 1933–1951 (U.S. Bureau of Mines Minerals Yearbook, 1933–1951) indicate significant copper production from mines of this group (so-called Buckskin district).

Veins Near the Buckskin Stock

Quartz-pyrite-molybdenite veins mostly in Precambrian rocks on the northwest side of the Buckskin stock cut 35 Ma dikes of the later white porphyry; the veins are judged to be about 27 Ma on the basis of fission-track ages (Bookstrom and others, 1987). Some of these veins also contain sphalerite, galena, tetrahedrite, huebnerite, fluorite, and rhodochrosite (Bookstrom and others, 1987, p. 18). Bookstrom and others (1987) related the veins to the Climax igneous-mineralizing episode of similar age about 5 km northwest of Alma.

A quartz-tetrahedrite-fluorite-rhodochrosite vein described by Kosnar (1979) at the Sweet Home mine southeast of the Buckskin stock (fig. F7) probably is related to the same episode of mineralization. The vuggy northeast-trending vein also contains pyrite, sphalerite, galena, chalcopyrite, argentite, tennantite, freibergite, bornite, stromeyerite, native silver, apatite, calcite, siderite, and goyazite (hydrated basic strontium-aluminum phosphate), listed in general paragenetic sequence (Kosnar, 1979, p. 333). Altered wallrocks contain sericite, quartz, huebnerite, pyrite, and molybdenite. Veins at higher altitude than the rhodochrosite-bearing vein contain huebnerite and molybdenite (Kosnar, 1979, p. 338).

Mineral Zoning

Ore deposits in the Alma district do not appear to show district-wide mineral zoning. However, some individual groups of deposits display areal variation in abundances and proportions of different minerals, suggesting local sources of mineralizing fluids for the different groups. The primary (unweathered) ore deposits near the London fault in the vicinity of London Mountain had highest gold contents in the south part of the system north of Pennsylvania Mountain, whereas low gold contents were found in deposits at the north end of the system near New York Mountain. According to Singewald and Butler (1933, p. 114), the gold-bearing quartz veins of the North London, South London, American, and London Extension mines are characterized by dark sphalerite and formed at moderately high temperatures. Silver-lead replacement deposits that contain lighter colored sphalerite and are presumably of lower temperature formation were common farther north near New York Mountain. Very little production came from the small deposits still farther north. Singewald and Butler concluded that the source of mineralizing fluids was centered in the south part of the London system and that the fluids on rising followed the fractured porphyry zone that rises gradually northward beneath an inverted-V "roof" formed by impermeable clay gouge in the London fault and the shales in the lower part of the Minturn Formation (fig. F8).

The group of deposits in the hanging wall of the London fault south of Pennsylvania Mountain (Sherwood, Sacremento, and other mines, fig. F7) displays an inner zone productive of silver that is bounded on the east by a semicircular belt enriched in barite, beyond which silver content of deposits is too low to be minable. Singewald and Butler (1941) inferred that solutions rising along the London fault leaked upward and outward into the hanging wall along fissures near the mines.

Vertical zoning is evident in Buckskin Gulch and on Mount Lincoln and Mount Bross. Here, vertical fissures rich in gold and pyrite in Precambrian rocks and in the Sawatch Quartzite grade upward into silver-lead-manganese veins. The veins extend up into overlying carbonate rocks near the tops of Mount Lincoln and Mount Bross, where they merge with veins and replacement bodies that contain silver, lead, zinc, copper, and manganese (A.V. Heyl, written commun., 1985).

Placer Deposits

Placer gold was mined along the South Platte River 1–2 km northeast of Alma from medium to coarse gravel above shale bedrock. Large nuggets, as much as several ounces in weight, were not uncommon (Vanderwilt, 1947, p. 161–163). Fineness of the placer gold, based on production data for the years 1934–1941 (Vanderwilt, 1947, p. 163) is about 830; the gold is alloyed principally with silver. In the 20th century, especially during the 1930's and in recent years, rich gold placers have been mined high on the east slope of Pennsylvania Mountain (fig. F7). The gold placers do not have a known source. Their position, however, suggests their source was a now eroded part of the London vein system to the west.

SUMMARY AND CONCLUSIONS

Abundant porphyry stocks, sills, and dikes were emplaced along the Colorado mineral belt, including the Alma district, during the Laramide orogeny. Following emplacement of the Buckskin stock and most of the porphyry sills in the Alma district, regional compression resulted in development of the London and similar high-angle reverse faults and associated drag folds, as well as development of the Cooper Gulch thrust fault system. The strike of the major reverse faults was probably controlled in part by dominant northwest-trending foliation in the Precambrian gneisses and schists. A major episode of fracturing to form numerous dominantly northeast trending minor faults commenced early in the period of porphyry intrusion and continued until after most of the porphyries were emplaced. Slight local offset of the London fault occurred on the northeast faults during this episode. The trend of the faults is parallel with that of the Colorado mineral belt, and it also accords roughly with major shear zones and alignments of foliation in Precambrian rocks, such as the broad zone of northeasterly foliation that passes just north of London Mountain. Some strike-slip movement occurred on faults of the northeast set.

After the London fault was formed, but before it became inactive, mineralization of the London vein system took place. In an early barren phase hydrothermal fluids strongly and widely altered the porphyries, for example the early White porphyry. Then quartz deposition in the London and associated veins occurred, followed successively by sulfide and gold deposition. Possibly carbonaceous material in Minturn shale wall rocks and fragments enclosed in the quartz veins played a role in deposition of ore minerals in the veins. The bulk of mineralization took place along minor southwest-dipping fractures that parallel the London fault, within fractured porphyry in the footwall of the London fault. Sericitic alteration of wall rocks accompanied ore deposition. Flow of hydrothermal fluids through the London ore system may have been directed through the fractured porphyry zone at the base of the Minturn Formation beneath an impermeable cap of clay gouge in the northeast-dipping London fault and beneath impermeable basal shales in the southwest-dipping Minturn Formation.

Probably at the same time as the gold-bearing quartz veins of the London system formed, silver-lead replacement deposits formed in carbonate rocks near the top of the Leadville Limestone. Their deposition was preceded by locally strong silicification of the carbonate rocks. Although Singewald and Butler (1941) stated that the lighter colored sphalerite characteristic of the replacement deposits suggested that the replacement deposits were a lower temperature element of the system, possibly the chemical and physical differences between the deposit types were a result of different host-rock environments. Singewald and Butler (1941) also cited the fact that replacement ore along a fissure in the Leadville was continuous upward to the McDonald vein in the porphyry zone, a relation that suggests contemporaneity of formation.

The absolute age of ore deposition in the London system is not known, as no minerals from the deposits have been dated radiometrically. However, it was younger than about 67 Ma, the age of the Lincoln Porphyry whose emplacement preceded ore deposition. The later white porphyry dikes were emplaced following ore deposition as evidenced by the fact that some dikes cut through ore. The age of the later white porphyry may be as young as about 35 Ma, setting a younger limit on the time of the main period of ore deposition. However, the later white porphyry was altered extensively by hydrothermal fluids, suggesting that the 35 Ma age may be a result of thermal resetting by a young mineralizing event (quartz-pyrite-molybdenite?) unrelated to the principal episode of mineralization in the Alma district.

The ore deposits that formed in the hanging wall of the London fault south of Pennsylvania Mountain are similar to the silver-lead replacement deposits in carbonate rocks in the London ore system, and they probably formed during the same episode of mineralization as did the London deposits. The same probably is true also for similar deposits near the Sherman fault, and near Mount Lincoln and Mount Bross. The different groups of deposits, however, apparently formed at separate centers of mineralization controlled by major faults.

The ore deposits that replaced beds in the Sawatch Quartzite in the hanging wall of the Cooper Gulch fault system, judged by their metal content, apparently are mineralogically similar both to the gold-bearing quartz veins of the London ore zone and to the silver-lead replacement deposits in carbonate rocks. Probably they too formed during the same general main period of mineralization of the other deposits.

The heat source that provided the energy to drive the hydrothermal system(s) that deposited the ores of the Alma district probably was Laramide intrusives emplaced in Precambrian rocks at depth beneath the district. Magma chambers that were the source of the porphyry intrusives with which the ores are spatially associated may have continued to throw off heat long after the porphyries were emplaced at higher levels, to account for the generally post-porphyry age of mineralization and for the widescale hydrothermal alteration of the porphyries. At the present state of knowledge, whether or not the later white porphyry was genetically related to a young phase of mineralization, unrelated to the principal episode in the district, is only speculative.

In addition to the likelihood that new ore bodies will be found in the known groups of mines in the Alma district (note the recent high-grade gold vein discovery by Cobb Resources Corp. in the London mine; The Mining Record, 1984), possibilities exist for the discovery of new zones of ore deposits. For example, much ground remains unexplored in the footwall of the London fault south of Pennsylvania Mountain, and in the footwall of the Sherman fault, where the porphyry sills emplaced in the basal shales of the Minturn Formation, and the immediately underlying carbonate rocks at the top of the Leadville Limestone, have been strongly fractured close to major feeder structures. The favorable interval lies at depths as great as 1,000 m in these zones. Perhaps this same favorable interval also contains deposits where minor faults have broken the sedimentary rocks in the area north and west of Alma, but they would be more difficult to explore for because of uncertainty as to which of numerous minor faults might have served as significant feeder structures. The remaining low-grade pyritic gold ores of the Phillips mine in Buckskin Gulch (Patton and others, 1912, p. 234) may be amenable to modern concentration and recovery methods.

Carbonaceous shales and perhaps sparse limy intervals in the basal Minturn Formation may have been favorable hosts for "invisible" gold and silver mineralization of the "Carlin type" near the more conventional gold-bearing quartz veins and silver-lead replacement deposits. The inconspicuous character of known Carlin-type deposits suggests that such deposits in a mineralized environment like that in the Alma district would be easily overlooked.

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Precious Metals in the Leadville Mining District, Colorado

By Tommy B. Thompson[1]

Abstract

The Leadville district has yielded 3.25 million ounces of gold and 256 million ounces of silver in 127 years of production since 1860. Placer gold, quartz-pyrite-precious metal veins, and base- and precious-metal, dolomite-hosted replacement bodies (of Leadville type mineralization) have contributed the bulk of the precious metals in the district. Ore bodies of Leadville type mineralization have been the major producer of gold and silver.

Gold occurs principally as electrum (Au:Ag=1:1) whereas silver is present also in argentian tetrahedrite. Both minerals are late in the sulfide paragenetic sequence. Electrum occurs either in a peripheral zone adjacent to a central base metal zone within the replacement bodies or within and adjacent to veins that cut the replacement bodies. Argentian tetrahedrite occurs within the base metal zone, particularly where late veinlets cross that zone. District-wide, gold is concentrated in a zone peripheral to and within the centrally located Breece Hill stock, and along low-angle, east-dipping thrust faults west of Breece Hill. Silver is concentrated in a zone peripheral to the gold-enriched zone.

The precious–base metal deposits are related to a middle Tertiary igneous intrusive as shown by metal zoning about the Breece Hill stock. Sulfur isotope analyses on pyrite (δ^{34}S: +1.2 to +3.2 per mil), sphalerite (δ^{34}S: −0.5 to +2.2 per mil), and galena (δ^{34}S: −2.4 to +0.7 per mil) yield calculated temperatures of crystallization from pyrite-sphalerite and sphalerite-galena pairs of 420±21 °C and 450±23 °C, respectively. These temperatures agree closely with pressure-corrected fluid-inclusion values during sulfide precipitation of 380–445 °C. The ore fluid $\delta^{34}S_{H_2S}$ is estimated to have been +1.9 per mil and magmatic in origin.

The age of mineralization in the Leadville district has been determined by fission-track dating of annealed apatite and zircon from pre-ore igneous rocks to be 33.8±5.0 Ma.

INTRODUCTION

The Leadville district was discovered in 1860 by prospectors exploring for gold in the Arkansas River and its tributaries. Despite extensive Pleistocene glaciation of the Mosquito Range, one tributary, California Gulch, had not been scoured of its heavy-mineral content. Subsequent gold placer operations upstream recovered significant quantities of cerussite with the gold. Ultimately, the source of the silver-rich lead carbonate was found in surface and near-surface exposures of replacement bodies within the Paleozoic carbonate rocks. As a result of these discoveries, the district has been a metal producer for about 130 years. The precious metal content, particularly silver, was very important in the first 40 years of production; however, since the deregulation of gold pricing, the importance of gold in district ore bodies has been reestablished. Estimated precious metal production from 1860 to 1986 is 3.25 million ounces of gold and 256 million ounces of silver.

The Leadville district is near the central part of the Colorado mineral belt, a northeast-striking zone of Laramide to Tertiary igneous activity and associated mineral deposits (fig. F9). The igneous activity appears to have been localized by a series of shear zones that have been active since Precambrian time (Tweto and Sims, 1963).

Reported here will be the aspects that pertain to precious metal distributions in the district. It is not the intent of this report to discuss regional and local stratigraphy and structure; they have been reported elsewhere as will be indicated herein. Ore mineralogy will be reported only in the detail required to discuss gold-silver distributions, and stable isotope data will be presented in a preliminary fashion.

Previous Work

A classic monograph on the Leadville district was completed by Emmons (1886) in which detailed descriptions and mine geology were reported during the early development of the district. Subsequent works on district geology (Emmons and others, 1927; Behre, 1953; Tweto, 1960; 1968) described stratigraphic and structural details of local geology. District-wide zoning of the ore deposits (Loughlin and Behre, 1934) at Leadville and in adjoining districts of the Mosquito Range supported

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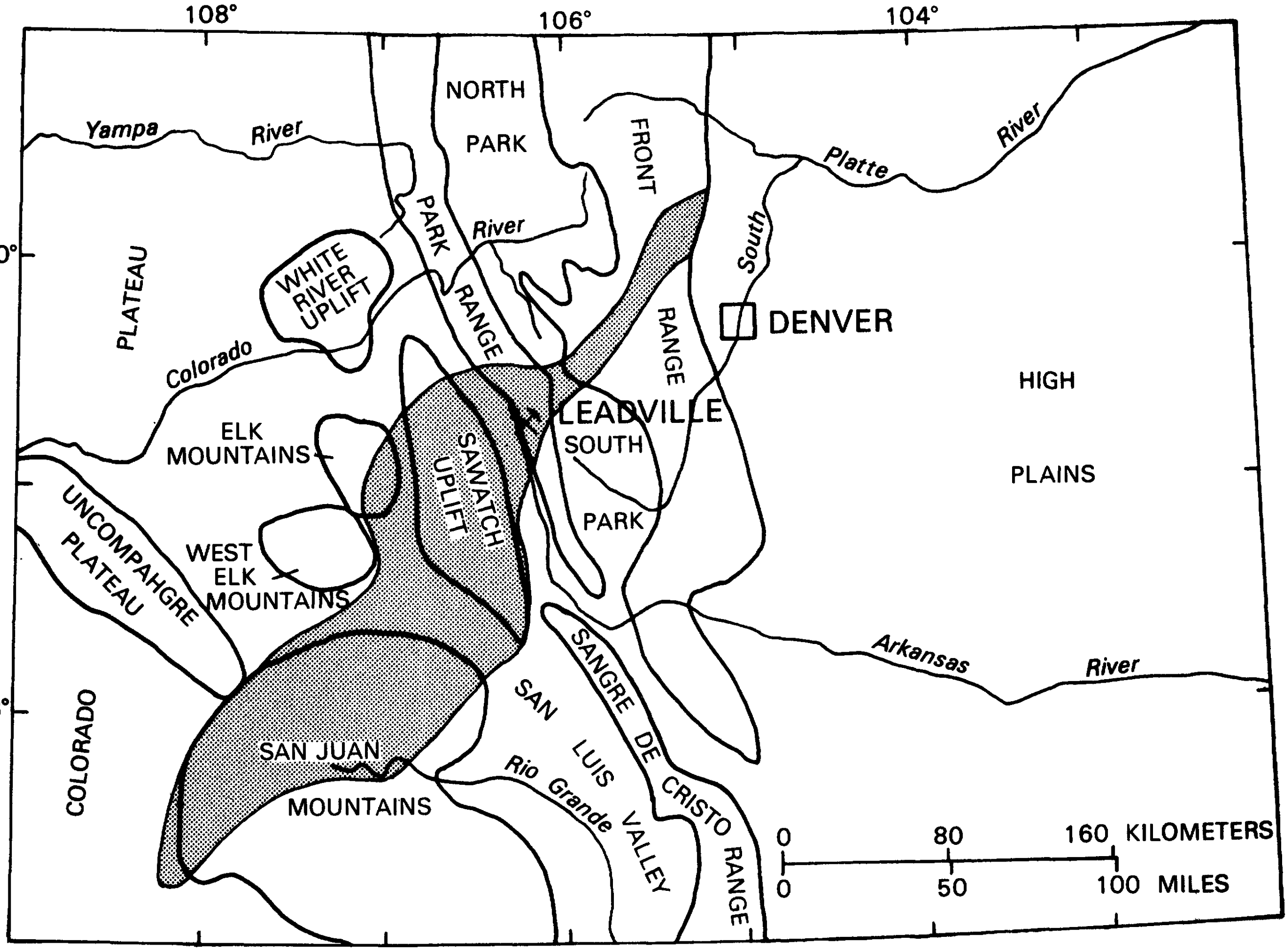


Figure F9. Index map of the Colorado mineral belt (patterned) showing location of the Leadville district. Principal mountain ranges outlined.

the belief that all deposits in the region formed contemporaneously. More recently, studies of regional stratigraphy (Banks, 1967; Nadeau, 1971) have focused on the depositional environment of the Leadville Dolomite and erosion of its upper surface with development of Late Mississippian karst features. Studies of the ore deposits of the Leadville district (Jonson, 1955; Linn, 1963; Arehart, 1978; Johansing, 1982; Osborne, 1982; Hazlitt, 1984) have described ore controls, mineralogy, hydrothermal alteration, fluid inclusions, and metal zoning of individual or collective groups of ore bodies. Although some authors have ascribed a Late Cretaceous age or a Paleozoic age to some or all of the mineral deposits in the Leadville district (Emmons and others, 1927; Ogden Tweto, oral commun. to A.V. Heyl, 1983; De Voto, 1983; Tschauder and Landis, 1985), none have been able to clearly document such timing for the ore emplacement. Fission-track dating of annealed zircon and apatite separates from pre-ore igneous rocks in the main Leadville district has indicated that the replacement ore developed 33.8±5 Ma (Thompson, 1986). Hydrothermal alteration and ore fluid parameters have been described by Thompson (1976) and Thompson and others (1983) for ores within the Black Cloud mine in the Leadville district. Recently completed stable-isotope analyses on ore minerals and wallrocks have been described (T.B. Thompson, unpublished data; T.B. Thompson and David Beaty, unpublished data); these research efforts were funded by Noranda Exploration, Inc. and the National Science Foundation (Contract No. EAR-8407308).

GEOLOGIC SETTING

The Leadville district is on the eastern flank of the Precambrian-cored Laramide (Tweto, 1975) Sawatch uplift (fig. F10). At Leadville the Paleozoic rocks dip to the east, 12°–30°, and are broken by early Laramide eastward-dipping reverse faults as well as by Tertiary extensional faults. The Paleozoic section is repeated up onto the Mosquito Range (fig. F11) due to northwest-and northeast-striking faults with relative displacements of west side down. These faults also exposed the carbonate-hosted replacement deposits to oxidation and subsequent erosion dispersal.

Only Paleozoic sedimentary rocks are preserved within the Leadville district. The section is relatively thin (<300 m) (fig. F12) and represents shallow-water marine deposition. Three dolomite units, the Ordovician Manitou Dolomite, Devonian and Mississippian Chaffee Group, and Mississippian Leadville Dolomite, have hosted the bulk of the sulfide replacement bodies; the Leadville Dolomite historically has been the principal host. Details of regional stratigraphy have been presented elsewhere (Tweto and Lovering, 1977; Banks, 1967; Nadeau, 1971; Thompson and others, 1983).

The Colorado mineral belt shear zones (Tweto and Sims, 1963) served to localize Laramide-Tertiary igneous activity, and in the Leadville district the regional northwest- and northeast-striking faults focused multiple episodes of igneous activity (fig. F11). Virtually all the igneous activity predated ore deposition; however, one igneous event and associated hydrothermal brecciation took place following ore deposition. The post-ore igneous and breccia bodies cut and dilute ore.

The earliest igneous activity, emplacement of Pando Porphyry sills and dikes within the district, occurred 69.9 Ma (Tweto, 1975). This event was followed by intrusion of the Lincoln Porphyry at 65.6 Ma (modified from Tweto, 1975), the Sacramento Porphyry (43.9 Ma fission-track date on apatite and zircon, this report), the Evans Gulch Porphyry (undated; cut by the Johnson Gulch Porphyry), and the Johnson Gulch Porphyry (43.1±4.3 Ma fission-track date on apatite and zircon, this report). The Lincoln Porphyry forms sills in the northeastern part of the district, whereas the Sacramento Porphyry forms a thick (≈200 m) sill east of the main district and near the crest of the Mosquito Range. The Evans Gulch Porphyry forms sills, dikes, and a small stock (referred to informally within the district as the Sunday stock). The Johnson Gulch Porphyry forms a large stock beneath Breece Hill and laccolithic extrusions northwest and southeast from the stock. Dikes of Johnson Gulch Porphyry extend south and southwest from the Breece Hill stock. Thin (<50 m) sills of Johnson Gulch Porphyry are present along the western margin of the district where they separate the Chaffee Group from the Leadville Dolomite. A small stock of Johnson Gulch Porphyry is present in Iowa Gulch to the south of the Breece Hill stock.

Post-mineral igneous activity is represented by several small pipelike bodies of biotite-bearing rhyolite porphyry. K-Ar dating of sanidine from the rhyolite yielded an age of 38.5±0.6 Ma (Cunningham and others,

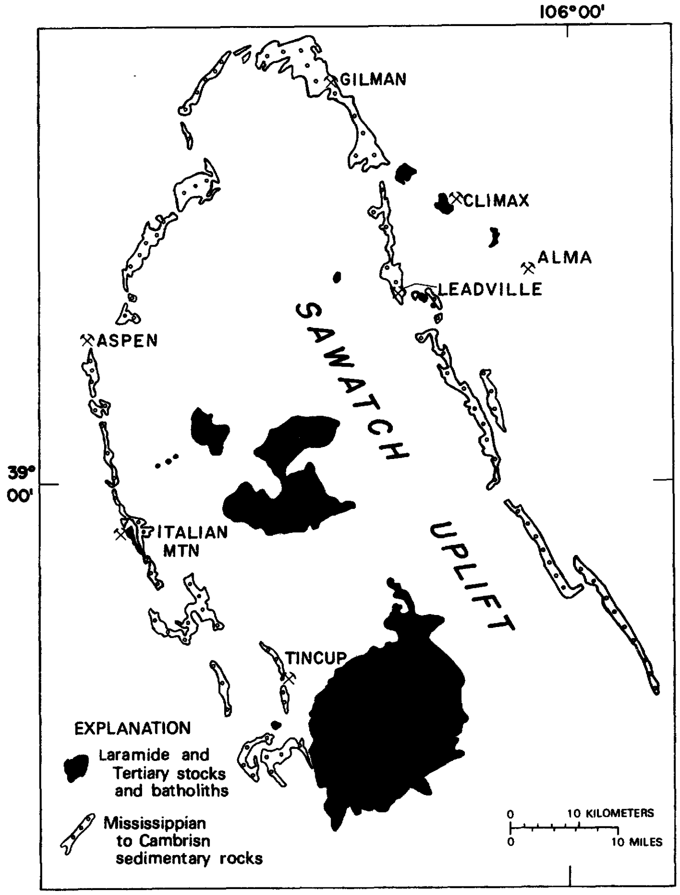


Figure F10. Map of the Sawatch uplift showing locations of districts characterized by manto deposits.

1977), but the rhyolite at the sample locality has been subjected to hydrothermal brecciation subsequent to crystallization, and argon retention is questionable.

MINERAL DEPOSITS

Mineral deposits at Leadville are of seven types:

1. Placers in California Gulch;
2. Contact metamorphic magnetite-calc-silicate carbonate bodies adjacent to two stocks (Thompson, 1976; Thompson and Arehart, 1978);
3. Vein quartz-pyrite-precious metal-(tungsten) deposits within and adjacent to the Breece Hill stock;
4. Veinlet and disseminated quartz-pyrite-gold in porphyry (Meaves and Darnell, 1970);
5. Base metal veins;
6. Base- and precious-metal dolomite-hosted replacement bodies (referred to here as of "Leadville type mineralization" (LTM)); and
7. Silver-barite-minor base-metal, dolomite-hosted replacement bodies (referred to here as of "Sherman type mineralization" (STM)).

All but the fourth type have contributed to district production. In this report the emphasis will be on those with precious metal contents, that is, types 3, 6, and 7. Little scientific work has been directed to the district placers, and only traces of unmined placer material remain within California Gulch.

Vein Quartz-Pyrite-Precious Metal-(Tungsten)—Type 3

More than 100 quartz-pyrite-precious metal veins occur within or adjacent to the Breece Hill stock. Most strike between N. 12° W. and N. 27° E. and dip more than 70°. The average grade produced from these veins was approximately 0.5 oz Au/ton and 30–40 oz Ag/ton (Emmons and others, 1927). Replacement of wallrock rather than open-space filling characterizes the veins (Emmons and others, 1927; Osborne, 1982). Additionally, two "stockwork" zones developed along the Weston fault where it intersects the Breece Hill stock. Subsidiary northeast-striking faults cut the stockwork zones, and breccia bodies developed at their mutual intersections. Pyritic-gold ores were precipitated in breccia voids and matrix. Two of these breccia bodies contain scheelite and wolframite in subeconomic concentrations.

Several major fault zones that locally contain vein minerals occur outside of the Breece Hill center. Among these are more than 15 major veins in the Ibex workings (fig. F13), the Winnie-Luema vein, the Fortune vein, and the Sunday vein. These have contributed significantly to the precious metal production of the district.

The Garbutt vein (fig. F13) is the easternmost vein in the Ibex group and is one of the most continuous of that group. Production from the vein between 1914 and 1922 from siliceous sulfide ores totalled 7,806 tons with weighted averages of 0.47 oz Au/ton and 7.29 oz Ag/ton (Emmons and others, 1927). The vein follows a slightly arcuate course from its southern end northward, forming a crescentic concave-westward trace for nearly 630 m. It dips westerly at 70° in the upper 330 m, is vertical for 50 m, and flattens to a nearly horizontal attitude before steepening to the east at 60°–65° for 30 m to the bottom of the mine (Emmons and others, 1927). The vein cuts Pennsylvanian sandstones and shales and Tertiary porphyry sills. The pyritic vein pinches considerably where shales form the wallrocks.

The Winnie-Luema and Fortune veins are northeast of the Breece Hill center (fig. F13). Both have strike lengths in excess of 1,000 m, and both have had post-mineral movement. The Fortune vein system produced nearly 10 short tons of ore between 1938 and 1955, averaging 15 percent Pb + Zn, 0.2 oz Au/ton, and 4 oz Ag/ton (Jonson, 1982). The vein strikes north over a distance of 1,300 m and dips 75° west. Numerous northeast-striking veins abut the footwall of the Fortune, and these have acted as feeders for replacement ore where carbonate rocks form the wallrocks. Vein ore along the Fortune fault extends over a strike length of 350 m and has a vertical dimension of 100 m; the ore body rakes 15° north (Jonson, 1982). The maximum ore-body width was 30 m where the wallrocks are thin-bedded Peerless Formation shales and quartzite. The presence of arsenopyrite in the northernmost branch fault off the Fortune fault, and southward-decreasing Zn:Pb ratios, led Walker (in Jonson, 1982) to suggest that ore fluids moved from north to south on the Fortune fault. All other data from other vein systems (metal concentrations and fluid-inclusion analyses), however, indicate fluid flow radially outward from the Breece Hill center.

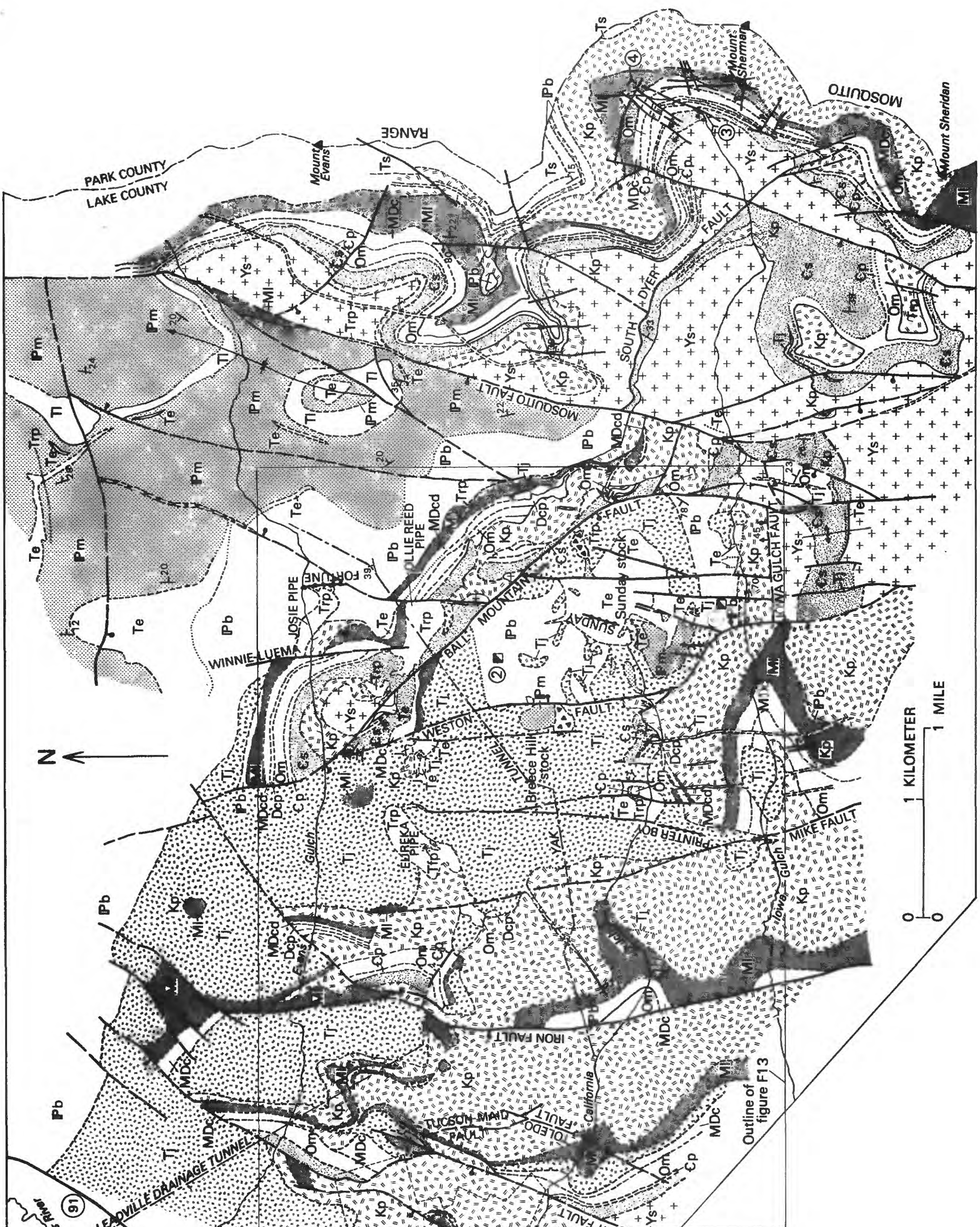
The Sunday vein (figs. F13 and F14) is east of the Breece Hill center and located within the Sunday stock (fig. F11), composed of Evans Gulch Porphyry. It was previously accessible by means of two shafts, now caved, and an adit, the Garibaldi. The adit is caved at its portal. Production is recorded to 1920 with gold grades near 0.1 oz Au/ton and 6.0 oz Ag/ton (Emmons and others, 1927; Behre, 1953). Secondary enrichment has been recognized down to the tunnel level, but, to date, no production below that level has occurred. Exploration in the active Black Cloud mine is focusing on the down-dip potential of the Sunday vein and associated replacement ore.

Wallrock alteration adjacent to the veins in the district consists of an inner zone of silicification containing pyrite, which gives way outward to sericitic, argillic, and propylitic assemblages in the Breece Hill stock. Most alteration halos are restricted to less than 10 m from the vein. The breccia zones within the Breece Hill center along the Weston fault (or its subsidiary structures) contain intensely sericitized rock fragments. On the northern ends of the Winnie-Luema and Fortune veins, silicified wallrock becomes the most distinctive alteration type (Jonson, 1982).

Fluid inclusions in quartz from the veins have been analyzed by heating and freezing methods. The filling temperatures from quartz range from 379 °C down to 330 °C; salinities are less than 5 equiv. wt. percent NaCl (Osborne, 1982) (fig. F15).

Leadville Type Mineralization (LTM)—Type 6

Leadville type mineralization (LTM) consisted of massive sulfide replacement of dolomite beds. Contemporaneous and later-stage veins associated with the replacement ore bodies indicate that the ore fluids were introduced along faults. The replacement ore bodies are dominated by pyrite with lesser marmatite, galena,



PARK COUNTY
LAKE COUNTY
MOSQUITO RANGE
Mount Evans
Mount Sherman
Mount Sheridan
MOSQUITO FAULT
SOUTH DYER FAULT
BALL MOUNTAIN FAULT
WESTON FAULT
IOWA GULCH FAULT
SUNDAY
Sunday stock
Breece Hill stock
OLLIE REED PIPE
JOSIE PIPE
FORTUNE
WINNIE-LUEMA
EUREKA PIPE
YAK TUNNEL
PRINTER BOY
MIKE FAULT
Iowa Gulch
IRON FAULT
TUCSON MAID FAULT
TOLEDO FAULT
California Gulch
PENDERY FAULT
VALENTINE FAULT
LEADVILLE DRAINAGE TUNNEL
East Fork Arkansas River
LEADVILLE
24
91
Outline of figure F13
N
0 1 KILOMETER
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EXPLANATION

IGNEOUS ROCKS

- Tfp — Tertiary fragmental porphyry
- Trp — Tertiary rhyolite porphyry
- Tj — Tertiary Johnson Gulch Porphyry
- Ts | Te — Ts Tertiary Sacramento Porphyry; Te Tertiary Evans Gulch Porphyry
- Tl — Paleocene Lincoln Porphyry
- Kp — Upper Cretaceous Pando Porphyry
- Ys — Middle Proterozoic St. Kevin Granite

SEDIMENTARY ROCKS

- IPm — Pennsylvanian Minturn Formation
- IPb — Pennsylvanian Belden Formation
- Ml — Mississippian Leadville Dolomite
- MDc — Mississippian and Devonian Chaffee Group
  - MDcd — Mississippian? and Devonian Dyer Dolomite
  - Dcp — Devonian Parting Formation
- Om — Ordovician Manitou Dolomite
- Ꞓp — Cambrian Peerless Formation
- Ꞓs — Cambrian Sawatch Quartzite

- Contact—Dashed where approximately located, dotted where concealed
- Fault—Bar and ball on downthrown side; arrow shows dip; dashed where projected (45)
- Strike and dip of bedding (20)
- Anticline—Arrow shows plunge
- Syncline—Arrow shows plunge
- Breccia
- Vein quartz
- Water drainage tunnel
- Adit
- Shaft
- j — Jasperoid

MINE INDEX

1. Black Cloud
2. Irene
3. Sherman
4. Continental Chief

Figure F11. Geologic map of the Leadville district, Lake County, Colo. Geology east of Iron fault by Tommy B. Thompson, 1974–1980; geology west of Iron fault by Emmons and others (1927).

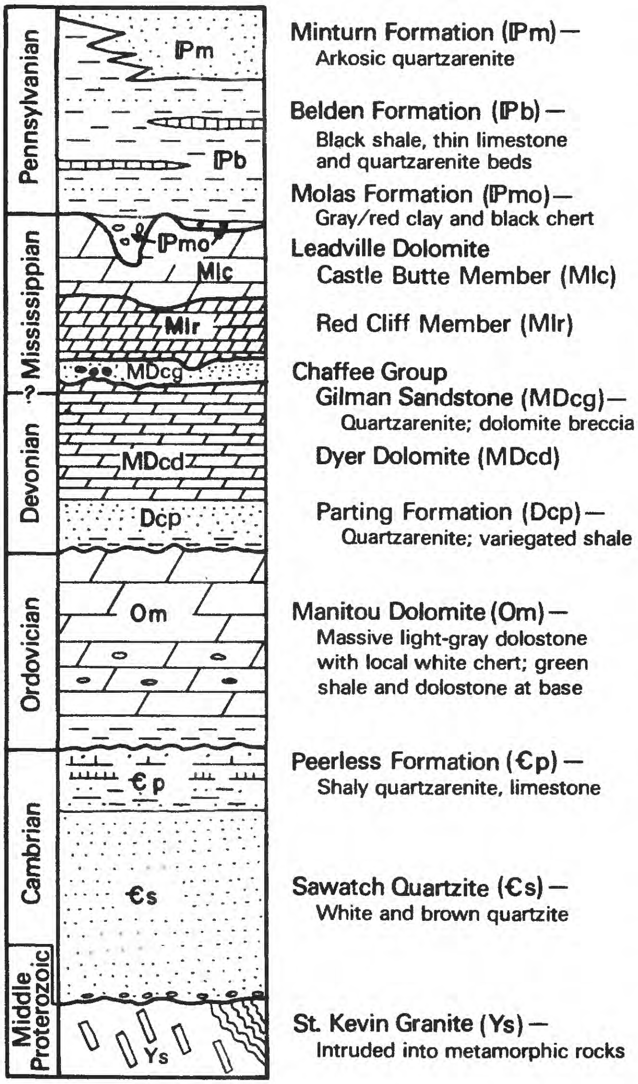


Figure F12. Leadville stratigraphic section. Wavy line, unconformity.

chalcopyrite, tetrahedrite, pyrrhotite, marcasite, electrum, barite, dolomite, and fluorite (Thompson and others, 1983). The ore bodies commonly exhibit layering of intergrown sulfide-gangue minerals parallel to dolomite bedding or to faults. In some localities the layering is concentric with unreplaced dolomite cores. Layering of friable sulfide minerals is seen in some ore bodies, particularly adjacent to post-mineral breccias (referred to informally as "fragmental porphyry" in the mine nomenclature; Hazlitt, 1984). This layering commonly exhibits contortions, locally with small wallrock clasts, suggesting that this form of layering developed where intense late-stage fluidization along ore fluid conduits occurred. Some LTM bodies formed by replacement of magnetite skarn bodies adjacent to the Breece Hill or Sunday stocks (Thompson, 1976; Thompson and Arehart, 1978). In such ore bodies, relict magnetite is commonly found. The LTM ore bodies have strike lengths from less than 100 m to more than 1,200 m with widths up to 200 m. Thicknesses range from a few meters to 60 m.

The only accessible LTM ore bodies within the Leadville district are in the Black Cloud mine in a down-dropped block between the Ball Mountain and Weston faults (fig. F14). Ten replacement ore bodies have yielded metals, and exploration continues within the down-dropped block. The ore bodies are numbered in the order of their discovery except for the *504* ore bodies, which are localized along the 504 vein. Replacement ore in the mine is found within the Manitou, Dyer, and Leadville Dolomites. As discussed in following pages, metal zoning within the down-dropped block and in individual ore bodies has been recognized.

A composite paragenetic diagram for LTM minerals within the Black Cloud mine ore bodies appears as figure F16. A skarn stage is shown, but not all sulfide bodies formed by replacement of a skarn mass. In general, iron sulfides, quartz, and siderite were the earliest LTM minerals, followed by base metal sulfides and precious metals. Late veins and vug fillings repeat the paragenetic sequence with the addition of dolomite, barite, and fluorite. Barite and fluorite are relatively rare in LTM ore bodies. Silver occurs principally in tetrahedrite and electrum, whereas gold occurs only in electrum. In polished sections tetrahedrite is seen commonly in galena and less so in sphalerite. The tetrahedrite appears to have replaced both minerals. Electrum normally is seen replacing marmatitic sphalerite.

Precious metals in the LTM bodies occur in at least two different positions: (1) gold (electrum: Au:Ag = 1:1) occurs in pyritic margins of some bodies (Thompson, 1976; Arehart, 1978; Thompson, 1986); (2) gold (electrum) and silver (in tetrahedrite) occur adjacent to ore fluid conduits (fissure veins) with significant decreases at short distances from the conduits (Thompson, 1986). These two types of occurrences are illustrated in figures F17 and F18. In figure F18, a longitudinal section nearly parallel to and transecting the strike of the 504 vein, and within sulfide-mineralized ground, shows higher silver ratios relative to zinc and lead where the 504 vein crosses the plane of the longitudinal section. The data points also reflect the stratigraphic control on replacement ore: no values occur in the Parting Formation sandwiched between the Leadville and Dyer Dolomites.

Correlation matrices of assay data show strong correlation of silver with gold, with copper, and to a lesser extent with lead, depending on the datum along which assay values are selected (table F2). Within zoned bodies gold may be associated only with pyritic ore-body margins or it may be found within a base metal-rich central zone cut by gold-bearing veinlets. Silver correlates (table F2) with copper and lead but normally does

Table F2. Correlation matrices of assay data from the Number *3* ore body, Black Cloud mine, Leadville district, Colorado

[Numbers indicate the range of possible values for the correlation coefficient at a 45 percent confidence interval. Significant correlations are those having either two positive or two negative values]

	Au	Ag	Pb	Zn	Cu
Correlation matrix for 63 ore samples from locality 1					
Ag	–.17, +.33				
Pb	+.10, +.55	+.15, +.57			
Zn	+.35, +.70	–.30, +.20	+.16, +.58		
Cu	–.43, –.05	+.55, +.81	–.30, +.20	+.11, +.50	
Fe	–.27, –.65	+.14, +.57	–.35, +.15	–.74, –.42	+.29, +.67
Correlation matrix for 75 ore samples from locality 2					
Ag	+.17, +.58				
Pb	+.06, +.48	–.05, +.41			
Zn	+.19, +.58	–.23, +.24	+.29, +.65		
Cu	–.07, +.39	+.50, +.77	–.40, +.06	–.47, –.03	
Fe	–.22, +.26	–.12, +.35	.45, –.02	–.42, +.03	+.23, +.61
Correlation matrix for 52 ore samples from locality 3					
Ag	+.20, +.64				
Pb	+.01, +.52	–.20 +.35			
Zn	–.08, +.44	–.28, +.27	+.58, +.84		
Cu	+.08, +.57	+.53, +.82	+.07, +.58	+.10, +.58	
Fe	–.27, +.28	–.13, +.42	–.77, –.43	–.58, –.84	–.53, –.03

not correlate with zinc. The correlation with copper reflects the presence of significant argentian tetrahedrite, generally within the central base metal-rich zone.

Reconstructing district-wide primary metal zoning at Leadville is difficult, due to the strong oxidation effects that have redistributed metals along the western edge of the district and along near-surface parts of ore bodies. Within the Black Cloud mine (fig. F14) where no oxidation of ore bodies has occurred, it is possible to illustrate zoning from the center of the district outward to the southeast. Zinc:lead ratios decrease to the southeast; Ag:Zn + Pb decreases to the southeast except along the *504S* and *N* ore bodies on the 504 fault. Ag:Au ratios increase to the southeast (fig. F13) from the Number *3* to Number *4* ore bodies; however, the Numbers *5*, *6*, and *7* ore bodies exhibit sharply lower ratios. Whereas silver concentrations are very similar in the three ore bodies, gold values are significantly different; and the ratio shift apparently reflects variation related to local channels of fluid flow. This variation may have resulted from proximity to the source of ore fluid and metals as indicated by abundant fragmental porphyry adjacent to and cutting all three ore bodies. In other words, ore bodies *5*, *6*, and *7* show ratios similar to those of ore bodies *3* and *8* near the eastern edge of the Breece Hill Center (fig. F13). The silver concentration within unoxidized LTM bodies ranges between 2 and 6 oz Ag/ton, while that of gold is generally less than 0.1 oz Au/ton.

In summary, gold on a district-wide basis is more concentrated near the Breece Hill stock or along major faults whereas silver increases with distance from the Breece Hill stock (fig. F13). Due to the easterly dips of the Paleozoic strata and east-dipping Laramide thrust faults, ore fluids appear to have migrated farther to the west than east from the Breece Hill stock, causing the district to have asymmetrical metals distribution and zoning about the Breece Hill area. Post-mineral faulting has further distorted the district metal zoning.

There appears to have been both lateral and vertical metal zoning between various fault-bounded zones within the Leadville district (fig. F19). For example, the smaller ore bodies of the Julia Fisk and First National mines just west of the Black Cloud mine (fig. F13) occur outside of the down-dropped block. They contain lower base metal values, but the silver grades are significantly higher (> 6.0 oz Ag/ton). Additionally, rhodochrosite is present, whereas manganosiderite or siderite is present within the deeper level ore bodies. Gold and bismuth were produced at the Lillian mine to the west of these two mines as byproducts of the sulfide ore production (Emmons and others, 1927; Behre, 1953). Increasing distance from the Breece Hill center and

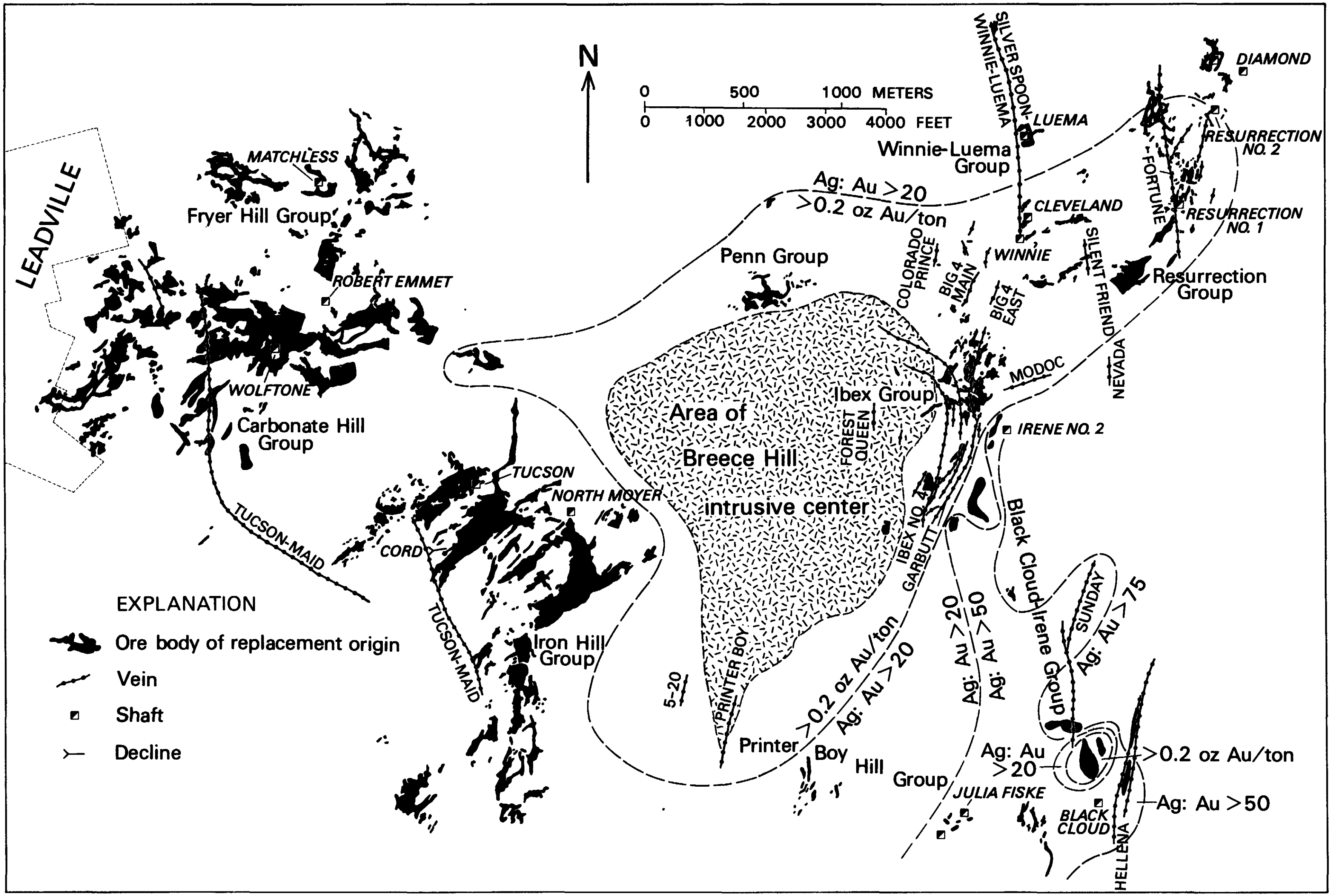


Figure F13. Map of the Leadville district showing the Breece Hill intrusive center, distribution of ore bodies, and district-wide gold and silver zonation. Long-dashed lines separate areas of the indicated gold content and Ag:Au ratios of ores.

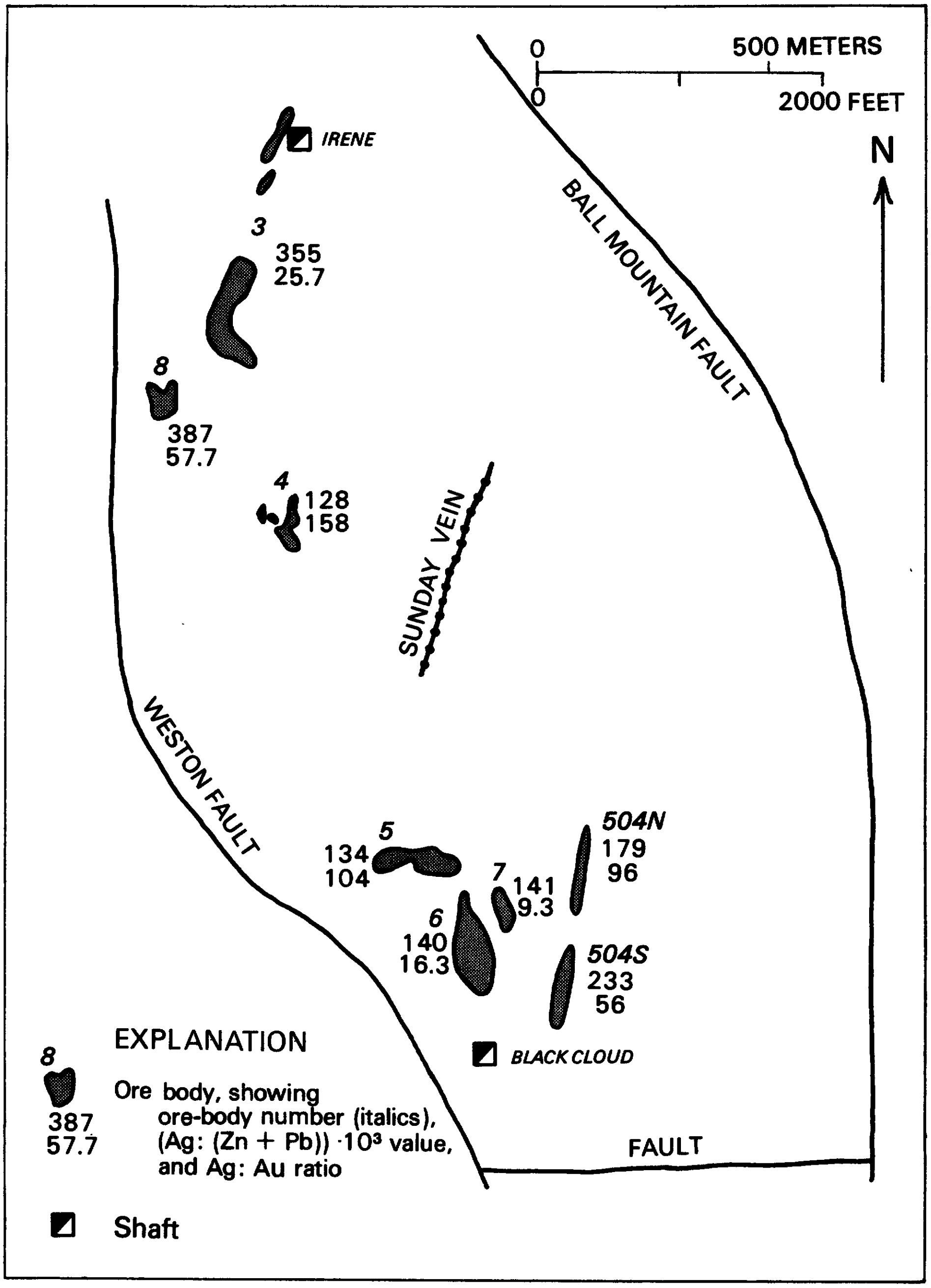


Figure F14. Map showing distribution of ore bodies and the Sunday vein in the down-dropped block, Black Cloud–Irene area.

shallower position of the favorable stratigraphic horizons during the mineralizing events appear to have favored higher silver concentrations. Oxidized ore bodies beneath Carbonate and Fryer Hills yielded silver concentrations of several hundred to several thousand ounces per ton, but the few data on sulfide body grades show that silver concentrations at East Fryer Hill ranged between 7.3 and 22.7 oz Ag/ton (Emmons and others, 1927).

The eastward-dipping Tucson-Maid fault (figs. F11, F19, F20) localized ore fluids from the Breece Hill center, with significantly higher precious-metal and copper values. Within the Tucson mine (fig. F20) unoxidized ores were found below the fourth shaft level (Emmons and others, 1927). Sulfide replacement bodies (LTM) in the Manitou Dolomite contained no appreciable gold but 8.0 oz Ag/ton, no copper, 11.65 percent Pb, and 26.2 percent Zn. These ore bodies were encased in a manganosiderite zone, replacing dolomite. Closer to the Tucson-Maid fault on the sixth and seventh levels (fig. F20), metal content ranged between 0.045 and 0.52 oz Au/ton; from 17.15 to 148.0 oz Ag/ton; 2.8 to

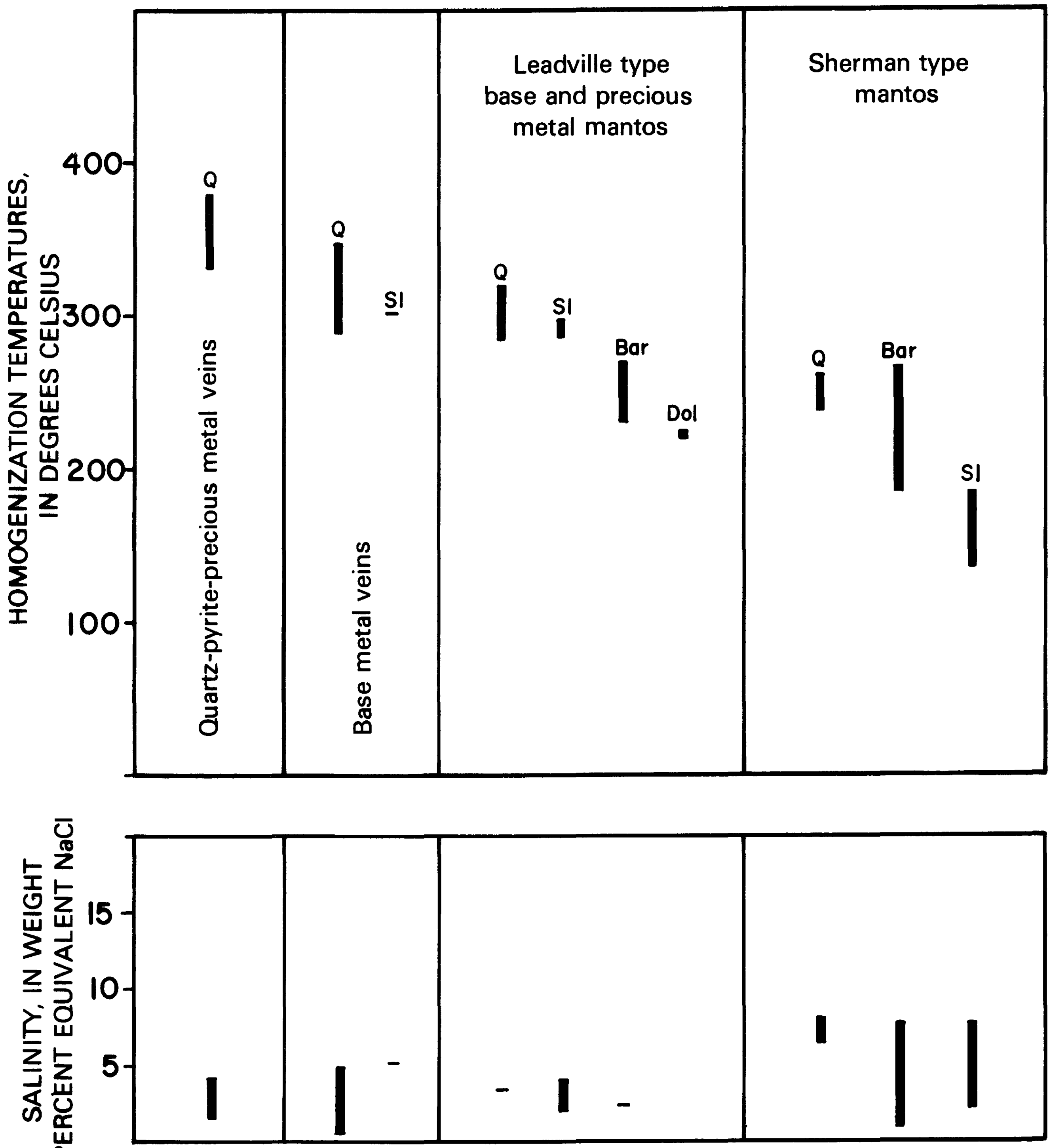


Figure F15. Fluid-inclusion data for the Leadville district. Q, quartz; Sl, sphalerite; Bar, barite; Dol, dolomite.

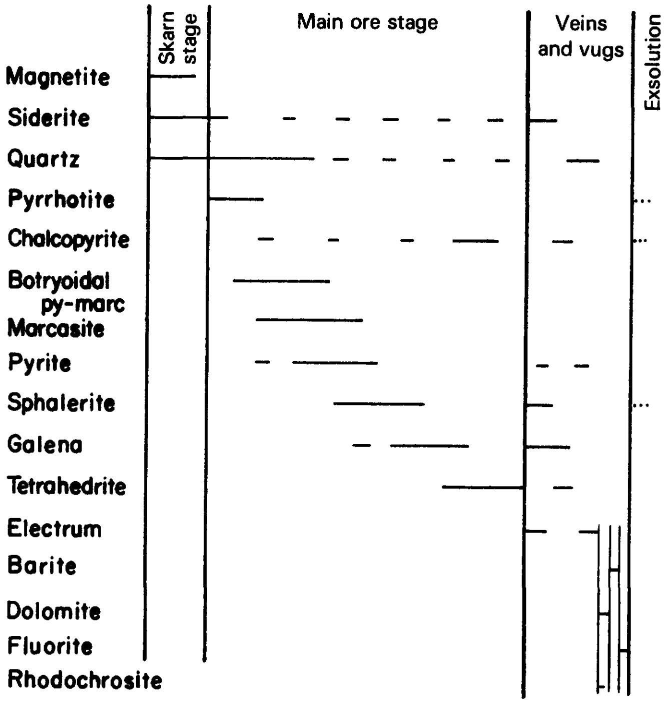
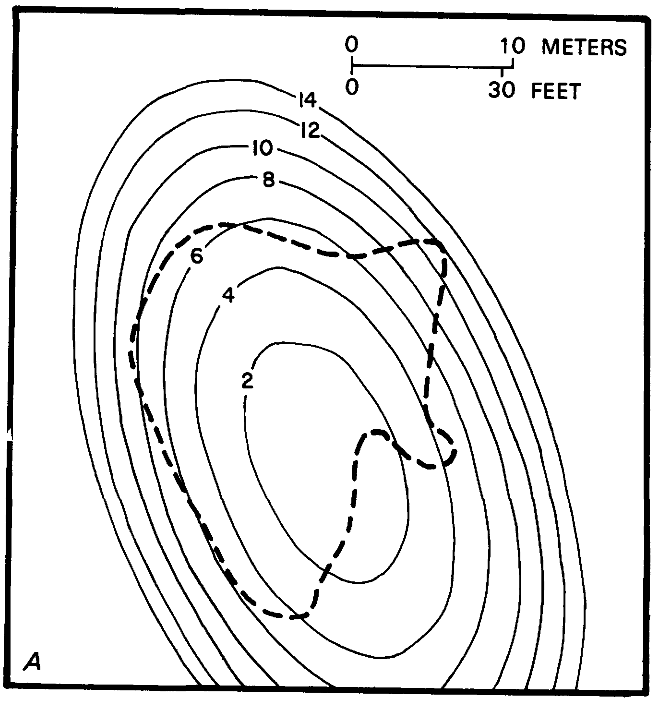


Figure F16. Paragenetic diagram of ore-related minerals in the Leadville district; py-marc, pyrite-marcasite.

9.95 percent Cu; 12.3 to 13.2 percent Pb; and from 4.5 to 34.3 percent Zn. On the ninth level where the fault cut brecciated Sawatch Quartzite, sorted ore yielded assays of 14.45–15.27 oz Au/ton; 3,987.0–4,109.0 oz Ag/ton; and 42.5–44.7 percent Pb (Emmons and others, 1927).



Hydrothermal alteration related to LTM ore bodies was influenced by the wallrock composition. Dolomitic wallrocks exhibit very limited alteration effects adjacent to ore bodies near the Breece Hill center, principally slight recrystallization along dissolution tubes that extend away from the massive sulfide body. These have been referred to as "birdseye" texture due to the white (bleached) dolomite and quartz contrasted against the normal dark gray of the dolomite. In many exposures of the "birdseye" texture, the centers of tubes contain small euhedral pyrite, galena, and (or) sphalerite crystals. The "birdseye" tubes are 1 to 3 cm in diameter and may extend as much as 15 m from a sulfide ore body. Local dolomite "sanding" adjacent to the massive sulfide bodies suggests that the ore fluids were slightly acidic beyond the zone of dolomite replacement by sulfides. Wallrock silica (reported as "flint" in Emmons and others (1927), but in reality jasperoid) occurs adjacent to the distal LTM ore bodies beneath Carbonate and Fryer Hills (figs. F13 and F19) as well as adjacent to some LTM bodies north of the Breece Hill center. As mentioned, dolomite beds adjacent to the Tucson-Maid fault have been replaced by manganosiderite (figs. F19 and F20), which oxidizes on mine dumps and near surface (to 120-m depths) to manganese oxides.

Igneous wallrocks exhibit much more extensive wallrock alteration effects and trace-metal dispersion than dolomitic wallrocks (Thompson, 1976). The alteration halo may extend as much as 100 m from the ore body. Generally, an intense sericitic (phyllic) replacement of all igneous minerals is exhibited immediately adjacent to the ore body. Peripheral argillic and propylitic assemblages continue beyond the phyllic zone. Siderite/manganosiderite is a common assemblage mineral in the two outermost alteration zones.

Due to the intense hydrothermal alteration exhibited in the igneous wallrocks, accessory minerals present appear to have been thermally annealed, and thus are

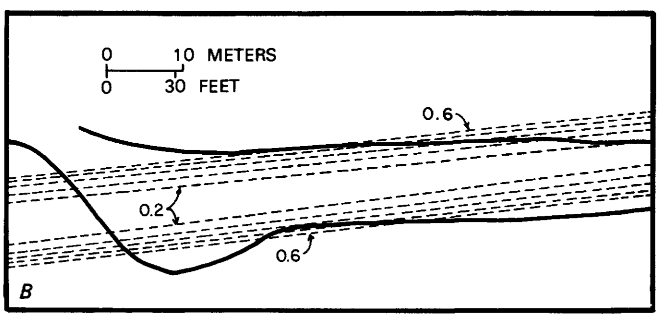


Figure F17. Trend surfaces for precious metal distributions in the Number *3* ore body. *A*, Au:Fe second order trend surface on cross section through the ore body (outlined by dashed line). *B*, Ag:Zn second order trend surface on longitudinal section through the ore body (outlined by solid lines).

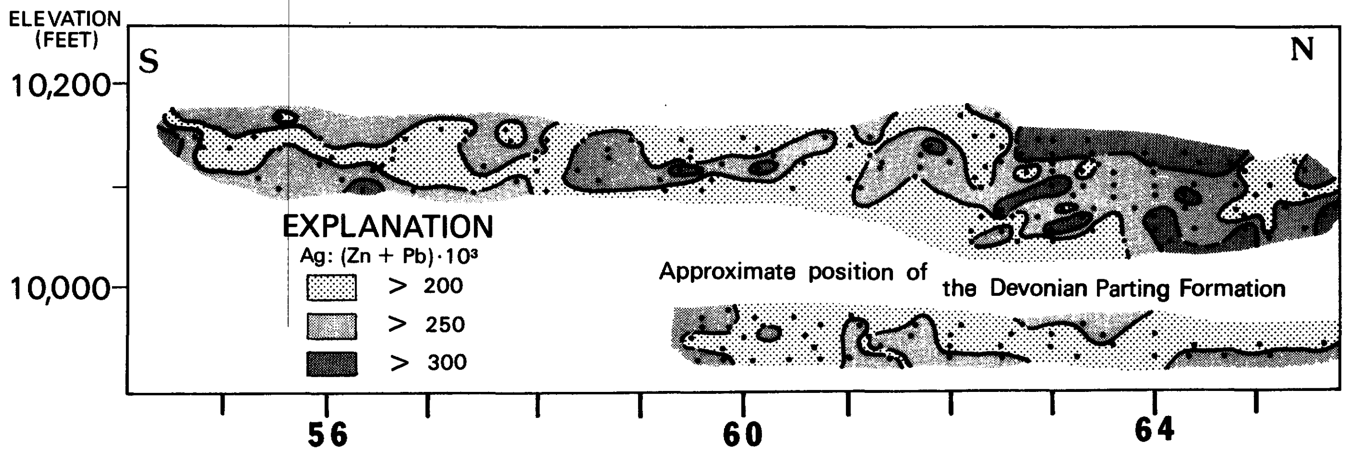


Figure F18. Ag:(Zn+Pb).10^3 ratio map on longitudinal section through the *504S* ore body. X-axis shows distances, in hundreds of feet, from an arbitrary point.

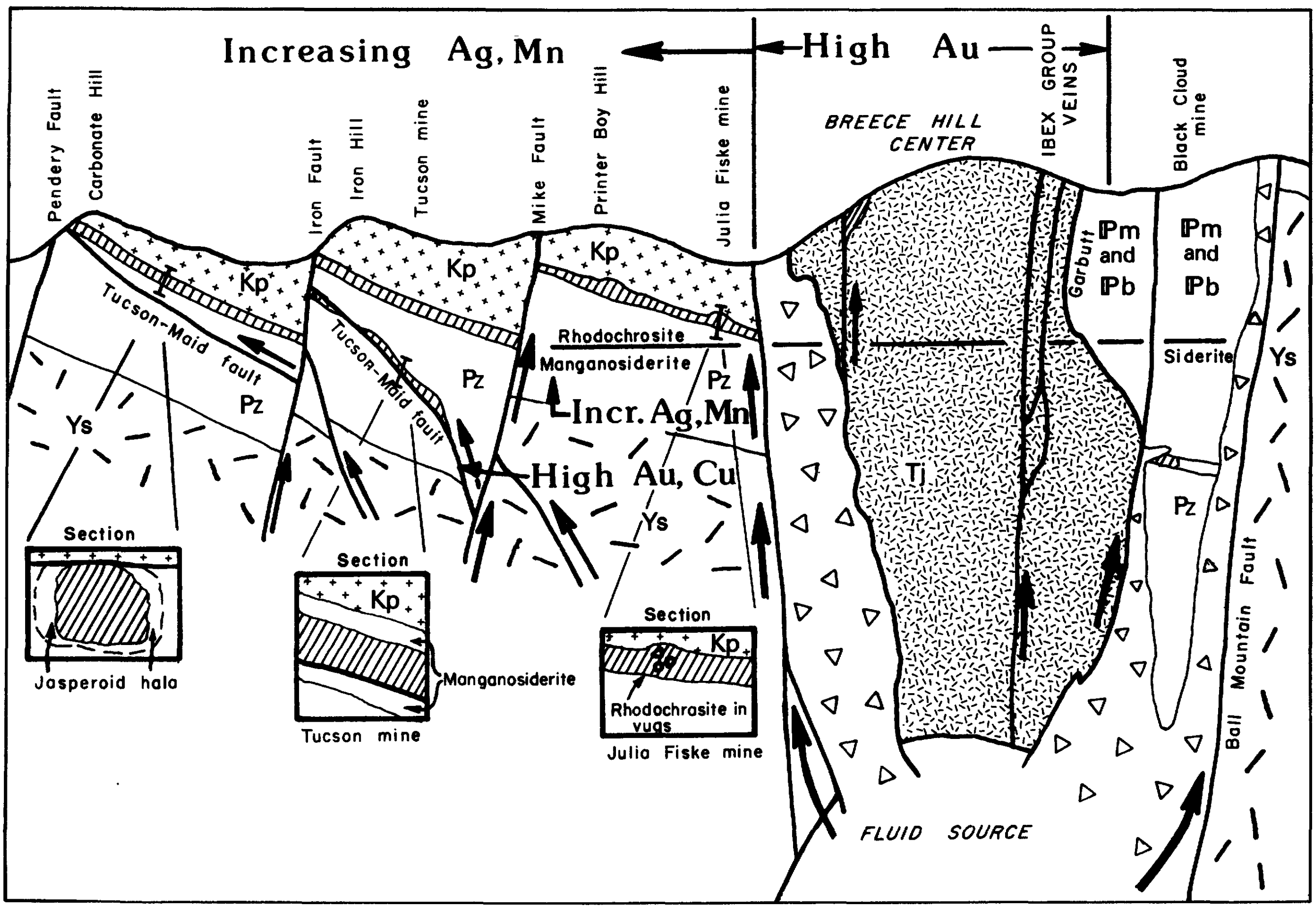


Figure F19. Diagrammatic district-wide cross section showing ore-body types. Ore zones shown by cross lining; Ys, Middle Proterozoic St. Kevin Granite; Pz, Mississippian and older Paleozoic formations; IPm and IPb, Pennsylvanian Minturn and Belden Formations; Kp, Cretaceous Pando Porphyry sills; Tj, Tertiary Breece Hill porphyry stock (Johnson Gulch Porphyry); triangular symbols show zone of brecciation.

suitable for fission-track dating. Samples from adjacent to the Number *4* and *504S* (fig. F14) ore bodies were utilized for such dating. In some places near the ore bodies, apatite was completely destroyed, leaving only zircon for dating. The combination of zircon only and apatite + zircon yielded an age of 33.8±.5.0 Ma (Thompson, 1986) for ore emplacement.

Fluid-inclusion studies of the Black Cloud LTM ore bodies have focused on quartz, sphalerite, barite, and dolomite. Most of the sphalerite is marmatitic and thus opaque. Filling temperatures from early quartz range between 245 and 355 °C (fig. F18). Sphalerite-hosted fluid inclusions yield filling temperatures between 240 and 300 °C. Quartz contemporaneous with base metal sulfides yields filling temperatures between 210 and 290 °C. Late dolomite in vugs yields filling temperatures of 220 to 255 °C; barite in vugs yields filling temperatures of 230 to 270 °C. Pressure correction for the filling temperatures has been determined by sphalerite geobarometry. The estimated pressure at the time of orebody formation approximates 1.2 Kb. This pressure requires a correction of +90 °C to the filling temperatures. Thus, the ore formation temperatures are estimated to have ranged from 445 °C during early stages of development down to 300 °C in the waning stages.

Studies of sphalerite and rhodochrosite from the Julia Fisk (fig. F13) ore bodies yielded slightly lower filling temperatures than those from the Black Cloud ore bodies. The average filling temperature for sphalerite is 224 °C whereas that for rhodochrosite is 221 °C. These temperatures overlap the lower end of filling temperatures for minerals of the same paragenetic stages in the Black Cloud, supporting the interpretation that Julia Fisk ores formed at slightly shallower levels than those of the Black Cloud mine. Pressure based on stratigraphic reconstructions and elevation differences compared to the Black Cloud ore bodies approximates 850 bars. Thus, the temperature correction for fluid-inclusion filling temperatures is +85 °C; the Julia Fisk ore bodies are estimated to have formed at temperatures of 300 to 310 °C during main-stage sulfide deposition.

Sulfur isotope analyses of pyrite, sphalerite, and galena have been completed from ore bodies within the Black Cloud mine (fig. F21). The samples of all three minerals were generally from single hand specimens, and they exhibit, for the most part, equilibrium conditions at the time of ore formation. The pyrite $\delta^{34}S$ ranges between +1.2 and +3.2 per mil; sphalerite exhibits a range from –0.5 to +2.2 per mil; galena ranges between –2.4 and +0.7 per mil. Calculated temperatures from pyrite-sphalerite and sphalerite-galena pairs yield values of 420±21 °C and 450±23 °C, respectively. Ore fluid $\delta^{34}S_{H_2S}$ is estimated to have been +1.9 per mil.

Sherman Type Mineralization (STM)—Type 7

Sherman type mineralization (STM) was first described by Behre (1953) and later by Johansing (1982). The essential characteristics are early coarsely crystalline barite, brown to olive-green sphalerite with galena in open spaces within dolomite, and elevated silver content compared to LTM ores. The ore bodies are typically small (that is, <50,000 tons (Johansing, 1982)) and contain less than 25 percent sulfides. Unlike LTM bodies, the STM ores are hosted entirely within the Leadville Dolomite, either as replacements along faults or bedding planes or as open-space fillings within sediment-filled karst features. Zinc + lead concentrations are generally less than 5 wt. percent combined.

Johansing (1982) recognized five stages of mineralization (fig. F22): (1) quartz-pyrite, (2) white barite-dolomite, (3) sphalerite-argentian tetrahedrite-chalcopyrite, (4) galena-acanthite, and (5) quartz-dolomite-golden barite-calcite.

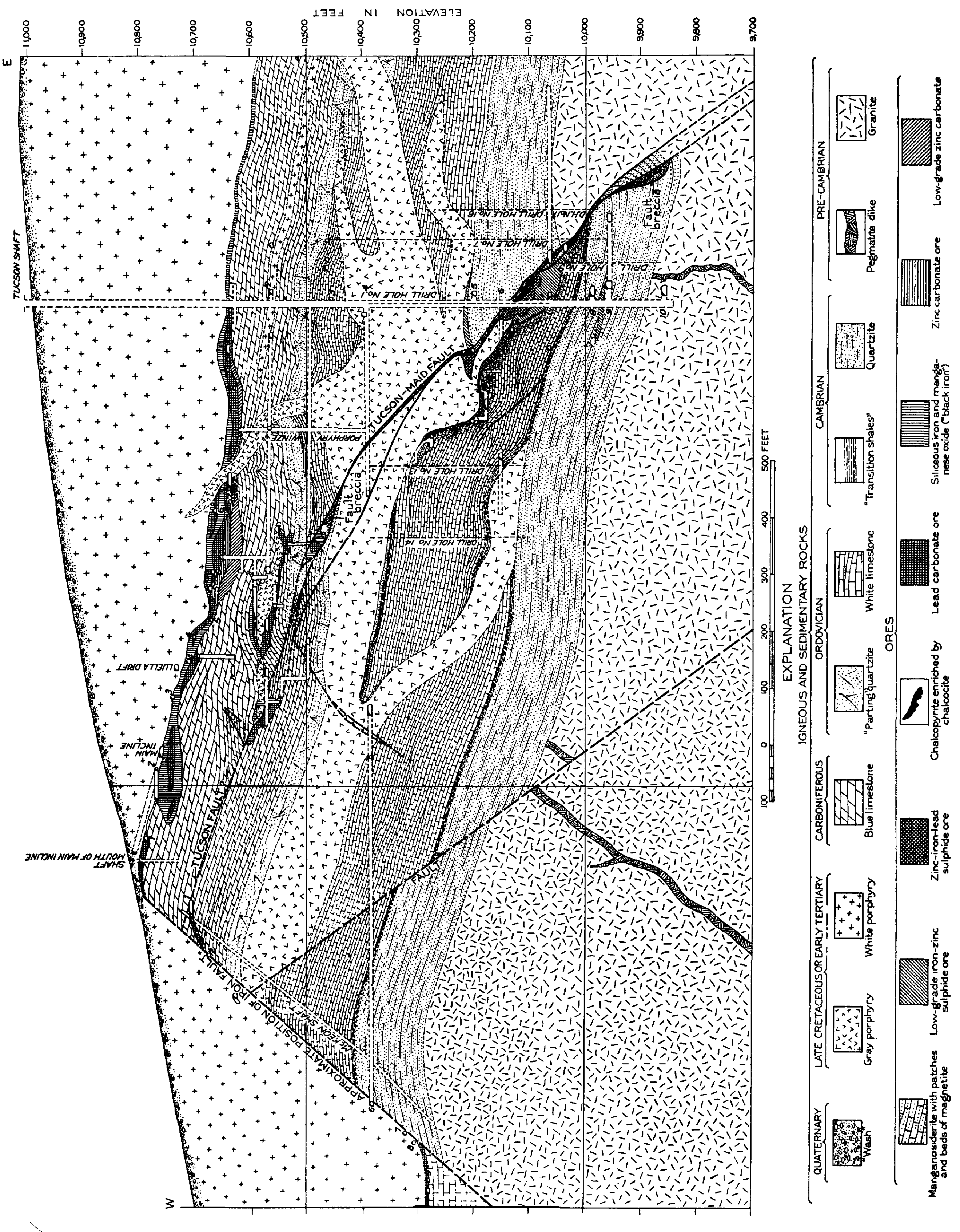
Loughlin and Behre (1934) considered the STM ores to be cooler mesothermal ores related to the Leadville district; however, Johansing (1982) and Thompson and others (1983) have shown that two separate ore fluids were involved in forming the respective ore types. The actual age of formation for STM ores has been controversial: some have ascribed them to a late Paleozoic age (DeVoto, 1983; Tschauder and Landis, 1985), and others to a Tertiary age (Thompson and others, 1983). The question of age is under current investigation. STM deposits are found throughout the Mosquito Range, and extending east into the Alma district (Johansing, 1982).

Wallrock alteration associated with STM systems is minor and often negligible. Where present, altered rocks contain minor silica along faults or marginal to the ore bodies.

Fluid inclusions of STM ore and gangue minerals were analyzed by Johansing (1982). The filling temperatures in quartz, barite (early and late), and sphalerite range between 180 and 267 °C (fig. F22).

Sulfur-isotope analyses of barite and galena document that ore-fluid sulfur in STM bodies was compositionally distinct from that of LTM bodies (Thompson and others, 1983). Similarly, the lead-isotopic compositions of galena from the two ore types are easily distinguished; STM galena lead is strongly radiogenic, whereas LTM lead is normal.

Data are not available to document if any internal zoning occurs within STM bodies, but their relative small size would suggest that little zoning is likely. Some base


E
W
ELEVATION IN FEET
11,000
10,900
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10,600
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10,000
9,900
9,800
9,700
TUCSON SHAFT
TUCSON-MAID FAULT
TUCSON FAULT
FAULT
APPROXIMATE POSITION OF IRON FAULT
MCLEOD SHAFT
SHAFT MOUTH OF MAIN INCLINE
MAIN INCLINE
OLIVELLA DRIFT
PORPHYRY WINZE
DRILL HOLE No. 1
DRILL HOLE No. 7
DRILL HOLE No. 9
DRILL HOLE No. 13
DRILL HOLE No. 14
DRILL HOLE No. 16
Fault breccia
100 0 100 200 300 400 500 FEET
EXPLANATION
IGNEOUS AND SEDIMENTARY ROCKS
QUATERNARY
"Wash"
LATE CRETACEOUS OR EARLY TERTIARY
Gray porphyry
White porphyry
CARBONIFEROUS
Blue limestone
ORDOVICIAN
"Parting" quartzite
White limestone
CAMBRIAN
"Transition shales"
Quartzite
PRE-CAMBRIAN
Pegmatite dike
Granite
ORES
Manganosiderite with patches and beds of magnetite
Low-grade iron-zinc sulphide ore
Zinc-iron-lead sulphide ore
Chalcopyrite enriched by chalcocite
Lead carbonate ore
Siliceous iron and manganese oxide ("black iron")
Zinc carbonate ore
Low-grade zinc carbonate

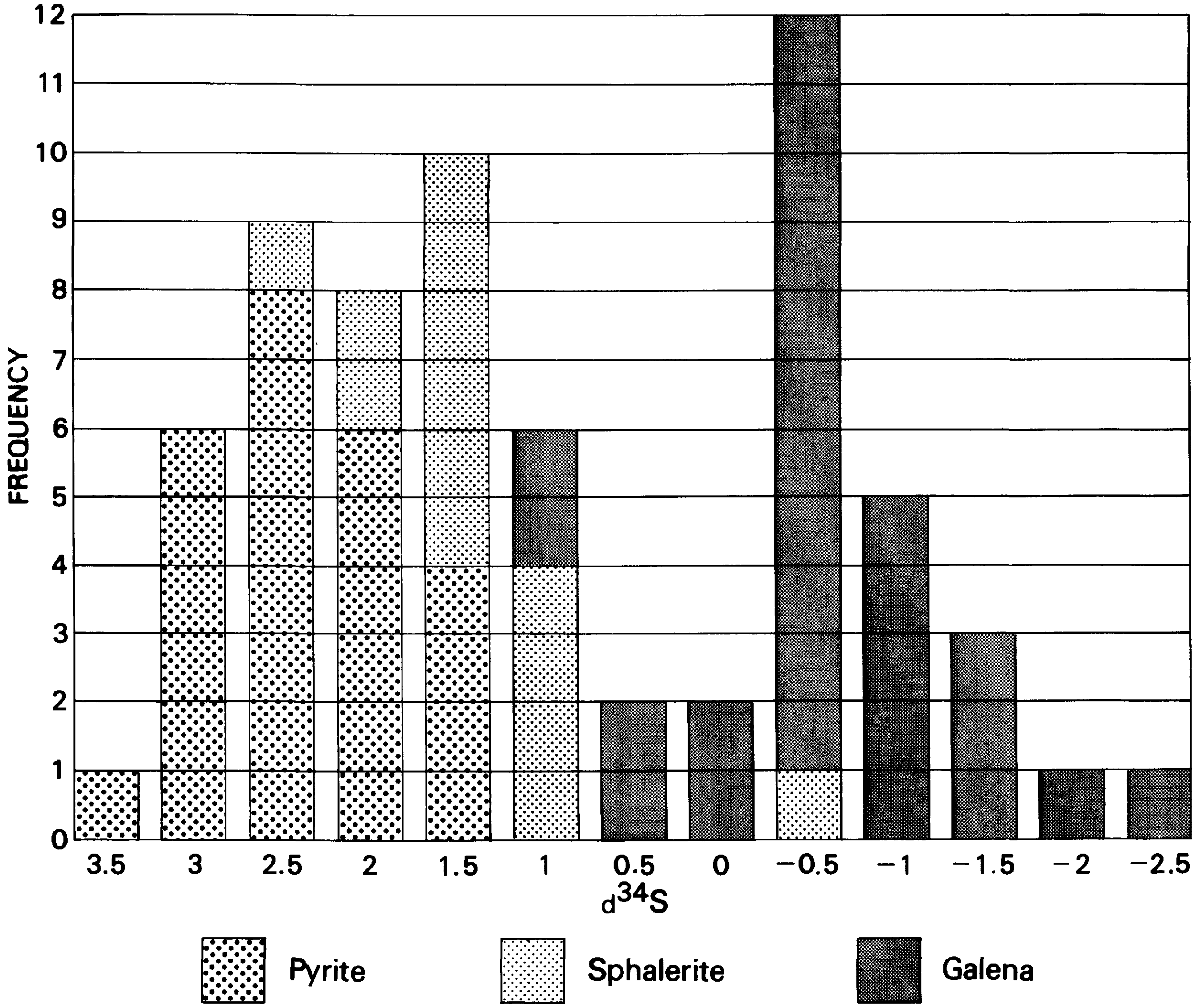

Figure F21. Sulfur-isotope analyses of pyrite, sphalerite, and galena, Leadville district.

metal bodies without appreciable silver have been noted within the Sherman mine. STM ores lack any significant gold but are significantly enriched in silver compared to unoxidized LTM bodies.

Figure F20 (facing page). N. 63° E. cross section through Tucson mine (from Emmons and others, 1927, fig. 18). "Pre-cambrian" granite is Middle Proterozoic St. Kevin Granite; Cambrian quartzite is Cambrian Sawatch Quartzite; Cambrian "transition shales" are equivalent to the Cambrian Peerless Formation; Ordovician white limestone is Ordovician Manitou Dolomite; Ordovician "parting" quartzite is Devonian Parting Formation; Carboniferous blue limestone is Devonian Dyer Dolomite (below) and Mississippian Leadville Dolomite (above); Late Cretaceous or early Tertiary white porphyry is in part Pando Porphyry; Late Cretaceous or early Tertiary gray porphyry is in part Johnson Gulch Porphyry.

SUMMARY

Two different mineralized systems are found in the Leadville district. The principal ore production in the district has come from the LTM bodies and coeval veins within or adjacent to the Breece Hill stock. These exhibit a central higher-temperature zone of gold- and silver-bearing veins surrounded by lower-temperature vein and replacement bodies with abundant base metal, silver and gold concentrations. Silver appears to increase outward from the Breece Hill center. Individual ore-body zoning reflects a preferential siting of gold and silver either peripheral to a central base metal zone or adjacent to veins that were conduits for the ore fluids, and that cut the central base metal zone.

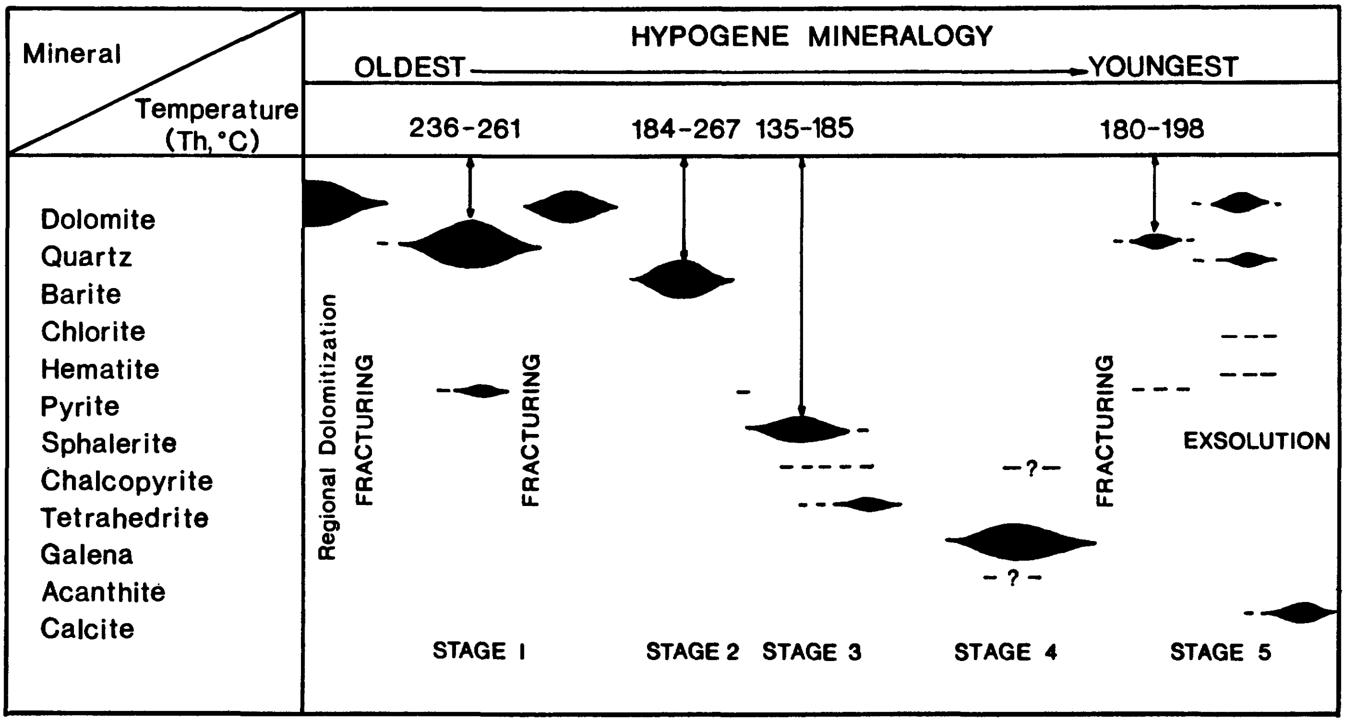

Figure F22. Paragenetic diagram showing fluid-inclusion data for Sherman type mineralization (from Thompson and others, 1983).

The STM ore bodies have contributed small amounts to the district's total production. They appear to have been formed by water that scavenged lead and sulfur from shallow crustal rocks (Thompson and others, 1983). They are relatively older than ore bodies of the LTM system; radiometric and fission-track dating has not resolved the question of Paleozoic versus Tertiary age for STM ore bodies.

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