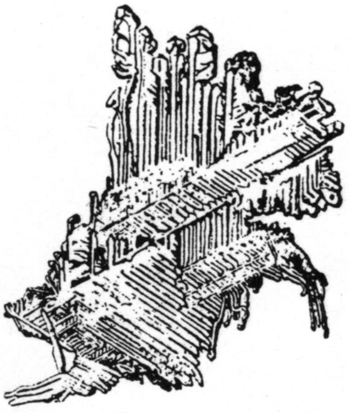

MINERALOGY OF PRECIOUS METAL DEPOSITS

A Symposium on the Mineralogy of Gold and Silver
Deposits in Colorado and other Areas

Program, Extended Abstracts, and Field Guides

Green Center

Colorado School of Mines

Golden, Colorado Aug. 12-15, 1988

Colorado Chapter, Friends of Mineralogy and
Department of Geology, Colorado School of Mines

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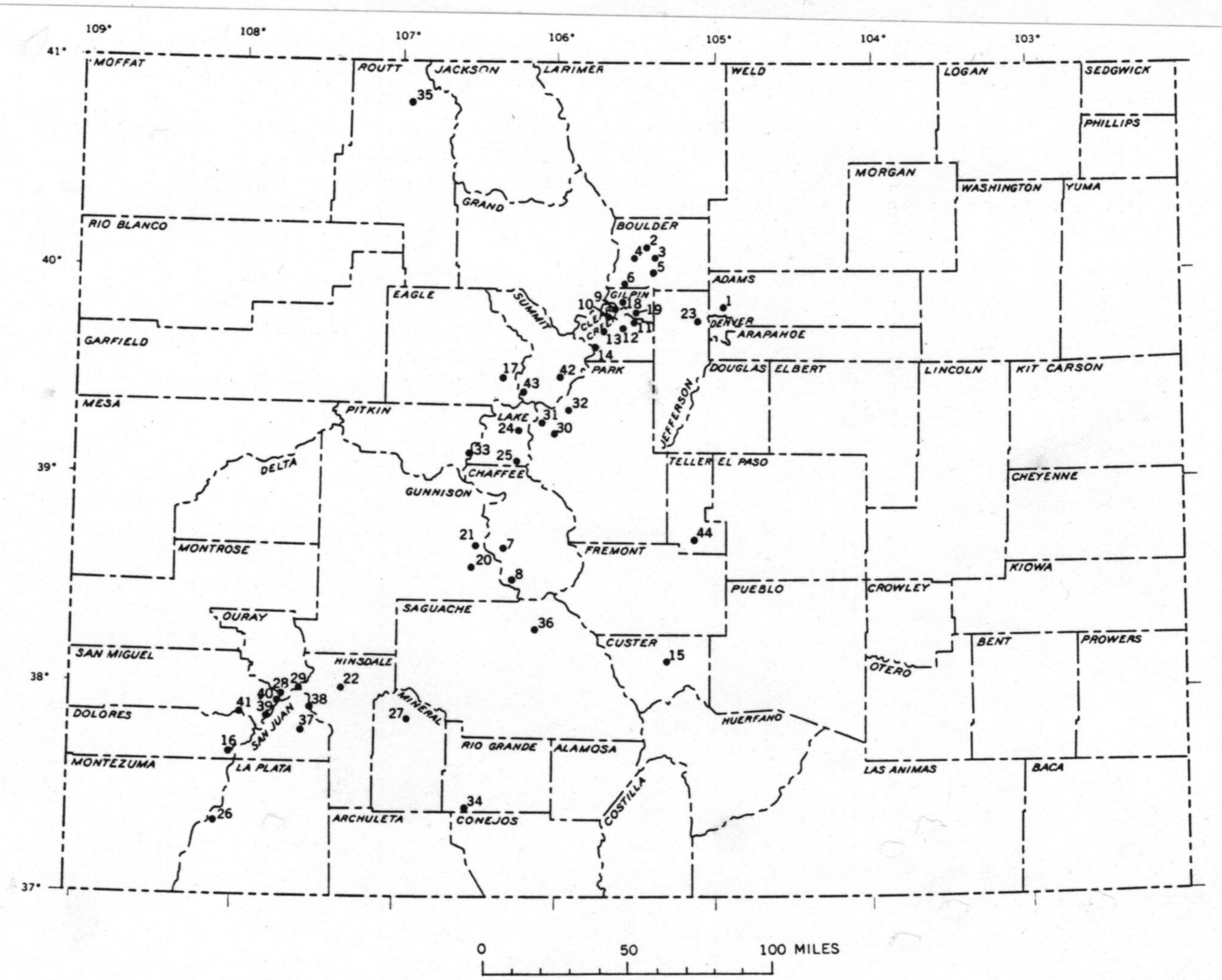

Adams County:
1, Clear Creek placers.

Boulder County:
2, Jamestown; 3, Gold Hill-Sugarloaf; 4, Ward; 5, Magnolia; 6, Grand Island-Caribou.

Chaffee County:
7, Chalk Creek; 8, Monarch.

Clear Creek County:
9, Alice; 10, Empire; 11, Idaho Springs; 12, Freeland-Lamartine; 13, Georgetown-Silver Plume; 14, Argentine.

Custer County:
15, Rosita Hills.

Dolores County:
16, Rico.

Eagle County:
17, Gilman.

Gilpin County:
18, Northern Gilpin; 19, Central City.

Gunnison County:
20, Gold Brick-Quartz Creek; 21, Tincup.

Hinsdale County:
22, Lake City.

Jefferson County:
23, Clear Creek placers.

Lake County:
24, Leadville; 25, Arkansas River valley placers.

La Plata County:
26, La Plata.

Mineral County:
27, Creede.

Ouray County:
28, Sneffels-Red Mountain; 29, Uncompahgre.

Park County:
30, Alma; 31, Fairplay; 32, Tarryall.

Pitkin County:
33, Independence Pass.

Rio Grande County:
34, Summitville.

Routt County:
35, Hahns Peak.

Saguache County:
36, Bonanza.

San Juan County:
37, Animas; 38, Eureka.

San Miguel County:
39, Ophir; 40, Telluride; 41, Mount Wilson.

Summit County:
42, Breckenridge; 43, Tenmile.

Teller County:
44, Cripple Creek.

Gold-mining districts of Colorado; from A.H. Koschmann and M.H. Bergendahl, U.S. Geological Survey Prof. Paper 610, Principal Gold-Producing Districts of the United States, p. 85, 1968.

MINERALOGY OF PRECIOUS METAL DEPOSITS

A SYMPOSIUM ON THE MINERALOGY OF GOLD AND SILVER DEPOSITS IN COLORADO AND OTHER AREAS

PROGRAM, EXTENDED ABSTRACTS, AND FIELD GUIDES

Peter J. Modreski, editor

held at
Metals Hall, Green Center
Colorado School of Mines
Golden, Colorado
August 12-15, 1988

sponsored by
FRIENDS OF MINERALOGY, COLORADO CHAPTER
c/o Jack Murphy, Geology Department
Denver Museum of Natural History
City Park
Denver, Colorado 80205

and
DEPARTMENT OF GEOLOGY
COLORADO SCHOOL OF MINES
Golden, Colorado 80401

symposium co-chairmen: James F. Hurlbut, Peter J. Modreski

symposium committee: James Hurlbut, Eugene Foord, Dan Kile, James McGlasson, Peter Modreski, Barbara Muntyan, Jack Murphy, Karen Wenrich

with special thanks to (among others): Leonard Beach, Harold Caldwell, Earl Detra, Dick Dwelley, Bruce Geller, Phil Hannum, Tom Hendricks, Rob Johansing, Dianne Kile, Regina Modreski, Al Rogers, Valois Shea, Paul Sims, Mark Steen, Chauncey Walden

FRIENDS OF MINERALOGY, COLORADO CHAPTER
Denver, Colorado
August, 1988

SYMPOSIUM SCHEDULE

Friday, August 12

7:45 - 8:30 registration
8:30 - opening remarks
8:45 - A review of precious metal mineral deposit types (keynote address) by Samuel B. Romberger
9:30 - Mineral zoning in the western San Juan district, Colorado, by John E. Dreier

10:00 - 10:30 coffee break

10:30 - Mineralogy and geology of the Galena mining district, Hinsdale County, Colorado, by Stanley L. Korzeb
11:00 - Timing, zoning, and genesis of silver along the Bulldog Mountain vein system, Creede district, Colorado, by Geoffrey S. Plumlee

11:30 - 1:30 lunch break

1:30 - Tellurian canfieldite, Ag-Bi-bearing galena, and associated Pb-Bi-Ag-Cu sulfosalts from three Colorado mining districts, by Eugene E. Foord
2:00 - The petrology of mixed telluride, sulfosalt, sulfide ores in Buckeye Gulch, Leadville area, Colorado, by Demetrius C. Pohl and David W. Beaty

2:30 - 3:00 Coffee break

3:00 - Hydrothermal adularia in the Bodie mining district, Mono County, California--mode of occurrence, structure and chemistry, by Miles L. Silberman and Charles W. Chesterman
3:30 - Roscoelite in Colorado telluride ores, by Jeffrey P. Kurtz and Phoebe L. Hauff
4:00 - Mineral distributions in the Gold Hill mining district, Boulder County, Colorado, by Bruce Geller

Banquet 7:00 p.m. (Social hour 6:00 - 7:00 p.m.)

Rock Rest Inn, 16000 S. Golden Rd., Golden.
featured speaker:

Jack A. Murphy, Curator of Geology, Denver Museum of Natural History
"Highlights of Colorado Gold and Silver Occurrences"

Saturday, Aug. 13

8:00 - 8:30 registration
8:30 - The mineralogy of gold and silver (keynote address) by Philip C. Goodell and Kathryn Evans-Goodell
9:15 - The silver content of galena and sulfosalt minerals from hydrothermal ore deposits in Peru, Colorado, and New Mexico, by Peter J. Modreski

9:45 - 10:15 Coffee break

10:15 - Betekhtinite from the St. Cloud silver mine, Chloride mining district, New Mexico, by Paul F. Hlava and Douglas F. Irving
10:45 - Bismuth sulfosalts of Colorado, by Robert R. Cobban

11:15 - 1:15 Lunch break

1:15 - Specimen mineralogy of the San Juan Mountains, Ouray and San Juan Counties, Colorado, by Barbara L. Muntyan
1:45 - Mineralogy of the Creede district, Mineral County, Colorado, by Ed Raines

2:30 - 3:00 Coffee break

3:00 - Mineralogy of the Patch mine, Gilpin County, and the Alice mine, Clear Creek County, Colorado, by Daniel E. Kile and Peter J. Modreski
3:30 - Mineralogy of the Bessie G. mine, La Plata district, La Plata County, Colorado, by Arnold G. Hampson
4:00 - Mineralogy of the Camp Bird mine, Ouray County, Colorado, by Tom Rosemeyer
4:30 - Gold in Wyoming, by W. Dan Hausel

Poster papers: available for viewing all day Friday and Saturday:
Reports of platinum-metals in Colorado, by Robert R. Cobban

The Gold King mine, Silverton Caldera, southwest Colorado, by Bernhard C. Koch, Richard W. Hutchinson, and Bernhard Free

Multispectral remote sensing of precious metal deposits, by Fred A. Kruse, Phoebe L. Hauff, and Dan Taranik

Geology, mineralogy, and zoning of the Buffalo Boy vein deposit, San Juan County, Colorado, by Robert V. Perry

Paragenesis of the mineralization event at Aspen, Colorado, based on structural, textural, and mineralogical studies of the orebodies in the Smuggler mine, by Ralph J. Stegen, David W. Beaty, and Tommy B. Thompson

The presence of rectorite in hydrothermally altered porphyry associated with gold-rich mantos, Buckeye Gulch, central Colorado, by Gene Whitney, David W. Beaty, and Walter H. Hunt

Sunday, Aug. 14, and Monday, Aug. 15

7:30 a.m. Field trips leave School of Mines Campus

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A REVIEW OF PRECIOUS METAL MINERAL DEPOSIT TYPES

Samuel B. Romberger

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Golden, Colorado 80401

Historically, approximately 4,100 million ounces of gold have been produced worldwide, with 32 percent coming from South Africa and 8.5 percent from the United States. In 1987, the world production of gold and silver was 54 million and 428 million ounces respectively. In gold production the United States (4.9 million) stood behind only South Africa (20 million) and the U.S.S.R. (8.9 million ounces), while the U.S. was the fifth largest silver producer (38 million) behind Mexico (75 million), Peru (62 million), the U.S.S.R. (48 million), and Canada (40 million ounces). Most of the gold produced in South Africa is derived from Early Proterozoic quartz-pebble conglomerates of the Witwatersrand basin while in the United States most is produced from epithermal disseminated and vein deposits hosted by sedimentary and volcanic rocks of the western Cordillera. A smaller but significant amount is recovered from metamorphosed Archean iron formation, primarily from the Homestake deposit in the Black Hills of South Dakota. In Canada (3.8 million) and Australia (3.2 million ounces), the fourth and fifth largest gold producers in 1987 respectively, most gold is produced from quartz veins in metavolcanic and metasedimentary rocks in Archean greenstone terranes. Of the total annual world production of silver, two-thirds is derived from polymetallic base metal deposits and one-third from vein silver deposits. The former is typical of many deposits in Canada and the U.S. while the latter is typical of deposits in Mexico and Peru.

In the U.S. eleven mines or districts produced more than 50 percent of the total gold in 1987, while ten mines produced 65 percent of the silver. Nevada was the most important gold-producing state (41 percent) while Idaho was the most important silver producer (34 percent). Of the 25 most productive gold mines in 1987, all were operated primarily for their gold content even though the silver to gold ratio was often greater than one. However, of the 25 largest silver producers, only nine can be considered silver deposits; the others were either base metal or gold deposits where the silver was recovered as a by-product.

With the exception of the Homestake deposit of South Dakota, and those at Battle Mountain, Nevada, most of the important gold deposits belong to the epithermal type. Many of these deposits also produce significant amounts of silver where a few may have silver to gold ratios exceeding 100. The metals are deposited by dilute hydrothermal solutions at temperatures in the range of 200° to 300°C and at depths within a few hundred to a thousand meters of the paleotopographic surface existing at the time of ore formation. The processes responsible for the formation of epithermal deposits are similar to those occurring in many present day hot spring and geothermal areas. The age of mineralization for most of these deposits is Tertiary although a few may be Mesozoic. For most deposits the hosts can be divided into Paleozoic sedimentary rocks and Tertiary volcanic rocks, although a few occur in Mesozoic metamorphic rocks such as those in the detachment terranes of southwestern Arizona and southeastern California. The ore may be disseminated, occurring along grain boundaries and small microveinlets, or may occur in veins occupying major thoroughgoing fractures. Even though locally the ore can be described as disseminated, the distribution of ore bodies has a strong structural control. Disseminated mineralization occurs most commonly in sedimentary rock hosts whereas fracture-controlled veins are more common in volcanic hosts. The most common host lithologies for sedimentary rock-hosted disseminated ore are impure limestone and dolomite such as in many of the Carlin trend deposits, however, calcareous siltstones also host ore, such as at Alligator Ridge. In sedimentary terranes the formation of jasperoids, replacement of carbonate by silica, is an important part of the mineralizing process. Jasperoid bodies may or may not contain ore, however, they represent good indicators that processes responsible for mineralization may have occurred in their vicinity. Volcanic lithologies hosting ore range in composition from rhyolite (Round Mountain) to andesite (Comstock), although more mafic hosts are locally important (McLaughlin). The Sleeper deposit is hosted by Triassic siltstones and overlying Tertiary latites. The ores at the Mesquite deposit occur in fractures within Jurassic metamorphic schists and gneisses.

In epithermal deposits gold in primary unoxidized ores occurs most commonly as microscopic and submicroscopic grains of native gold and electrum associated with sulfides, most commonly pyrite. Only rarely does the gold occur in spectacular visible form, such as at Sleeper. In sedimentary rock-hosted deposits the arsenides realgar, orpiment, and sometimes arsenopyrite, cinnabar, and rare thallium and bismuth minerals occur. Barite, calcite, and quartz are common gangue minerals. Silver occurs as electrum or as silver sulfide as disseminations or crustifications in veins. Locally, ruby silver may also be found. Base metal sulfides are minor or absent in epithermal ores. In oxidized ores the gold occurs with various iron oxides, sulfates, and minor arsenates. Visible gold grains may be seen associated with limonite pseudomorphs after pyrite. Silver may be absent in the oxide ores, or present as various secondary chlorides.

A few productive gold deposits exhibit a close spatial and genetic relationship to igneous intrusions. At Battle Mountain gold occurs in a sulfide-rich skarn in limestone, siltstone, and conglomerate adjacent to a Tertiary porphyritic granodiorite. Gold occurs as grains along sulfide and sulfide-silicate grain boundaries. The associated minerals include actinolite, tremolite, quartz, calcite, pyrrhotite, chalcopyrite, pyrite, galena, and sphalerite, and locally chlorite, arsenopyrite, and marcasite. At Zortman-Landusky, Montana, low grade epithermal gold and silver mineralization occurs in breccia zones cutting Tertiary alkalic to calcalkalic igneous rocks ranging from diorite to granite intruding Precambrian gneisses and schists and overlying Paleozoic sedimentary rocks. Primary mineralization consists of gold and silver associated with pyrite and various gold and silver tellurides. At Summitville, Colorado, epithermal mineralization occurs in veins and disseminations in and adjacent to a Tertiary quartz latite porphyry intruded along a ring zone of a caldera complex. In primary ore gold occurs with pyrite and various copper sulfides.

The Homestake deposit in the Black Hills of South Dakota is the second largest producer of gold in the U.S. The ores are hosted by the Homestake Formation, an approximately 100 meter-thick iron formation that has been metamorphosed to a sideroplesite (iron-magnesium carbonate) schist. This formation occurs within a thick Archean succession of sedimentary rocks which have been metamorphosed to as high as amphibolite grade. The rocks have undergone multistage deformation which has resulted in a very complex structural setting for the orebodies. Gold is associated with pyrrhotite, arsenopyrite, chlorite, and minor pyrite in quartz veins cutting the Homestake Formation.

Silver is produced from a much broader range of deposit types than those producing gold. In Mexico and Peru most of the production is from epithermal vein deposits in volcanic terranes. The silver occurs as sulfides and sulfosalts in crustified bands in well developed quartz and carbonate veins. These deposits commonly contain significant amounts of lead, zinc, and copper. Similar deposits occur in the Creede district of Colorado. In Canada much of the silver is produced from Precambrian syngenetic base metal sulfide deposits hosted by both volcanic and sedimentary terranes.

In the United States the most productive silver deposits occur as veins and disseminations in Proterozoic metasedimentary rocks in northern Idaho and Montana. The most important ore hosts are the quartzites, argillites, and calcareous units of the Belt Supergroup that have been mildly metamorphosed, folded, and faulted during the Proterozoic and later during the Laramide orogeny of late Mesozoic time. In the Coeur d'Alene district a major northwest-trending fault zone serves as the main structural control on mineralization. The deposits occur along laterally and vertically continuous fractures and shear zones, and concentrations of ore occur in areas of intense structural deformation and in brecciated brittle wall rocks. Silver occurs in tetrahedrite, which is associated with galena, sphalerite, chalcopyrite, pyrite, pyrrhotite, magnetite, arsenopyrite, and minor amounts of copper sulfides and base metal sulfosalts. The gangue minerals are quartz, siderite, other carbonates, and barite.

The largest single producer of silver in the U.S. is the Spar Lake silver-copper mine near Troy, Montana. The deposit is stratiform and stratabound within the Revett Formation, a silty to argillaceous quartzite within the Belt Supergroup. The silver occurs with chalcopyrite, galena, bornite, and pyrite which occur as disseminations, along bedding plane features, and in small veinlets which crosscut bedding.

In addition to being a by-product of epithermal gold deposits in the western Cordillera, important quantities of silver are being recovered from porphyry copper deposits of Arizona and New Mexico, Mississippi Valley Type (MVT) deposits in southeast Missouri, and various other polymetallic sulfide replacement deposits, such as Leadville, Colorado. In the porphyry copper deposits the silver is associated with copper sulfides occurring as disseminations and veins in porphyritic intrusions and the skarns which developed in carbonates adjacent to the intrusions. The Tyrone deposit in New Mexico was the seventh largest silver producer in 1986, and eight porphyry copper deposits were among the top 25 silver producers in that year. Mississippi Valley Type deposits produce important quantities of lead and zinc as sulfides from open space fillings and minor replacements in karst breccias in Paleozoic limestones. Two of these deposits, The Buick and Magmont of southeastern Missouri, were among the top 25 silver producers in the U.S. in 1986.

MINERAL ZONING IN THE WESTERN SAN JUAN DISTRICT, COLORADO

Dr. John E. Dreier

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The ore deposits of the Telluride-Silverton-Arrastra Basin area collectively, termed here the Western San Juan District, have produced some 8.5 million oz. Au, 200 million oz. Ag, plus important quantities of Pb, Zn, and Cu from 50 to 60 million tons of ore. All of this production has come from underground mines that exploited unusually large, continuous and mineralogically zoned epithermal veins.

Production records, detailed deposit descriptions, and gross geologic observations show these deposits to be components of a single large mineralized system whose principal characteristic is a pronounced radial vertical zoning of ore, gange, and wall rock alteration minerals.

For the purposes of discussion, the district or system is divisible into three concentric zones: 1) an inner zone, 2) an intermediate zone, and 3) an outer zone.

The central zone consists of an area of five to ten miles square along the western margin of the Silverton Caldera. It is characterized by intensive clay-pyrite-alunite alteration, and it hosts small, vertically zoned, pipe-like mineral deposits famous for their very high grades and their telescoped, complex assemblage of Cu-Pb-Zn-Ag-As-Sb-Bi minerals. Locally, W and Mo minerals are present. In recent years the inner zone has been found to contain one or more large, disseminated Au/Ag deposits.

Peripheral to the inner zone is an intermediate zone characterized by well-defined veins of unusually large horizontal and vertical extent. These veins have a pronounced mineralogic zoning, and they continue uninterrupted through the outer zone.

At depth and towards the inner zone, veins of the intermediate zone have a generally high base metal content with Zn grades of above 7% and Cu grades of above 1%. Upwards and outwards the total base metal contents decline along with Zn and Cu grades, while first Pb and then Au contents increase. In the upper 200 to 600 feet of this zone the veins were virtually devoid of base metals but produced upwards of five million tons of ore grading between 0.4 and 1.0 opt Au.

Mineralization in the outer zone is typified by the assemblage marcasite-pyrargyrite-proustite-barite ± low contents of base metal sulfides. This mineralization is relatively uniform in mineralogy and grade along strike and with depth.

While wall rock alteration in the inner zone is characterized by the intensive development of clay-pyrite-alunite (advanced argillic), adjacent to the intermediate and outer zone veins it consists of calcite-chlorite-epidote-K feldspar ± sericite (propylitic).

MINERALOGY AND GEOLOGY OF THE GALENA MINING DISTRICT, HINSDALE COUNTY, COLORADO

Stanley L. Korzeb

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INTRODUCTION

The Galena Mining district, located in Hinsdale County, Colorado, extends from Engineer pass to Lake City along Henson Creek (figure 1). The Galena district was one of the largest producing districts in Hinsdale County producing silver and base metal ore intermittently from 1871 to 1969 (Korzeb, 1986, p. 12-17). The district was examined in 1984 by the U.S. Bureau of Mines as part of a mineral investigation for the Redcloud Peak Wilderness Study Area. The Pride of America Mine and a number of smaller prospects were included in the investigation.

Slack did the first detailed investigation in the district on the Ute-Ulay Mine in 1976 and 1980. Sanford and others investigated the Pride of America Mine in 1982. The examination conducted in 1984 by the U.S. Bureau of Mines resulted in observations similar to those of the earlier investigations. The veins examined by Sanford and others in the Pride of America Mine were found to be more representative of the veins in the district then those at the Ute-Ulay mine. The results of the early investigations by Slack, Sanford and others are summarized in this report.

HISTORY

Mining began in the Galena district in 1871 after the discovery of the Ute-Ulay veins (Irving and Bancroft, 1911, p.13). Complete production figures are unavailable but most of the silver, lead, zinc, and copper production of the district came from the Ute-Ulay Mine. The mine was active during 1871-1883, and intermittently from 1887 to 1969. In 1943 the mine produced 34 oz of gold, 9,329 oz of silver, 5 tons of copper, 191 tons of lead, and 16.5 tons of zinc (Burbank, 1947, p.440). The last period of major production was from 1951-1952 when Colorado Standard Mines produced over $300,000 in lead, zinc and silver. In 1968-1969 mining activity consisted of development work on the fifth level by Noramco Mining Company. (See Slack, 1976, p.177). LKA International Inc. operated the flotation mill at the Ute-Ulay mine in 1984 for processing a gold-telluride ore from the Golden Wonder Mine in the Lake district (Korzeb, 1986, p.15).

In addition to the Ute-Ulay mine the Pride of America Mine had limited production from 1880 to 1969. The Pride of America Mine was discovered in 1880 but early production figures are not available. From 1911 to 1954 the mine produced 179 tons of ore that yielded 4,021 oz of silver, 1,713 lbs of copper, 63,035 lbs of lead, and 46,150 lbs of zinc. This production came from the top portion of the Pride of America-Big Casino vein. (See U.S. Bureau of Mines records.) Production was intermittent from 1954 to 1969, during this time the ore averaged 10 ounces of silver per ton, 10 to 17 percent lead and zinc, 1 percent copper, and traces of gold. The most recent

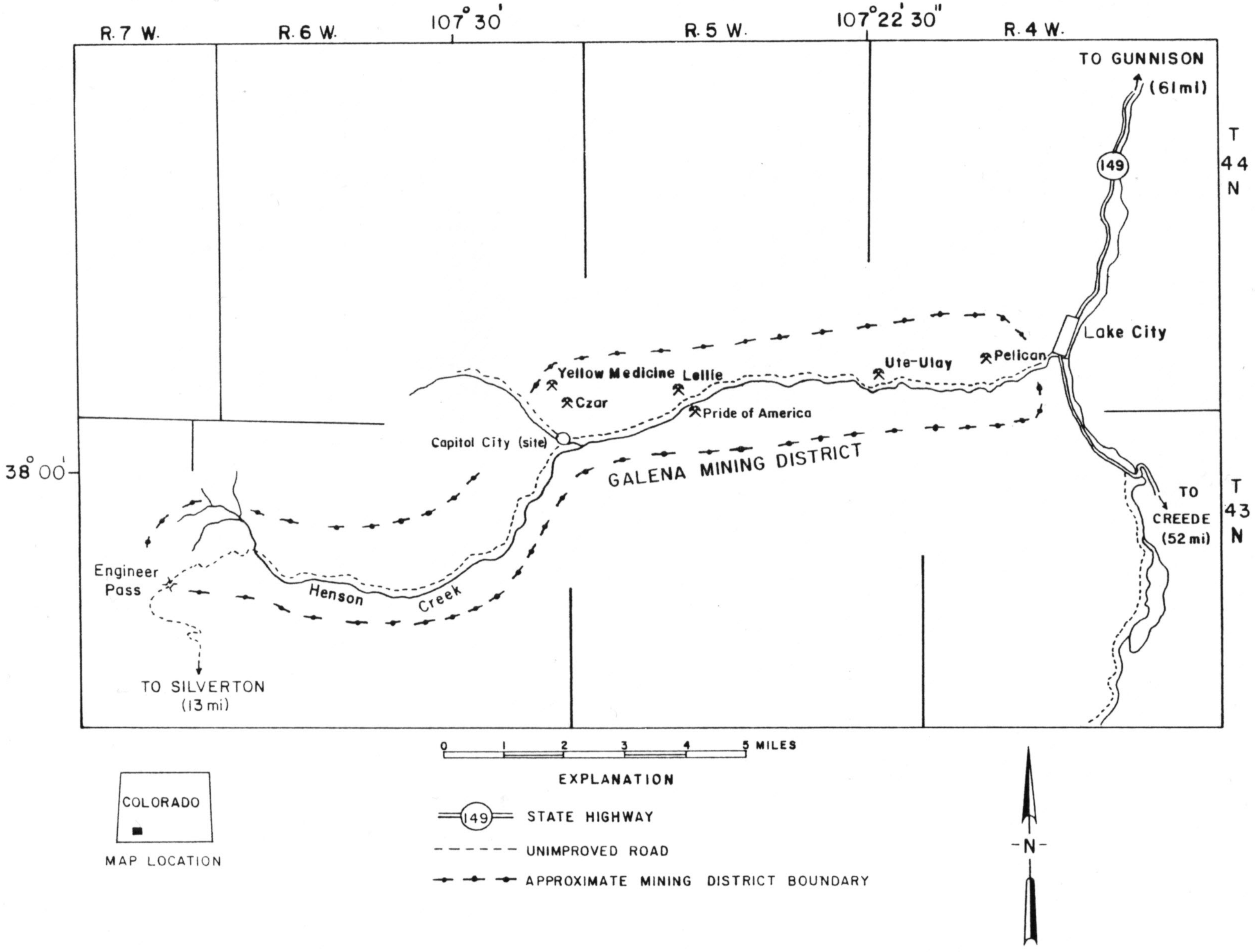

Figure 1.--Index map of the Galena mining district, Hinsdale County, Colorado.

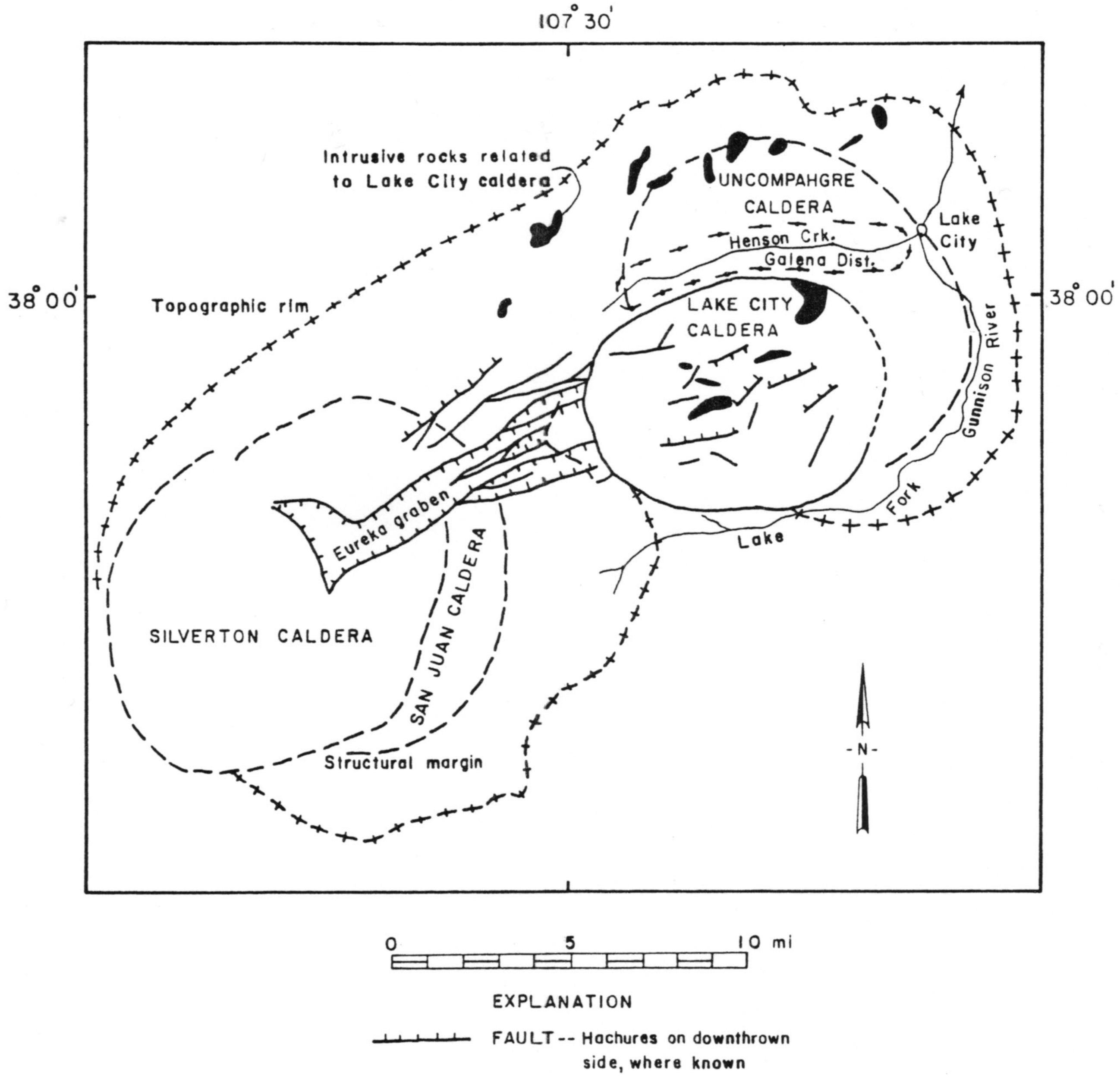

Figure 2.--Major geologic features related to the Galena mining district (from Steven and Lipman, 1976).

production was about 500 tons of ore that was shipped to the Ute-Ulay mill in 1965 and 400 tons of ore were shipped to Silverton for milling and refining in 1968-1969. Since 1969 the mine has been inactive. (See Sanford and others, 1986, p.3.)

GEOLOGY

The Galena mining district is located in the western part of the mid-Tertiary San Juan volcanic field of southwestern Colorado (figure 2). This volcanic field developed from the eruption of dacitic lava flows and breccias at 33-30 Ma (Lipman and others, 1973, 1976). These early eruptions were followed by eruptions of ash-flow tuffs which caused subsidence of the source areas to form calderas (Steven and Lipman, 1976). The Uncompahgre and San Juan calderas collapsed contemporaneously during the eruption of the Sapinero Mesa Tuff at 29 Ma (Lipman and others, 1973). After the calderas collapsed they were jointly resurged forming a broad elliptical dome extending from Silverton to Lake City (Lipman and others, 1973; Steven and Lipman, 1976). The Eureka graben formed along the crest of this dome from northeast trending extensional faulting (Luedke and Burbank, 1968). Several monzonitic stocks were intruded late in the development of the Uncompahgre caldera (Lipman, 1976).

In early Miocene time the 23.1 Ma Sunshine Peak Tuff was erupted causing the collapse of the Lake City caldera. The Lake City caldera is in the Uncompahgre caldera and truncates many of the older structures associated with the Uncompahgre-San Juan caldera complex, including faults of the Eureka graben. (See Sanford and others,1987.)

The veins in the Galena district along Henson Creek are hosted by the Eureka and Picayune Megabreccia Members of the Sapinero Mesa Tuff. These two members fill the moat area of the Uncompahgre caldera along the valleys of Henson Creek and the Lake Fork of the Gunnison River. The veins show three basic orientations: radial, being perpendicular to the Lake City caldera ring fault; concentric, parallelling the ring fault; and transverse, curving away from the caldera and are oblique to the other orientations. The transverse veins are common along Henson Creek and include veins developed by the Ute-Ulay, Pelican, and Pride of America mines. An important concentric vein is developed by the Vermont-Ocean Wave group. The transverse veins show an orientation identical with the faults of the Eureka graben suggesting a common origin. Collapse of the Lake City caldera truncated the structures of the Eureka graben interrupting the northeasterly continuation of the graben faults. The veins exposed along Henson Creek may be northeastward extensions of the Eureka graben. (See Slack, 1980.)

VEIN STRUCTURE

Most of the veins in the district are less then 3 feet wide and 2,100 feet long. All sizes of veins exist, from minor structures only a few inches wide and 20 feet long to the large Ute-Hidden Treasure vein that can be traced for 2,700 feet. The most productive vein, the Ute-Hidden Treasure, averages about 5 feet wide and reaches widths up to 18 feet. The veins split and branch laterally and vertically, change sharply or gradually in strike and dip, and pinch and swell abruptly. Post ore faulting was minimal with displacements averaging less then 3 feet.

Sulfide ore is confined to certain parts of the vein structures as ore shoots. The ore shoots generally are found within newly formed structural openings with variable geometry. Shoots of sulfide ore usually occupy positions near the foot walls of the veins but in the Pride of America Mine sulfide ore was found in the hanging wall and central parts of the vein structure. Major sulfide mineralization took place following reopening and brecciation of the veins. Localization of the ore is controlled by pinching and swelling, intersections with fractures or cross veins, branches or splits, and deflections in strike and dip. The ore shoots maintain an oblique pitch to the plane of the vein which is independent of the vein dip. The pitch of the ore shoots may be related to lithology which influenced the width and shape of fracture openings prior to mineralization. In the Eureka Member the veins at the Ute-Ulay Mine are narrow and choked with gouge. Below the Eureka Member the more competent andesite flows of the Picayune Megabreccia Member provided more uniform channels for ore deposition.

MINERALOGY

Slack (1980) recognized two major mineral assemblages in the veins of the Galena district; a quartz-base metal assemblage and a barite-precious metal assemblage. The quartz-base metal assemblage was earlier then the barite-precious metal assemblage and is found throughout the veins in the district. Patterns of mineral zoning, fluid inclusion studies and vein distribution suggest a genetic relationship of the quartz-base metal assemblage to the late stages of the Lake City caldera cycle.

Ore minerals of the quartz-base metal assemblage are pyrite, sphalerite, galena, and chalcopyrite with minor tetrahedrite-tennantite. Gangue minerals are quartz, calcite, rhodochrosite, rare ankerite and dolomite (?), and sericite. Some areas have trace amounts arsenopyrite, hematite, gold, fluorite, pyroxmangite, and anhydrite. Most minerals occur as fine to coarse intergrowths of anhedral grains. Euhedral crystals of quartz up to 5 cm long are common in vugs and open fractures. Some vugs have been reported to contain euhedral crystals of calcite and rhodochrosite up to 2 cm long. The sulfide minerals pyrite, sphalerite, galena, and chalcopyrite form granular aggregates and mutual intergrowths.

The quartz-base metal assemblage can be divided into separate stages of mineralization. Most of the veins in the district contain one or two stages but at the Ute-Ulay Mine four stages were identified by Slack (1980) and three stages were identified by Sanford and others (1986) at the Pride of America Mine. The first stage is a quartz-pyrite stage and is common for the veins throughout the district. This stage forms the margins of the veins; the quartz can be massive, fine grained, milky gray grading into radiating euhedral crystals. The associated pyrite forms individual disseminated cubes less then 1 cm or coarse aggregates 2 to 3 cm across. In the Pride of America Mine sericite is associated with this early stage. The sericite is fine grained and occurs as growth zones in the quartz.

The next mineralizing episode deposited a base-metal stage consisting of banded quartz-sulfide ores with the gangue and ore minerals occurring in different layers. All the productive veins in the district contain this stage. The most abundant minerals deposited during this stage are quartz, pyrite, sphalerite, galena and chalcopyrite. Accessory vein minerals are tetrahedrite-tennantite and rhodochrosite. Traces of gold, arsenopyrite, hematite, calcite, ankerite, pyroxmangite, chalcedony, and sericite occur locally. Pyrite and sphalerite were the first minerals to appear, followed by galena and later by chalcopyrite or tetrahedrite-tennantite.

The contact between the quartz-pyrite and base-metal stage is gradational; as sericite disappears sphalerite appears. An assemblage of intergrown quartz, pyrite, and sphalerite forms a transition zone between the two stages. Sphalerite is the first mineral to disappear at the end of this deposition stage. The proportions of minerals in this stage vary locally along the veins. At some locations the entire vein consists of massive sulfides and at others the veins can be massive quartz with sparse sulfides.

Two periods of fracturing and brecciation occurred within the banded quartz-sulfide ore stage. The appearance and disappearance of minerals generally coincides with periods of fracturing. In the Pride of America Mine barite and rhodochrosite first appear in a set of fractures, and tetrahedrite occurs in fractures in galena. Fracturing occurred after the precipitation of galena, chalcopyrite and tetrahedrite.

A massive rhodochrosite stage occurs in the veins at the Ute-Ulay Mine. The outer edges of this stage are characterized by coarsely crystallized quartz, and sphalerite rimmed with galena. The quartz and sulfide minerals grade into dense fine grained rhodochrosite with minor quartz. Late stage mineralization deposited medium to coarse grained rhodochrosite, tetrahedrite, and sericite with minor quartz, pyrite, arsenopyrite, hematite and chalcopyrite.

The last mineralizing stage of the quartz-base metal assemblage is the late quartz-carbonate-fluorite stage or a barite-rhodochrosite stage that occurs at the Pride of America Mine. This mineralizing stage was post ore and is deposited in vugs and open fractures near the center of the veins. The mineralogy is dominated by quartz, calcite, rhodochrosite, fluorite, and barite. The minerals from this stage typically occur in veinlets cutting fractures and as euhedral crystals in vugs.

A late barite-precious metal assemblage was recognized by Slack (1980). This assemblage occurs mostly in fractures and fault zones outside the Galena district east and northeast of the Lake City caldera. Vein systems in only two mines in the Galena district have this mineral assemblage, the Ute-Ulay and Vermont-Ocean Wave mines. The ore minerals are silver-rich tetrahedrite, pyrite, sphalerite, galena, and minor arsenopyrite and chalcopyrite. The accessory minerals are silver-copper-lead sulfosalts, tellurides, uraninite, and electrum. The gangue minerals are barite, quartz, jasperoid, minor rhodochrosite, and clays.

Slack (1980) divided the late barite-precious metal assemblage into three stages. In the Galena district two of these stages of mineralization are found in the vein system of the Ute-Ulay Mine. The earliest stage is the barite-sulfosalt ore stage. This stage is characterized by layered and brecciated jasperoid alternating with barite and ore minerals. The ore minerals are pyrite, sphalerite, galena, chalcopyrite, tetrahedrite, and other sulfosalts intergrown with bladed barite. The next mineralizing stage is the gold-silver telluride ore stage and is found only in veins outside the Galena district. The final mineralizing stage is the barite chalcedony stage which is characterized by barite, chalcedony and minor quartz. The minerals occur as coatings on euhedral crystals in vugs and open fractures.

Secondary oxidation has taken place in the vein systems, developing the bonanza ores that were first mined in the district. Iriving and Bancroft (1911) reported the secondary bonanza ores to consist of pyrargyrite, proustite, and native silver. In addition to the bonanza ores, covellite, chalcocite, and a Cu-sulfate replace chalcopyrite and tetrahedrite, and fill fractures in sphalerite and galena. Anglesite replaces galena and fills fractures in other vein minerals. Cerussite and wulfenite coat fractures and crystal faces of galena and sphalerite.

The contacts of adjacent mineralizing stages are gradational suggesting a continuous evolution of the mineralizing fluids during one event. Fracturing and brecciation of the different stages coincide with the beginning or ending of the deposition of certain minerals. The fractures are not filled with earlier mineral assemblages (for example, earlier deposited mineral assemblages do not repeat themselves after a later assemblage was deposited) suggesting major changes in mineralizing conditions and two separate episodes of mineralization. Many of the same minerals persist across the times of fracturing and no fracturing events correlate across all the stages, suggesting that mineral deposition was a single event from a continuously evolving hydrothermal fluid.

CONCLUSIONS

The most productive and largest veins in the Galena district developed in northeast-trending structures that may be extensions of the Eureka graben. The veins show multiple stages of mineralization that developed during one event from a continuously evolving mineralizing fluid. Prior to deposition of the base metal stage the veins were reopened and brecciated. The ore shoots that developed during the base metal stage are localized by pinching and swelling, intersections with fractures or cross veins, branches or splits, and deflections in strike and dip.

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TIMING, ZONING, AND GENESIS OF SILVER ALONG THE BULLDOG MOUNTAIN VEIN SYSTEM, CREEDE DISTRICT, COLORADO

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The Bulldog Mountain vein system is one of several major epithermal vein systems in the Creede mining district from which the bulk of the district's historical silver-lead-zinc-copper production has come. Although the Bulldog Mountain vein system was prospected heavily since ore was first discovered in the district in the early 1890's, economic mineralization was not discovered within the system until the mid-1960's. From start of mining in 1969 until closing in 1985, Homestake Mining Company's Bulldog Mountain mine produced more than 25 million ounces of silver and more than 48 million pounds of lead from the vein system (S. Caddey, oral comm., 1988; Roeber, 1981).

The Bulldog Mountain ores are mineralogically complex and strongly zoned. Seven major mineralization stages can be identified, each with a characteristic suite of minerals deposited and/or leached (Table 1). Spatial variations in mineralogy are present in some stages and are especially well developed in the second stage of mineralization (stage II). Silver was deposited at several different stages of the paragenesis, in a wide variety of minerals (Table 1).

The greatest amounts of silver were deposited during stage II mineralization (Table 1). In the northern part of the Bulldog Mountain mine, stage II mineralization is sphalerite- and galena-rich; silver occurs only in minor amounts within argentian tetrahedrite. Farther to the south along the vein system during stage II, however, abundant native silver and acanthite were deposited with copious barite and lesser amounts of sphalerite and galena. The native silver forms massive to dendritic growths within the barite and sulfides. These stage II native silver-acanthite occurrences formed the highest grade ore zones in the Bulldog Mountain vein system. Vein assays in stopes with this type of mineralization commonly were in excess of 1000 ounces Ag per ton (D. Vardiman, oral comm., 1983). One particularly high-grade sample (now archived at the Denver Museum of Natural History) weighs about 70 pounds, and is approximately two-thirds native silver! Fluid-inclusion, stable-isotope, and chemical modeling studies (summarized in Hayba et al., 1985, Bethke, 1988, and Plumlee, 1988) suggest that the zoned stage II mineralization reflects the progressive mixing of hydrothermal brines (T = 160 - 250 °C, salinities as high as 13 wt. % NaCl eq.) with dilute groundwaters: the northern sulfide-rich ores were deposited with small degrees of mixing, whereas the southern barite-native silver-acanthite ores were deposited after large degrees of mixing.

Lesser amounts of silver were deposited in the paragenetically late sulfide stages of the Bulldog Mountain system. A complex assemblage of silver- and copper-rich sulfides and sulfosalts was deposited in modest amounts throughout the vein system during the transition between main-stage base-metal sulfide mineralization (stage IV: Table 1) and late-stage botryoidal pyrite mineralization (stage V: Table 1). Polybasite-pearceite, pyrargyrite-proustite, mckinstryite, jalpaite, acanthite, and miargyrite occur as microscopic intergrowths within megascopic chalcopyrite, bornite, and tetrahedrite deposited during the transition. Also, exceptionally high concentrations of silver (as high as 5 wt. %), arsenic (as high as 12 wt. %), and antimony (as high as 6 wt. %) have been documented within some growth zones of the stage V botryoidal pyrite: microprobe and X-ray studies indicate that the silver, arsenic, and antimony are present in the pyrite crystal structure and not within microscopic accessory minerals. The late-stage sulfides formed during the thermal and hydrologic collapse of the waning Creede hydrothermal system (Plumlee and Rye, 1986, 1987; Plumlee, 1988), possibly during alternating periods of boiling and mixing.

Wire silver formed throughout the vein system very late in the paragenesis and accompanied widespread leaching of earlier sulfides and sulfosalts (Table 1). The wires vary from <1 to 4-5 cm in length and generally grow in curling bunches from corroded sulfides or sulfosalts. The origin of the wire silver occurrences is uncertain: the silver may reflect the transition from late hypogene conditions to supergene conditions, or it may have formed in the supergene zone below the water table.

Spangle and arborescent forms of native silver occur in the uppermost portions of the Bulldog Mountain ore zone. This silver, which is intergrown with halloysite and mixtures of various iron oxides/hydroxides (all minerals of clear supergene origin), formed in the oxidized supergene environment.

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Table 1. Schematic paragenesis of the Bulldog Mountain vein system, with stages listed from oldest to youngest. Capitalized minerals are those occurring in greatest abundances. Silver-bearing minerals are italicized. Summarized from Plumlee (1988) and Heald-Wetlaufer and Plumlee (1984).

STAGE I:	RHODOCHROSITE, chalcedony, minor sphalerite and galena.
STAGE II:	NORTH: SPHALERITE, GALENA, *argentian tetrahedrite*, minor chlorite, hematite. SOUTH: BARITE, SPHALERITE, GALENA, *NATIVE SILVER*, *acanthite*, quartz.
STAGE III:	QUARTZ, FLUORITE, minor sphalerite and galena; MAJOR BARITE LEACHING.
STAGE IV:	SPHALERITE, GALENA.
STAGE IV-V TRANSITION:	chalcopyrite, tetrahedrite, bornite, famatinite, *polybasite-pearceite*, *proustite-pyrargyrite*, *mckinstryite*, *jalpaite*, *miargyrite*.
STAGE V:	*BOTRYOIDAL PYRITE*, MARCASITE, stibnite, sphalerite, *proustite-pyrargyrite*, *acanthite*.
VERY LATE HYPOGENE OR REDUCED-ZONE SUPERGENE:	*wire silver*; leaching of sulfides and sulfosalts.
OXIDIZED-ZONE SUPERGENE:	*spangle and arborescent native silver*, halloysite, Fe-oxides/hydroxides

TELLURIAN CANFIELDITE, AG-BI-BEARING GALENA AND ASSOCIATED PB-BI-AG-CU SULFOSALTS FROM THREE COLORADO MINING DISTRICTS

by

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As part of a detailed investigation of Ag- and Bi-bearing galenas and associated sulfosalts, their genetic significance, and relationship to multiple episodes of mineralization, minerals of these types were examined from three mining districts in Colorado. The three districts include: the Dandy vein system, Idarado mine, Ouray County; the Leadville district, Lake County; and the Wombat mine in the Montezuma district. Complete details and additional references are given in Foord _et al._ (1985, 1988) and Foord and Shawe (in press).

DESCRIPTION OF STUDIED LOCALITIES

Dandy vein system, Idarado mine, Ouray County, Colorado

The Dandy vein system is part of a richly productive group of ore deposits whose northwest-trending and circumferential structures formed about 27.5 m.y. (million years) ago on the northwest side of the Silverton caldera in the western San Juan Mountains (Lipman _et al._ 1976). Sphalerite, galena, chalcopyrite, and pyrite occur with lesser amounts of sulfosalt minerals in replacement ores in the Eocene Telluride Conglomerate, and in northwest-trending and ring-fracture veins that cut the conglomerate ores (Mayor & Fisher 1972). Major gangue minerals in the conglomerate ores are quartz, epidote, chlorite, rhodonite, pyroxmangite, thulite, and carbonates; lesser amounts of sericite and clay minerals are present. Gangue minerals in the veins are similar but also include fluorite. The ores were deposited much later than formation of the structures in which they occur. According to Lipman _et al._ (1976), replacement ore in the Idarado mine was deposited about 17.0 ± 0.6 m.y. (K-Ar age on K-feldspar), whereas sericite from the same material gave an age (K-Ar) of 13.1 ± 0.4 m.y. Late-stage gold-quartz ore in the nearby Camp Bird-Pandora vein system and associated replacement ore were dated as about 10 m.y. (10.5 ± 0.5 m.y., K-Ar age on adularia, and 10.2 ± 0.3 m.y., K-Ar age on fine-grained K-feldspar, respectively) (Lipman _et al_. 1976). A post main ore-stage dike exposed in the Idarado mine gave an age of 11.0 ± 1.2 m.y. (fission-track age on zircon) (Lipman _et al_. 1976).

In the Idarado mine, three N65°W-trending and steeply southwest dipping quartz-sulfide-sulfosalt-oxide veins ranging from 0.3 to 1 m thick, referred to as the Dandy Nos. 1, 2, and 3 veins respectively, intersect as en echelon offshoots of the Basin vein, which is one of the nearly east-west-trending base-metal veins. The Dandy No. 1 and No. 2 veins are about 20 m apart and the No. 2 and No. 3 veins are about 30 m apart along the Basin vein drift. The Basin vein, averaging about 1 m wide, and the Dandy No. 1 and No. 2 veins locally contain specularite and Pb-Bi-Ag-(Cu) sulfosalts as well as the simple sulfides; sulfides and sulfosalts are scattered throughout the veins. The sulfosalts are more common near or in association with galena. The Dandy No. 2 vein seemed to contain less galena and more Pb-Bi-Ag-(Cu) sulfosalts than the Dandy No. 1 vein. No samples were collected from the Dandy No. 3 vein. All samples were collected along the Basin 2900 East Drift of the Idarado Mine by F. S. Fisher (U.S.G.S.) in 1972.

The Leadville district, Lake County, Colorado

The Leadville district is located on the west flank of the Mosquito Range in central Colorado. The ore deposits, which produced mostly silver, zinc, lead, and gold, are principally blanket or manto replacement deposits; however many veins also occur in the eastern part of the district (Tweto, 1968). The age of the primary mineralization is about 34 m.y. (T. B. Thompson, written commun., 1987) and extensive oxidation took place in Miocene time. High-bismuth silver-gold ore (but not bismuth ore per se) was described by Chapman (1941) who identified in it galenobismutite, aikinite, and alaskaite (a mixture), as well as Bi- and Ag-bearing galena [probably containing some exsolved matildite] (Chapman & Stevens 1933). These Bi-bearing minerals are associated with tellurides (e.g. altaite and hessite) and native gold as well as native bismuth and tellurium, and other ore minerals. Chapman (1941) assigned all of these minerals to a paragenetically late "bismuth stage", which followed those of galena, sphalerite and pyrite. Evidence for a distinct late stage of bismuth mineralization is best shown in the Greenback mine, along the Tucson-Maid fault (Chapman 1941).

The Wombat mine, Montezuma district, Colorado

The Montezuma district of central Colorado, located on the Continental Divide, south of Loveland Pass, is a small base-metal and silver mining district containing vein deposits associated with a Tertiary quartz monzonite porphyry stock transecting Precambrian gneisses (Lovering 1935, Botinelly 1979). Ore minerals of the Montezuma district are dominantly galena, sphalerite, pyrite, and tetrahedrite-tennantite, but a large variety of unusual sulfides and Pb-Bi-Ag-(Cu) sulfosalts occurs in the area (Botinelly 1979). On the basis of X-ray powder diffraction data only, Botinelly identified aikinite, matildite, berryite, galenobismutite, pavonite, hammarite, lillianite, and schirmerite from the district. A variety of antimony- and arsenic-bearing sulfosalts also were identified in the district. Minerals identified from X-ray powder diffraction data from the Wombat mine (Theodore Botinelly, pers. comm., 1983) include: pyrite, chalcopyrite, sphalerite, galena, bismuthinite, matildite, pyrargyrite, arsenpolybasite, schirmerite, and galenobismutite. In this study, vein material consisting of 1 to 3 mm veinlets of a gray sulfosalt coated by black sooty acanthite in quartz, collected by R. R. Cobban (Denver Museum of Natural History) from the Wombat mine dump on the south side of Lenawee Mountain, near Soda Spring, was determined to be an Sb-bearing member of the lillianite homologues.

RESULTS

Dandy vein system, Idarado mine, Ouray Co., Colorado

A suite of 12 polished sections from vein ore samples from two en echelon offshoots (known as the Dandy No. 1 and Dandy No. 2 veins) of the Basin vein in the Idarado mine was studied by Mosburg (1972). Minerals recognized by Mosburg are: quartz, chalcopyrite, pyrite, sphalerite, magnetite, hematite, silver- and bismuth-bearing galena, and three unidentified Pb-Bi-Ag-(Cu) sulfosalts. These same polished sections were provided for additional mineralogical study by Frederick S. Fisher of the U.S. Geological Survey. The unidentified sulfosalts occur only as inclusions and intergrowths in the galena where they may also be in contact with other common sulfides. Matildite, β-$AgBiS_2$, exsolved from high-temperature galena, and seven Pb-Bi-Ag-(Cu) sulfosalts, have been identified in this study (Table 1).

Electron-microprobe analyses indicate that the most common previously unidentified sulfosalt is a member of the aikinite-bismuthinite series and is either aikinite or friedrichite. Two samples show friedrichite and three others show compositions intermediate between aikinite and friedrichite. X-ray powder diffraction studies of this mineral by Mosburg (1972) gave a pattern resembling that of pure aikinite but with the lines slightly shifted to lower d-spacings. Her compositional data also indicated compositions between aikinite and friedrichite; friedrichite was not described until 1978, by Chen et al. (1978). Single-crystal X-ray studies will be necessary to determine whether the mineral is a non-stoichiometric aikinite or a non-stoichiometric friedrichite. Electron-microprobe analyses of all seven of the sulfosalts are given in Table 1, and these analyses, along with others, are plotted in terms of atomic percent on Figures 1 and 2.

Mosburg was unable to identify her second sulfosalt, a silver-rich variety and her third sulfosalt of intermediate Cu-Ag content, because of the then imperfect knowledge about the gustavite-lillianite homologous series, and because of lack of sufficiently precise X-ray data.

In this study, only aikinite-friedrichite has been positively identified among Mosburg's three unidentified Pb-Bi-Ag-(Cu) sulfosalts from the Dandy vein system. Other sulfosalts (characterized by electron-microprobe analyses), except for one, are present as grains too small for X-ray diffraction studies. However, based on our current expanded knowledge (Craig 1967, Salanci & Moh 1969, Goodell 1975, Bente 1980, Mariolacos 1979, 1980) of the phase equilibria in the system Pb-Bi-Ag-Cu-S, and on our expanded mineralogical knowledge (Makovicky and Karup-Møller 1977a,b; Makovicky 1981, Karup-Møller & Makovicky 1981, Zak & Prachar 1981), identification of these other six sulfosalts may with some limits be based upon the microprobe compositional data and X-ray powder diffraction data only.

One of the seven sulfosalts, found only in one (8C) of the ten sections examined, is a member of the lillianite-gustavite series with the composition $Gus_{65}Lill_{35}$ (Table 1, Figure 1). The mineral occurs as laths and subhedral grains in galena and aikinite-friedrichite. No exsolution is evident and it is homogeneous in composition. The composition of this and the other sulfosalts and galena from the Dandy vein system are shown in Figures 1 and 2. Similar material was found in one assemblage from Nye County, Nevada examined by Foord et al. (1988).

Another sulfosalt, found in the same section (8C), may be eskimoite(?) or heyrovskyite$_{ss}$(?) (however $N_{chem} = 8.4$)*. The mineral occurs as sparse

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*N_{chem} = A calculated parameter based on the content of Pb and Bi in a sulfosalt of the lillianite homologues, and the number of galena-type layers and bismuthinite-type layers.

euhedral laths in aikinite and galena. The laths are 3-4 micrometers long and 1 micrometer wide. An average composition for the mineral is given in Table 1 and is shown on Figure 1.

The composition of a possible copper analogue of eskimoite(?) or heyrovskyite$_{ss}$(?) is given in Table 1 and plots along the N = 7 line (Figure 1), very nearly on the position of eskimoite (Karup-Møller 1977; calculated $N_{chem} = 7.25$). The mineral was found in one polished section (6D). Silver and bismuth substituted heyrovskyite from Castlegar, B.C. (Karup-Møller & Makovicky 1981) has essentially the same composition as eskimoite from Ivigtut, Greenland (Makovicky & Karup-Møller 1977a,b) and may be considered dimorphous with eskimoite. Some of the Se-rich heyrovskyite from Darwin, Calif. (Czamanske & Hall 1975, Makovicky & Karup-Møller 1984) also has a composition very similar to eskimoite and schirmerite. If this phase is structurally an eskimoite, then it is the Cu-dominant equivalent species and should logically be called cuproeskimoite, analogous to pavonite and cupropavonite.

A mineral with the composition of heyrovskyite$_{ss}$ also plots along the N = 7 line between eskimoite and Ag-free heyrovskyite (Table 1, Fig. 1). The mineral was found in two sections (8C, 8G). Calculated $N_{chem} = 7.62$ and 7.12 respectively. X-ray diffraction studies of material from 8G showed a mixture of a mineral with lines matching heyrovskyite and minor galena.

One polished section (8Q) contains laths hosted by Ag- and Bi-bearing galena which may be either vikingite (N = 5.5) or another member of the lillianite-gustavite homologous series with N = 6, e.g. treasurite series (calculated $N_{chem} = 6.06$). The laths are approximately 2 x 10 micrometers and show no evidence of exsolution.

The Ag- and Bi-bearing galenas (PbS_{ss}) from the Dandy vein system also were examined with the electron-microprobe and average compositions for ten samples are given in Table 2.

The compositions shown in Table 2 are plotted in Figure 1. It can be seen that all samples lie along the PbS-$AgBiS_2$ join. One "galena" from sample 6D which has the composition $Gal_{68}Mat_{32}$ was determined under high magnification to be an intergrowth of Ag- and Bi-bearing galena and matildite.

Leadville district, Lake County, Colorado

A sample of sulfide and sulfosalt-bearing ore labelled "kobellite" from an unspecified mine in the Leadville district, Colorado, and collected prior to about 1930, from the Lazard Cahn collection was provided by Dr. W. W. Pinch (Pinch Mineralogical Museum, Rochester, N.Y.) for study. Based on the known distribution of Bi and Te in the district, and on comparison to Bi-rich ores described by Chapman (1941), the material likely came from one of three areas: Tucson mine, Iron Hill, or the Greenback mine (ore body) which was the source of the 'galena' analyzed by Chapman & Stevens (1933). No kobellite was found. Major minerals present are pyrite, chalcopyrite and Ag- and Bi-bearing galena. Matildite is exsolved from the galena and forms a reticulate network of sub-micron-sized elongate bodies along the octahedral cleavage. Some veinlets of matildite are also present. The galena adjacent to the veinlets is "cleaned up" because of incorporation of Ag and Bi into the matildite.

Additional matildite occurs as rounded inclusions within the galena. Small amounts of hessite, Ag_2Te, and a mineral with the composition $Ag_8SnTe_2S_4$ are present in clot-like myrmekitic aggregates intergrown with galena and exsolved matildite. Individual clots are as much as several hundred micrometers across, but individual grains of hessite and the $Ag_8SnTe_2S_4$ are $\leq$50 micrometers across. This mineral is what has been called "tellurian canfieldite." Optical properties are close to those reported for this mineral (Soeda _et al_. 1984). In polished section, the "tellurian canfieldite" looks like tetrahedrite-tennantite; a smooth gray, isotropic mineral lacking crystal form, twinning or cleavage. In air, some grains show weak reflection pleochroism from gray to yellowish gray. Anisotropy is weak without tint, and there is weak orange internal reflection. Mean reflectances at the four standard wavelengths are: 470nm 29.6%, 546nm 28.6%, 589nm 27.8%, 650nm 26.9%. Because of the paucity and small grain size, X-ray diffraction studies were not possible. "Tellurian canfieldite" is an uncommon mineral and has been reported from only about six world-wide localities (Soeda _et al_. 1984, Wimmers 1985). It has also been found from the A.Y. and Minnie Mine in the Leadville district, Colorado with a mineral assemblage similar to that of the material described here (G. K. Czamanske, U.S.G.S., pers. comm., 1988). Both canfieldite and "tellurian canfieldite" have been found at Panasqueira, Portugal (Wimmers 1985). Extremely sparse amounts of aikinite and two unidentified Cu-Pb-Bi-Ag sulfosalts are present in late-stage crosscutting veinlets. One of the unidentified sulfosalts may be Cu-Bi substituted galena. A structural formula, calculated on the basis of 1 S atom, is: $(Pb_{0.48}Bi^{3+}{}_{0.26}Cu^{1+}{}_{0.24}Ag^{1+}{}_{0.01})_{0.99}S$. Only two grains, each <5 micrometers across were found. Electron microprobe analyses of the hessite, "tellurian canfieldite," galena-matildite intergrowths, aikinite and two unidentified sulfosalts are given in Table 3. Compositions of the aikinite, the galena-matildite intergrowths, and the two unidentified sulfosalts are plotted on Figures 1 and 2.

A structural formula, based on 4 S atoms, for the "tellurian canfieldite" is: $Ag_{7.69}Sn_{0.96}Te_{2.00}S_{4.00}$. Virtually all other reported "tellurian canfieldites" are deficient in Ag (i.e. <8.00) as is the Leadville material. Further studies are in progress to determine if canfieldite and "tellurian canfieldite" are two distinct mineral species.

Wombat mine, Montezuma district, Colorado

Two polished sections prepared of vein quartz containing a lead-gray sulfosalt collected by R. R. Cobban (Denver Musem of Natural History) from the dump of the Wombat mine on Lenawee Mountain contain what appears to be a single-phase, homogeneous mineral whose composition plots on the ourayite series (N = 11) line. The mineral occurs as elongated and flattened prisms as much as 0.5 mm in width and 2 mm in length or as intergrown clumps of crystals as much as 3 mm across made up of interlocking sheaves of individual crystals. The exterior portions of all crystals are coated with aggregates of sooty black acanthite containing minor pyrite and chlorargyrite. The acanthite coating is as much as 30-40 micrometers in thickness. The acanthite also occurs as veins in the ourayite(?) crystals. The composition, in weight percent, of the mineral (average of 10 points) is: Sb 1.8(1), Te 0.1(1), S 16.3(3), Pb 31.5(5), Bi 39.2(6), Ag 11.4(5), total 100.3. A notable feature of this probable ourayite is its content of nearly 2 wt. % Sb. A structural formula, calculated on 104 S atoms is: $Ag_{21.6}(Bi_{38.4}Sb_{3.0})_{41.4}Pb_{31.1}S_{104}$.

Table 1. COMPOSITIONS OF SEVEN SULFOSALTS EXSOLVED AND/OR INCLUDED WITHIN SILVER- AND BISMUTH-BEARING GALENA FROM THE DANDY VEIN SYSTEM, IDARADO MINE, OURAY, COLORADO AS DETERMINED BY ELECTRON MICROPROBE

Sample nos.	8C	8C,8G		6D	8C	6E,6G,6H,8B,8C	80	8Q
mineral	esk(?) or hey	heyrovskyite		Cu-esk or hey	Gus$_{65}$ Lil$_{35}$	aikinite- friedrichite	Fried	N=6 phase (treasurite or eskimoite?)
no. of points	(2)	(5)		(5)	(2)	(10)	(2)	(2)
		(1)	(4)					
Element								
Cu	0.8	0.4	0.3	3.8	0.5	9.4	8.7	0.2
S	16.9	16.3	15.2	16.2	16.7	17.3	17.1	16.2
Pb	31.7	43.2	44.5	31.4	29.6	32.6	31.8	27.8
Bi	41.3	33.3	34.5	44.9	47.5	40.7	42.9	45.9
Ag	9.6	5.8	5.7	4.5	5.9	0.0	0.0	9.7
Te	---	---	0.1	0.1	0.1	---	0.0	0.1
Total	100.3	99.0	100.3	100.9	100.3	100.0	100.5	99.9

Note - Sb, Zn, As, and Fe looked for but not detected. --- not determined. All values given in weight percent.

Table 2. COMPOSITIONS OF GALENA AND GALENA-MATILDITE INTERGROWTHS FROM THE DANDY VEIN SYSTEM, IDARADO MINE, OURAY, COLORADO AS DETERMINED BY ELECTRON MICROPROBE

Sample nos.	6A	6B	6D	6D	6E	6G	6H	8B	8C	80	8Q
mineral	G	G	G+M	G	G	G	G	G	G	G	G
no. of points	(4)	(2)	(2)	(4)	(2)	(2)	(2)	(3)	(2)	(2)	(4)
Element											
Cu	0.1	0.1	0.1	0.0	0.1	0.2	0.0	0.0	0.1	0.0	0.0
Sb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
S	13.6	13.7	14.5	14.2	14.0	14.0	14.0	13.6	14.0	13.9	13.8
Pb	79.6	78.6	63.7	76.9	78.4	80.1	75.9	77.4	81.1	77.0	77.8
Bi	4.4	4.7	14.6	5.6	4.6	3.4	5.9	5.7	2.5	5.4	5.1
Ag	2.4	2.5	7.7	3.0	2.7	2.0	3.1	3.2	1.4	2.9	2.8
Total	100.1	99.6	100.6	99.7	99.8	99.7	98.9	100.0	99.2	99.2	99.5

Note - Zn, As, and Fe looked for but not detected. All values given in weight percent. G = galena, M = matildite.

Table 3. COMPOSITIONS OF GALENA-MATILDITE INTERGROWTHS, HESSITE, "TELLURIAN CANFIELDITE(?)", AIKINITE AND TWO UNIDENTIFIED SULFOSALTS FROM A SAMPLE OF HIGH-GRADE SILVER ORE FROM THE LEADVILLE DISTRICT, LAKE COUNTY, COLORADO AS DETERMINED BY ELECTRON MICROPROBE

Mineral	G+M*	Hessite*	"Te-canfieldite"**	Unk 1*	Unk 2*	Aikinite*
no of. points	(11)	(2)	(5)	(6)	(2)	(4)
	Range					
Element						
Cu	0.0-0.2	0.0	0.0	16.0	7.7	10.6
Sb	0.0-0.1	0.0	0.0	0.0	0.0	0.0
Te	0.0-0.2	36.4	19.3	0.0	0.0	0.0
S	13.8-14.0	0.0	9.7	17.8	16.2	16.7
Pb	69.6-77.0	0.0	0.0	20.1	50.0	35.5
Bi	10.8-5.5	0.0	0.0	39.8	27.5	37.5
Ag	5.6-3.1	64.3	62.8	6.5	0.5	0.2
Sn	---	---	8.6	---	---	---
Total	99.8-100.1	100.7	100.4	100.2	101.9	100.5

Note - * Fe and Zn looked for but not detected. ** Fe, Zn, As, Ge, Se, Hg, Cl and F looked for but not detected. --- not determined. All values given in weight percent. G = galena, M = matildite.

The composition of the ourayite (Our_{73}) is shown on Figure 1. X-ray powder diffraction data for this mineral are close to those given for ourayite. Additional studies are underway to fully characterize this mineral.

In polished section and in air, the mineral is white and shows no reflection pleochroism. Bireflectance is about 3%. Reflectance values for the four standard wavelengths are: 470nm R_1 43.5% R_2 46.1%, 546nm R_1 43.0% R_2 46.0%, 589nm $R_1\Delta$42.5% R_2 45.3%, 650nm $R_1$42.5% R_2 45.0%. Anisotropy is strong and anisotropic colors range from blue-gray to cream-yellow. Under crossed polars what appear to be macroscopic single crystals are seen to be a composite of intergrown crystals.

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FIGURES

1. Ternary plot (atomic) for the system Pb-Bi(Sb)-Ag(Cu) showing compositions of minerals analyzed in this study. Symbols: open circle, 'galena' from Leadville, CO (Chapman & Stevens 1933); solid circles, samples from Dandy vein system; solid square, ourayite from the Wombat mine; X's, range of galena-matildite intergrowths and Cu-Bi galena? from Leadville; open squares, samples from the Jackass mine.

2. Ternary plot (atomic) for the system Pb-Bi-Cu showing compositions of minerals examined in this study. Symbols: solid circles, samples from Dandy vein system; open circle, aikinite from Leadville, CO.

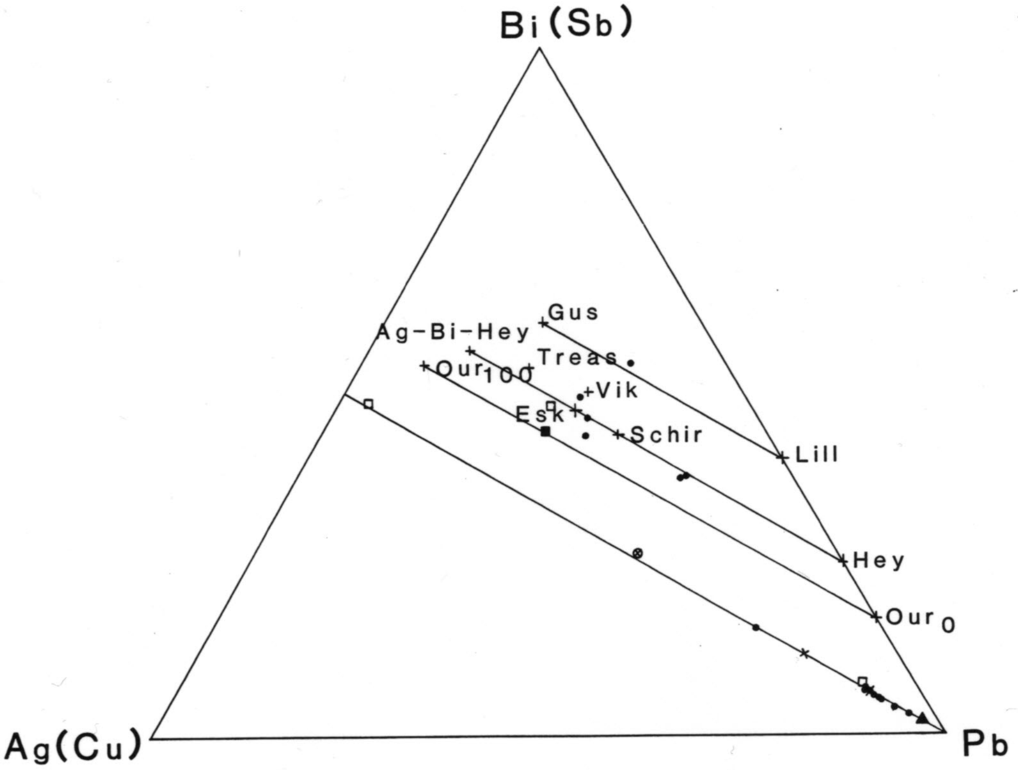

FIGURE 1

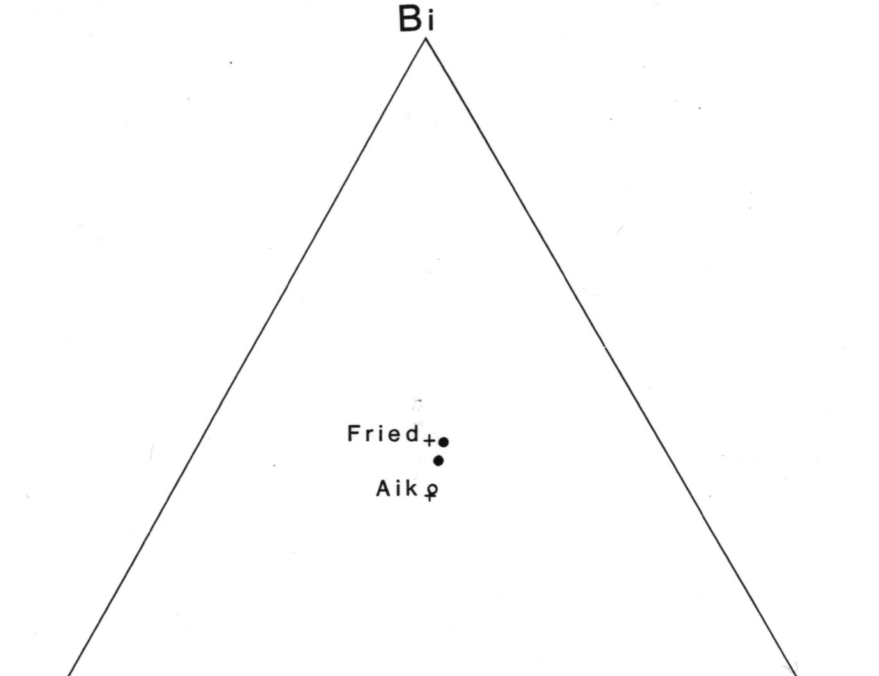

FIGURE 2

THE PETROLOGY OF MIXED TELLURIDE ,SULFOSALT, SULFIDE ORES IN BUCKEYE GULCH, LEADVILLE AREA, COLORADO.

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Introduction

In 1984 a very high-grade, gold- and silver-bearing mineralized zone was discovered in Buckeye Gulch, about 8 kilometers north of Leadville, Colorado. The precious metals are contained in a 0.6m-thick massive sulfide manto within the Leadville Dolomite, which displays an unexpected diversity of telluride minerals. Manto orebodies with generally similar geology are well-known at nearby mining districts at Leadville and Gilman. Although telluride minerals are present at both Leadville and Gilman, they are not common and the number of phases is small. The purpose of this paper is to document the Buckeye Gulch occurrence and to interpret its significance.

Regional Geology

Buckeye Gulch is located on the eastern side of the Sawatch uplift between Leadville and Gilman, Colorado (Fig.1). Cambrian through Mississippian sedimentary rocks in this area have an aggregate stratigraphic thickness of about 200m, and are overlain by 3000+m of coarse clastic Pennsylvanian sedimentary rocks . The sedimentary section is intruded by a number of sills of several lithologies, including Lincoln Porphyry, Pando Porphyry, Sacramento Porphyry and two other unnamed porphyries. Within Buckeye Gulch, the outcrops consist of Lincoln Porphyry and the Minturn Formation: the lower Palaeozoic section includes the Mississippian Leadville Dolomite, which is the principle host for the manto deposits at Gilman, as well as those in the nearby Leadville (Emmons et al., 1927; Tweto, 1968; Thompson et al., 1982), Aspen (Spurr, 1898; Stegen et al., in press), and Tennessee Pass (Beaty et al.,1987) mining districts (Fig. 1).

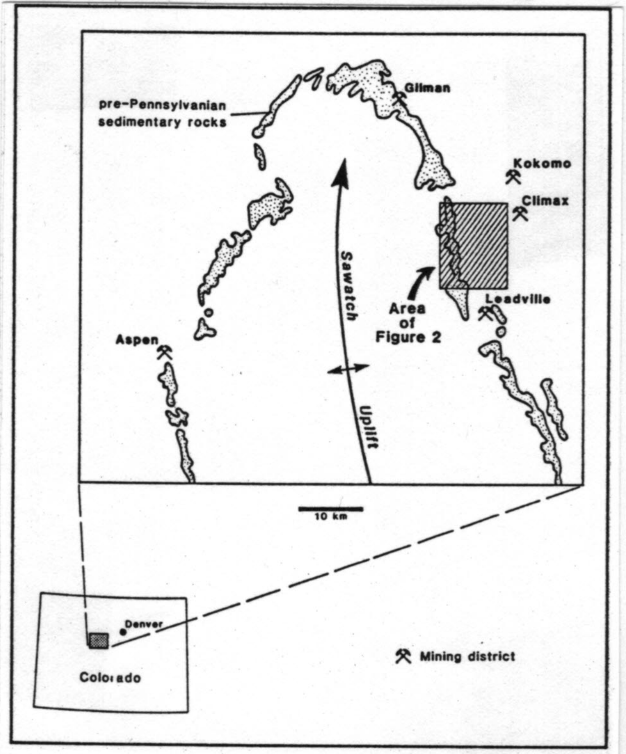

Figure 1. Index map showing the area of the current study.

Local Geology

Within Buckeye Gulch is a zone of hydrothermal alteration and veining (Fig. 2). A number of mineralization effects have been observed in outcrop in the area, including steeply-dipping quartz-pyrite veins (with as much as 698 ppm Ag and 84 ppm Au), small galena- and sphalerite-bearing mantos in the Minturn Formation, argillic and phyllic alteration of porphyry, and gold-rich soils. Erosion of the gold-bearing hydrothermal products has resulted in the accumulation of a gold placer at the mouth of Buckeye Gulch. The outcropping quartz veins have both high $\partial^{18}O$ and contain fluid inclusions with T_h=240-330^{o}C. In the subsurface the alteration increases in grade to phyllic, dolomitic, and sulfidic (including pyrite, galena, sphalerite and (?)acanthite alteration of biotite), and the Minturn Formation becomes progressively recrystallized to hornfels and calc-silicate skarn, dolomite veining increases toward the contact of the Leadville Dolomite. In drill hole BG-4 (-90^{o}, TD = 577m), the Leadville Dolomite is variably recrystallized to dolomite marble and locally replaced by pyrite (up to 95% over 3m), as well as minor amounts of other minerals. Of twelve deep holes in Buckeye Gulch, seven are anomalous in Au or Cu, four are anomalous in Zn, and one is barren. The favored interpretation of the data to date is that Buckeye Gulch represents a Leadville-type system, but with a different bulk composition (Au-rich, Zn-poor).

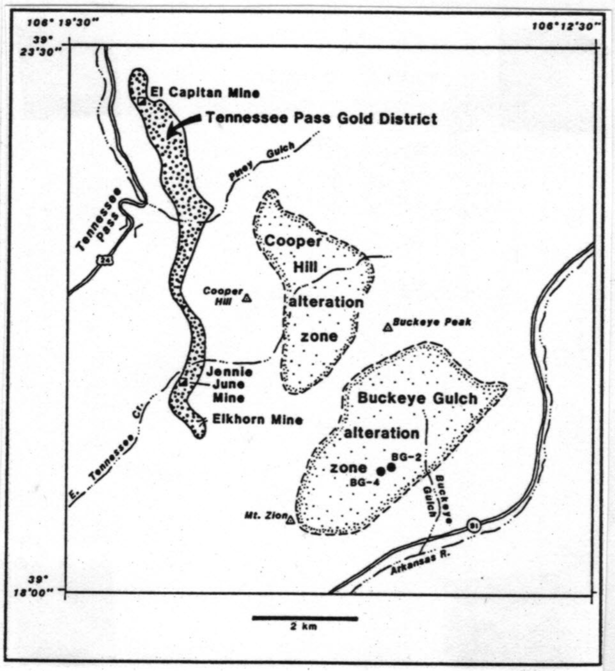

Figure 2. Map showing area of significant mineralization and locations of drill holes BG-2 and BG-4. Geology taken from Beaty et al., 1987.

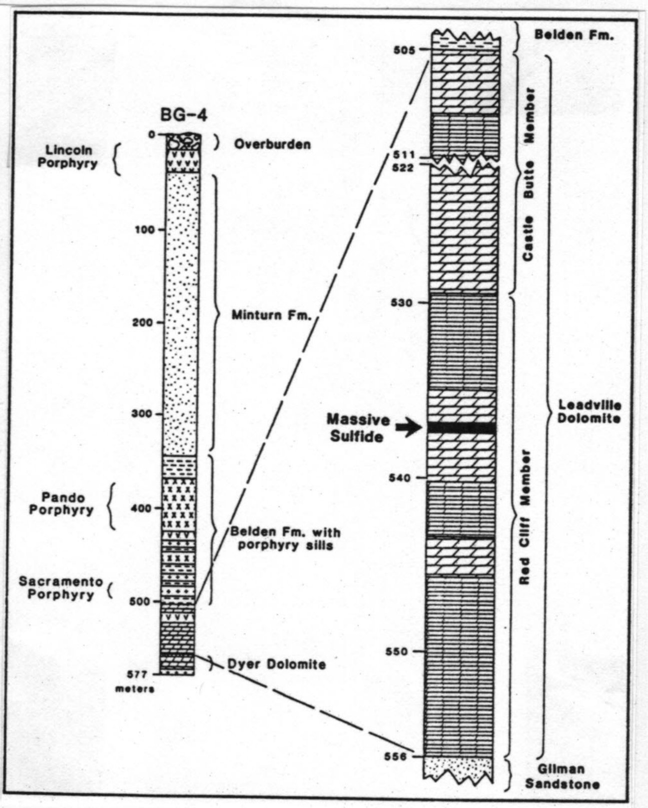

Figure 3. Graphic log of drill-hole BG-4 . Telluride-bearing samples discussed in the text taken from the massive sulfide zone at 537.2m to 537.8 m depth. A quartz-monzonite sill present from 511-522m has been removed from the right-hand column for clarity. Symbols in the expanded Leadville Dolomite section indicate coarse- and fine-grained lithologies.

Mineralogy and Ore Textures

Four polished thin-sections of massive pyrite ore from drill holes BG-2 and BG-4 (Fig. 2) were studied in detail. In both drill holes the mineralized material consists of massive, coarse-grained, subhedral to euhedral pyrite in a matrix of coarsely crystalline white dolomite. The dolomite is in part recrystallized to finer-grained carbonate. In thin-section, the pyrite appears unzoned, is mildly fractured and brecciated, and shows only minor rotation of the fragments. Fractures are filled by dolomite. Trace amounts of clinozoisite occur scattered throughout the carbonate and tend to be concentrated along pyrite margins. The manto mineralization effects from the two drill holes are broadly similar but different in detail. The assemblage in drill hole BG-2 consists of pyrite with bornite and pyrrhotite inclusions, with late sphalerite and tetrahedrite-tennantite infilling along grain boundaries. The assemblage in drill-hole BG-4 consists of massive pyrite with a complex assemblage of Au-Ag-Pb-Hg tellurides, and minor base metal sulfides.

Pyrite-Bornite-Pyrrhotite Assemblage: Traces of bornite and rare pyrrhotite occur as small ovoid inclusions 10-50 µm in diameter sporadically distributed throughout the pyrite. Sphalerite occurs as patches along grain boundaries and fracture veinlet infillings with subordinate amounts of tetrahedrite-tennanite. The latter phases postdate the pyrite-bornite-pyrrhotite mineralization.

Pyrite-Au-Ag-Pb-Hg Telluride Assemblage: This assemblage occurs for the most part as minute 1-10 µm inclusions in pyrite. The inclusions often occur in trains and as linear arrays (Fig. 4) but random isolated inclusions are also present. The latter are generally larger, 10-50 µm, and rare inclusions reach 250 µm diameter. The inclusion arrays are generally confined to the cores of pyrite but in some instances appear to cross pyrite grain boundaries. The arrays often exhibit rhombic outlines, suggesting that they may be relict after a pre-existing mineral structure, possibly a carbonate (Fig. 4). Fractures in pyrite are occasionally infilled by tellurides and other sulfides particularly where the fracture transects concentrations of telluride inclusions. Telluride inclusions may be offset but are unbroken by throughgoing fractures (Fig.5, 6). The above textures suggest that the tellurides predate brecciation and possibly also pyrite growth and that pyrite may have replaced earlier carbonates with tellurides on grain surfaces and cleavages.

The following telluride minerals have been identified as inclusions in pyrite:- altaite, PbTe; hessite, Ag_2Te; stuetzite, $Ag_{5-x}Te_3$; native tellurium, Te; petzite, Ag_3AuTe_2; sylvanite, $AuAgTe_4$; kostovite, $AuCuTe_4$; coloradoite, HgTe; rickardite Cu_3Te_2; (?)weissite, Cu_2Te; as well as an unknown silver telluride (Fig. 7) whose composition is close to $(Ag,Fe)Te_3$ with a Ag:Fe ratio of between 8 and 11. Representative microprobe analyses of the various telluride minerals are given in Tables 1-3. Associated sulfides and sulfosalts are chalcopyrite, rare sphalerite, tetrahedrite-tennanite, and covellite, but these occur in very subordinate quantities.

Single phase inclusions of altaite, hessite/stuetzite, and subordinate chalcopyrite predominate (fig. 4). Only the larger inclusions are polyphase (Figs. 5, 6, 7) and in these, contacts between phases are usually sharp, suggesting that the phases form equilibrium assemblages. Rarely contacts between altaite and hessite are embayed (Fig. 5). Irregular replacement boundaries between chalcopyrite and rickardite, chalcopyrite and (?)weissite, and between tetrahedrite-tennanite solid solution and covellite are the rule. The following coexisting assemblages have been noted:-

native tellurium-hessite-sylvanite-kostovite
hessite-petzite-altaite-coloradoite-chalcopyrite
petzite-sylvanite
altaite-unknown Ag-Fe telluride-petzite
altaite-stuetzite
altaite-hessite
altaite-stuetzite-petzite
chalcopyrite-rickardite-tellurium-stueztite
chalcopyrite-(?)weissite
chalcopyrite-bornite-altaite
tetrahedrite-tennantite solid solution-covellite.

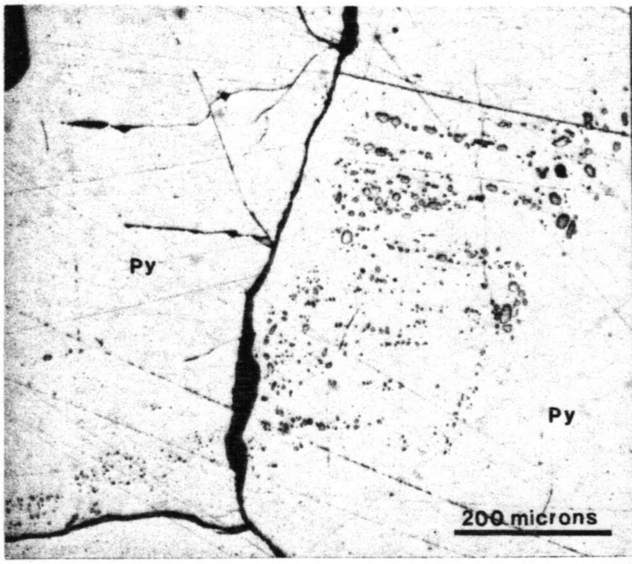

Figure 4. Crudely rhombic array of altaite (light grey) and stuetzite /hessite (darker grey) inclusions in pyrite (Py). Note inclusion train apparently crossing grain boundary. Inclusions range from <1μm to 25μm in diameter. Sample BG-4, 537.7m, plane-polarised light.

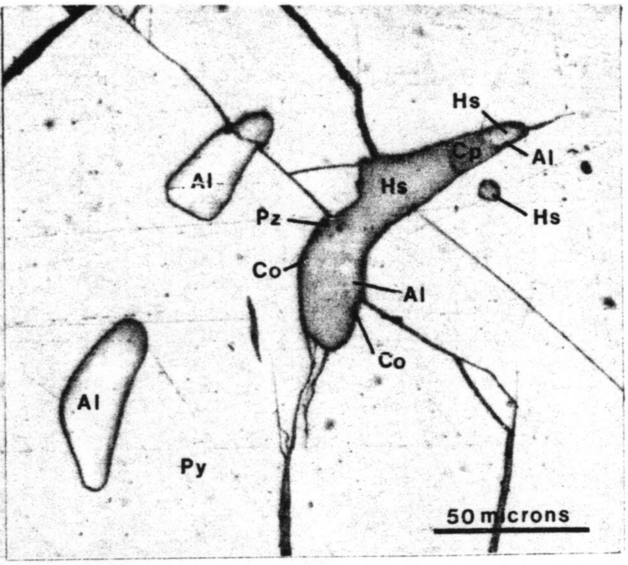

Figure 5. Fractures in pyrite (Py) offsetting single-phase and polyphase telluride inclusions. Large inclusion consists of hessite (Hs), altaite (Al), petzite (Pz), coloradoite (Co) and chalcopyrite (Cp). Sample BG-4, 537.7m, plane-polarised light.

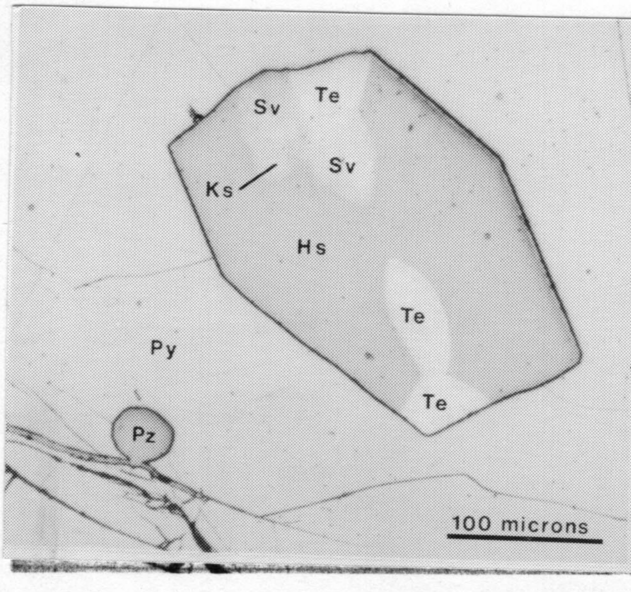

Figure 6. Large polyphase inclusion in pyrite (Py) consisting of native tellurium (Te), hessite (Hs), sylvanite (Sv) and kostovite (Ks). Both sylvanite and kostovite show twinning but less so in the latter. Smaller round inclusion and associated fracture filling is petzite (Pz). Sample BG-4, 537.7m, plane-polarised light.

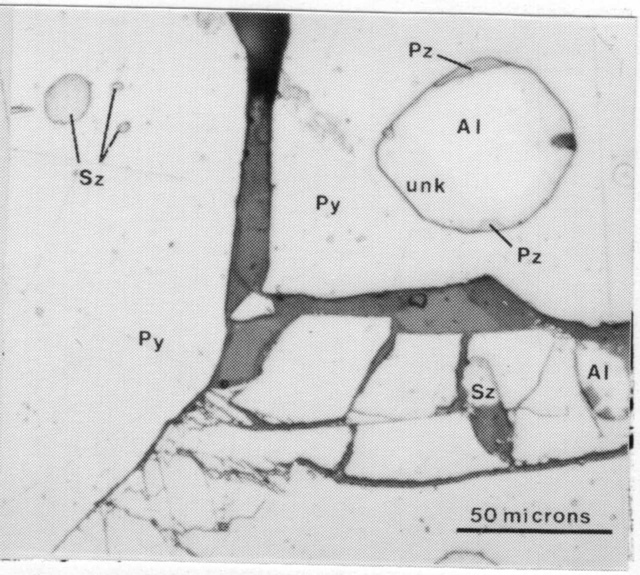

Figure 7. Isolated inclusions of altaite (Al) and stuetzite (Sz) in pyrite (Py). Rim around large altaite inclusion is pale-yellow unknown silver -iron telluride. (unk). Small darker areas are petzite (Pz). Sample BG-4, 537.7m, plane-polarised light.

Table 1. Hessite, stuetzite, altaite analyses from BG-4, 537.7m. Microprobe standards:- synthetic calaverite, Au; synthetic hessite, Ag, Te; synthetic altaite, Pb; synthetic freibergite, Cu, Fe, Sb, S.

Element	1	2	3	4	5	6	7	8	9	10	11
Au	---	---	0.02	0.16	---	---	---	0.02	---	0.07	---
Ag	62.59	60.73	60.57	57.11	58.15	57.81	57.54	0.29	---	0.13	---
Pb	---	0.08	---	0.03	---	---	---	63.97	61.30	61.26	61.31
Cu	---	---	0.08	0.10	---	---	---	0.09	---	0.15	---
Fe	---	---	3.13	0.64	---	---	---	0.37	---	1.10	0.92
Te	37.93	37.92	36.29	42.08	41.48	41.20	43.47	35.20	37.97	37.09	37.95
Sb	---	---	---	0.36	0.32	0.32	---	0.29	---	---	0.23
S	---	0.07	0.28	---	---	---	0.28	0.05	---	---	---
Totals	100.52	98.80	100.37	100.48	99.95	99.33	101.29	100.28	99.27	99.80	100.43

1-3, hessite; 4-7, stuetzite; 8-11, altaite.

Table 2. Sylvanite, kostovite,petzite native tellurium analyses from BG-4, 537.7m. Microprobe standards: synthetic calaverite, Au; synthetic hessite, Ag, Te; synthetic altaite, Pb; synthetic freibergite, Cu, Fe, Sb, S.

Element	1	2	3	4	5	6	7	8
Au	24.12	24.46	24.24	25.16	25.63	25.45	25.02	---
Ag	10.59	10.15	10.19	12.45	4.40	41.10	40.95	0.01
Cu	1.57	1.61	1.77	1.64	6.00	---	0.11	0.02
Pb	---	---	---	---	0.12	---	---	---
Fe	---	---	---	0.07	---	0.29	1.74	---
Te	62.44	60.66	64.57	60.62	63.34	32.29	31.70	98.98
Sb	0.48	0.45	0.54	0.47	0.59	0.26	0.29	0.71
S	---	---	---	0.03	0.03	---	0.06	0.13
Totals	99.20	97.31	101.31	100.44	100.12	99.39	99.88	99.85

1-4, Sylvanite; 5, Ag-Kostovite; 6-7, Petzite; 8, Native Tellurium.

Table 3. Analyses of unknown silver telluride from BG-4, 537.7m. Microprobe standards: synthetic freibergite, Ag, Cu, Fe, Sb, S; synthetic altaite, Pb; native tellurium, Te. Some Pb and Fe may be due to contamination by adjacent altaite and/or pyrite.

Element	1	2	3	4	5	6	7
Ag	20.34	20.55	20.37	20.36	20.60	19.18	20.07
Cu	---	---	---	0.04	0.03	0.09	0.02
Pb	---	---	1.44	1.56	---	1.19	1.21
Fe	1.31	1.09	1.08	1.50	1.36	1.57	3.17
Te	81.49	80.99	79.84	78.82	79.20	78.64	79.40
Sb	0.01	0.22	0.01	0.05	0.17	---	0.33
S	---	0.29	---	---	0.20	0.24	0.04
Totals	103.15	103.14	102.74	102.33	101.56	100.91	104.24

Bulk Geochemistry

The massive pyrite rock in drill-hole BG-4 was analyzed for 15 elements (Table 4). As expected, based on the mineralogy, the sample is rich in Te, Au, Ag, Pb, Cu, and As. Similar massive pyrite rocks are present in nearby drill-hole BG-2, and in several places in the Gilman and Leadville districts. To help interpret the rich intersection in drill-hole BG-4, a group of these pyrite rocks was analyzed for the same suite of elements. These data show some points of similarity, but also some significant differences. The Buckeye Gulch samples are richer in Au, Cu, Sb, Hg, Te, and Co and deficient in Pb, Bi, and Zn in comparison to their counterparts at Leadville and Gilman.

Table 4. Geochemistry of massive pyrite rocks, Leadville-Gilman area.

	Cu	Pb	Zn	Ag	Ni	Mo	Co	Mn	Cd	Bi	As	Te	Sb	Au	Hg
	ppm													ppb	
Leadville District															
#3 O.B., Black Cloud	12	880	36	17	<2	16	<1	33	<0.2	20	715	2	<2	710	160
Robert E. Lee Mine	36	1,330	675	426	<2	6	1	131	4.1	82	1500	24	29	250	7,100
Robert Emmet Mine	59	8,700	>20,000	121	<2	2	1	62	168	< 1	192	2.4	4	15	410
Moyer Mine	22	1,780	3,020	107	<2	3	<1	245	9.2	<1	1,900	12	<2	865	65
Buckeye Gulch Area															
BG-2 556.7-558.2m	18,500	1,200	1,400	104	<2	6	39	540	3.9	<1	2,500	880	215	1,740	20,000
BG-2 553.4-554.9m	4,300	2,400	300	106	11	3	35	114	1.0	<1	1,400	1500	85	2,940	70,000
BG-2 551.8-553.4m	1,200	1,400	400	169	3	5	3	49	0.7	<1	1,700	1020	79	2, 300	50,000
BG-4 537.2-537.8m	166	660	84	744	<2	7	2	465	2.8	2	485	580	<2	96,000	1,050
Gilman District															
NCI, No. 1 Manto	840	15,000	3,850	76	<2	2	<1	18,800	12	14	9,200	<0.2	16	160	260
27 Level, Coarse Pyrite	145	3,380	450	573	<2	1	2	30	1.5	238	480	300	<2	3,830	35

Discussion

The massive pyrite manto samples from drill-hole BG-4 show an unusually diverse suite of telluride minerals. Tellurides have been observed in parts of the Gilman and Leadville districts but only a small number of phases have been reported. Hessite and petzite are present as inclusions in galena in the chimney ores of Gilman and rich pockets of hessite and sylvanite are present in ores from the Sawatch Quartzite (Lovering et al., 1978). Altaite and hessite have been reported from parts of the Leadville district (Emmons et al., 1927). Stuetzite and empressite have been reported from the Empress Josephine mine in the Georgetown district (Thompson et al., 1951; Honea, 1964; Stumpfl and Rucklidge,1968; Stumpfl, 1970), and Kelly and Goddard (1969) report an extensive suite from Boulder County. However the diversity of the assemblage from drill-hole BG-4 appears to be unique.

Discrete tellurides have not been recorded in the samples investigated from drill hole BG-2 Apparently they have been replaced by a bornite-rich inclusion assemblage. This suggests the possibility that sulfur fugacities may been too high to stabilise tellurides except at improbably high tellurium fugacities (Afifi et al., 1988) or that f_{Te_2} was very low; relatively lower sulfur fugacities must have prevailed in the BG-4 ores. It is speculated that the high tellurium values noted in the bulk analyses of the BG-2 samples are due to tellurium substitution in other phases.

The assemblage native tellurium-sylvanite-hessite/stuetzite may be used as a geothermometer (Cabri, 1965; Kracek et al., 1966). The silver content in sylvanite of the above assemblage in BG-4 varies from 10.15-12.15 wt.% Ag indicating temperatures of formation from 325°C down to 250°C. These temperatures appear to be in good agreement with fluid inclusion temperatures reported by Beaty et al., (1987) for the Buckeye Gulch area.

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HYDROTHERMAL ADULARIA IN THE BODIE MINING DISTRICT, MONO COUNTY, CALIFORNIA--MODE OF OCCURRENCE, STRUCTURE AND CHEMISTRY

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ABSTRACT

Adularia occurs in gold- and silver-bearing quartz veins and in hydrothermally altered dacite host rocks of late Miocene age at the Bodie mining district, Mono County, California. Chemical analyses of vein adularia indicate a composition of 95 percent $KAlSi_3O_8$. Optical, physical, and X-ray crystallographic properties of the adularia are consistent with those of high sanidine. The adularia formed late in the history of the Bodie Hills volcanic field, during a period of intense potassium-silicate hydrothermal alteration and gold-silver mineralization and is characteristically best developed in the zone of gold mineralization. Because replacement of the intermediate host rocks by adularia approached completion, their Rb and Sr content and K/Rb ratio converge with values for the constituent adularia. Chemical and isotopic analyses of the adularia and associated vein minerals, quartz and calcite, were instrumental in determining the age and physico-chemical conditions present during the process of mineralization.

INTRODUCTION

Potassium feldspar is a product of potassium-silicate alteration in two distinctive environments: hydrothermally altered epizonal plutons of intermediate composition such as in porphyry copper deposits, and in hot-springs and epithermal ore deposits (Meyer and Hemley, 1967). In the former environment the feldspar is orthoclase or microcline; in epithermal mineral deposits and hot springs, potassium feldspar is typically referred to as adularia. Adularia is the dominant feldspar in hot-spring systems having a high potassium content and temperatures of 150°-250°C (Ellis, 1967). Adularia also occurs as a primary gangue mineral associated with quartz and calcite and in precious- and base-metal-bearing veins or as an alteration product in their wall rocks where it may be associated with sericite and quartz (Meyer and Hemley, 1967). Under conditions of intense potassium metasomatism, adularia may nearly completely replace the wall rock.

Adularia is a major gangue mineral in the gold- and silver-bearing quartz veins and is a common constituent of hydrothermally altered dacitic volcanic rocks of Miocene age in the Bodie mining district, Mono County, California (Fig. 1). K-Ar isotopic analyses of adularia have been useful in determining the age and duration of hydrothermal activity and mineralization (Silberman and others, 1972) and chemical and stable isotope analyses of adularia and associated calcite and quartz have provided data on the temperature and chemistry of the ore-forming fluids (O'Neil and others, 1973; and Koski and others, 1978).

HISTORY

William S. Bodey, originally from Poughkeepsie, New York, discovered placer gold at Bodie in 1859. He died that winter in a severe snow storm. The mining district was organized in July 1860, and in 1861 serious mining began. It was not until the late 1870's and early 1880's that lode production peaked. Activity declined after the early 1880's, but a resurgence in the 1890's and early 1900's was precipitated by two important technological advances. The first was development of the cyanide process of ore treatment, actually pioneered at Bodie. This greatly increased the efficiency of extraction of gold from the ore, and allowed working of the tailings, which were considerable, and had plenty of gold left in them. The second advance was the introduction of electricity. Bodie was the first mining district in the country to be electrified. Electrification greatly reduced the cost of pumping water out of the mines (Billeb, 1968).

The town site has many preserved historic buildings (which are highly photogenic) from various periods in Bodie's history. The California State Parks Department now controls the area as the Bodie State Historic Park. Before that, the Cain family, which owned most of the district, kept a watchman on the property in later years, to guard against vandalism, which has destroyed so much of the historical mining heritage of the west. The family donated the townsite to the State Park System in the late 1960's.

Mining actually continued to 1955 at a much reduced scale, when all activity ceased. The open cuts on Standard Hill were worked in the late 1930's. In the late 1960's and 1970's several companies, including ASARCO, Phelps-Dodge, and Homestake optioned the district for evaluation of future production. Galactic Resources at present holds most of the district.

GEOLOGIC SETTING

The Bodie mining district is located along the east margin of a complex field of Tertiary volcanic rocks (Fig. 1) in the southern part of the Bodie Hills (Chesterman, 1968; Silberman and others, 1972; Kleinhampl and others, 1975; Silberman, 1985). The district is underlain by a sequence of porphyritic biotite-hornblende dacite lava flows and tuff breccias named the Silver Hill Volcanic Series by Chesterman (1968). This sequence is intruded and domed by small dacite plugs, the largest of which underlies Bodie Bluff (Fig. 2).

The dominant structural element in the district is an irregular, faulted, north-trending anticline intruded by several small plugs. Two prominent sets of steeply dipping faults, one striking north to north-northeast, and a second normal to it, cut all units including the intrusive bodies. The major ore-bearing veins and fractures strike northeast, parallel to one of the major fault sets. Tuff breccia within a small graben on Bodie Bluff has been downdropped along northeast-striking faults against intrusive dacite. Faulting probably occurred during and shortly after intrusion of the dacite, and ore deposition was partly controlled by the graben structure and commenced shortly after intrusion of the plugs. The major productive mines are located within and near the graben. The district is credited with production of more than $30 million worth of gold and silver (Chesterman and others, 1986) from 1.5 million ounces of Au, and 7.3 million ounces of Ag (Buchanan, 1981).

MODE OF OCCURRENCE OF ADULARIA

Adularia has two distinct modes of occurrence in the district: (1) as a constituent gangue mineral of gold- and silver-bearing quartz veins, and (2) as a groundmass mineral in the hydrothermally altered dacite wall rock, adjacent to the veins and widely distributed in the upper 600 feet of the district within the zone of major production.

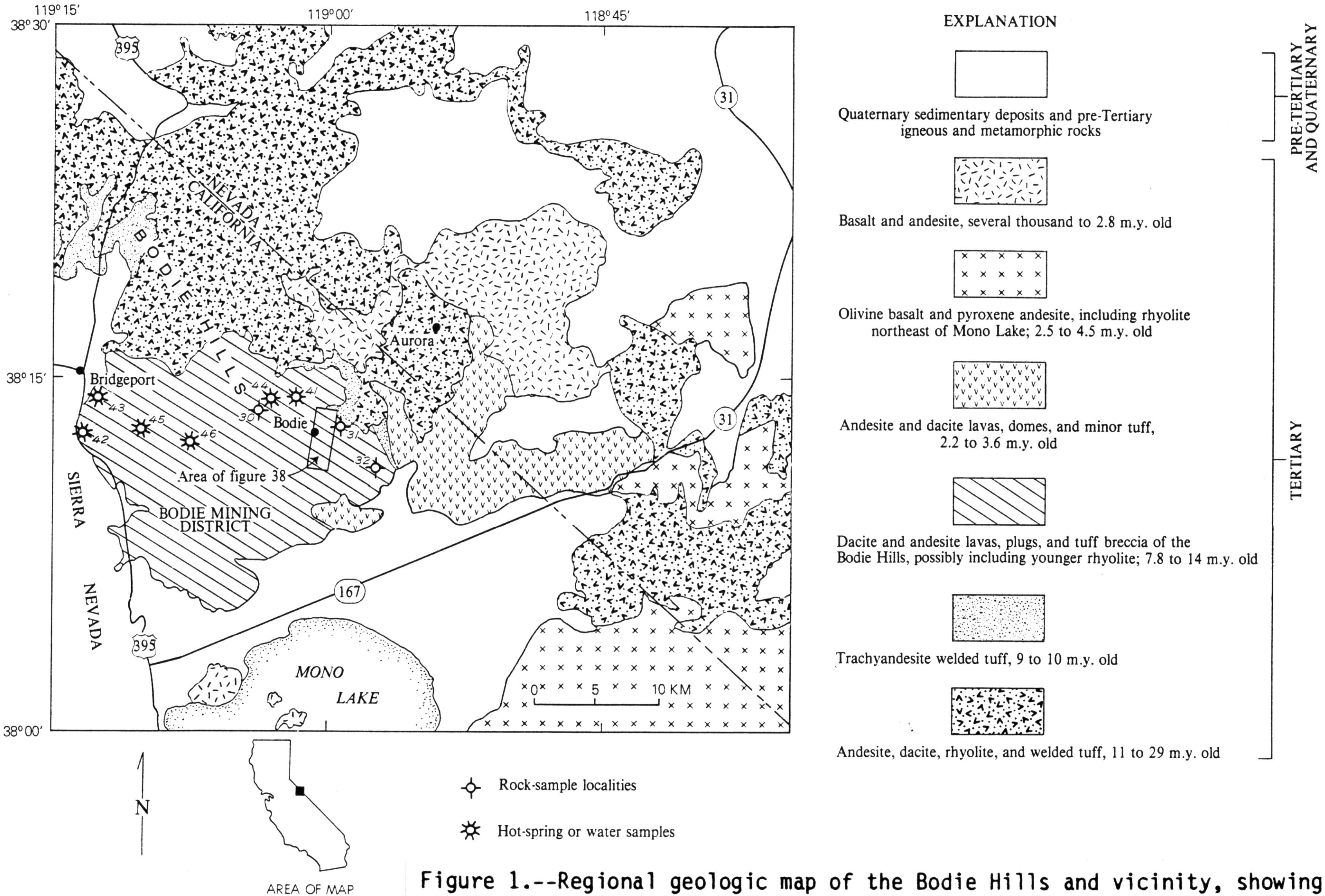

Figure 1.--Regional geologic map of the Bodie Hills and vicinity, showing age and dominant composition of the Tertiary volcanic rocks (modified from Silberman and others, 1972).

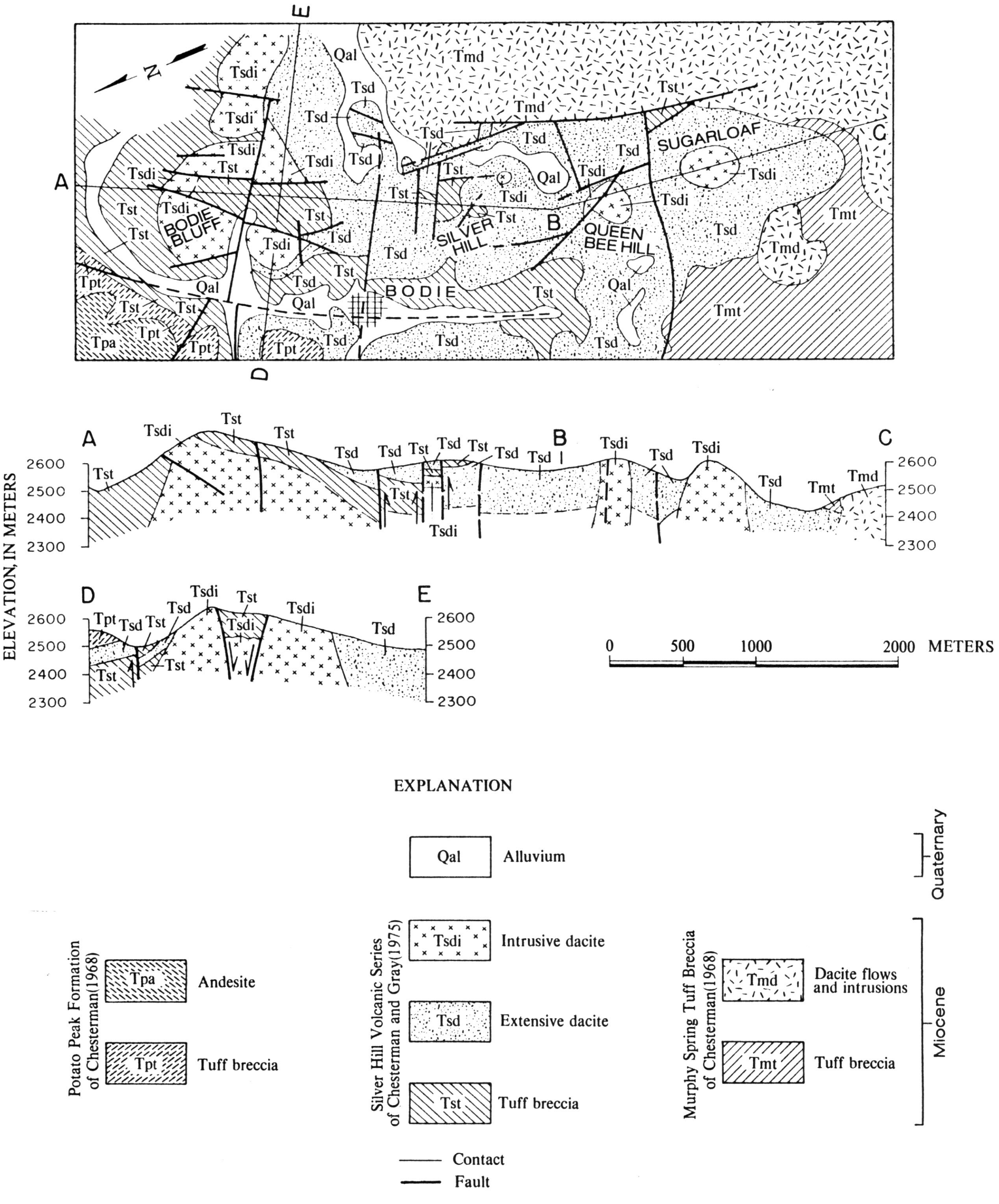

Figure 2.--Generalized geologic map and sections of the Bodie mining district, Mono County, California (Modified from Silberman and others, 1972).

The vein adularia occurs in subordinate to major amounts intergrown with quartz and calcite. Some of the adularia occurs as euhedral crystals completely enclosed within quartz, but the bulk of it occurs as drusy cavity linings or bands within the quartz veins, which in turn cut altered dacite wall rocks. In the former two instances the adularia crystals average about 1 cm across, although some free-growing crystals exceed 2 cm in the maximum dimension (Plate 1). The adularia in cavity linings is white to cream in color and exhibits well-developed crystal faces where the crystals project into the cavity. Late-forming fine-grained quartz and calcite occur locally as coatings on the adularia crystals. The adularia which occurs as bands in the quartz veins is fine grained and generally shows no crystal form. Chemical analyses of veins indicates that adularia can form as much as 63% of the vein material (O'Neil and others, 1973). Ore minerals associated with adularia-quartz veins are native gold and silver, argentite, pyrite, sphalerite, galena, stephanite, and tetrahedrite.

The adularia-quartz veins in the Bodie Bluff area (Fig. 2 and Photo Plate 2) are generally well-defined bodies exhibiting sharp contacts with their enclosing wall rocks. However, in the center of the district, southeast of Silver Hill (Fig. 2), veins consist of silicified and brecciated rock and grade imperceptibly over a distance of several meters into altered wall rocks. The adularia in the latter environment does not exhibit crystal form but occurs as clear, glassy grains, rarely more than 2 mm across, in a granular aggregate with fine-grained white quartz and coarse-grained white calcite occurring with sulfides in the matrix of the breccia and disseminated in the clasts.

The groundmass adularia is extensively developed in dacitic wall rock at Bodie Bluff. The adularia in this environment is usually fine grained, glassy, and white, and shows no crystal form. Its distribution in the dacite is irregular, but concentrations of up to 20 percent in the rock occur locally adjacent to quartz veins.

The two adularias studied in this report were separated from vein samples. B-270 (Plate 1) is coarse-grained adularia from a vein at Bodie Bluff; RC-D1B is fine-grained adularia obtained from vein or breccia matrix material near Silver Hill in the central part of the district. Descriptions of the veins in these different parts of the district have been given previously (O'Neil and others, 1973; Silberman and Berger, 1985; Chesterman and others, 1986).

PHYSICAL AND OPTICAL PROPERTIES

Some physical, optical, and X-ray structural data for the Bodie adularias were summarized by Cerny and Chapman (1986). More complete data are given here. Adularia from cavity linings in veins generally consists of elongated prismatic crystals of pseudo-orthorhombic habit (Plate 1). The feldspar breaks easily along {001} and has less prominent cleavages along {010} and {110}. Well-formed adularia crystals commonly exhibit the following forms: {110}, $\{10\bar{1}\}$, {001}. Vein adularia has a hardness of 6 on the Mohs scale and a specific gravity of 2.559 measured on a Berman balance.

Optical properties were determined for adularia cleavage fragments from sample B-270 using calibrated immersion oils. The optically homogeneous adularia gave the following indices of refraction: $\alpha = 1.517$, $\beta = 1.518$, and $\gamma = 1.522$. Measurements are within ±0.002 measured in sodium light. The birefringence is 0.005; the optic axial angle, $2V\alpha=64°$, measured by universal stage; the extinction angle, $\alpha:X=6°-12°$; and the O.A.P. $\perp$(010). The optical properties for B-270, particularly the low values for indices of refraction, are characteristic of potassium-rich monoclinic alkali feldspar (Deer and others, 1963). Adularia from sample RC-DIB is extremely fine grained, and is intergrown with quartz and coarse-grained calcite. Its optical properties were not determined.

STRUCTURAL STATE

Adularia samples B-270 and RC-D1B were analyzed by X-ray diffraction to determine structural state and unit-cell parameters. Powdered samples were mixed with reagent-grade LiF to provide an internal standard and placed in aluminum sample cells. The samples were scanned between 10° and 65° 2θ on a diffractometer using copper Kα radiation and a scintillation detector. Goniometer speed (1/4° 2θ per minute) and chart speed (1/4 in. per minute) were combined to produce diffraction patterns in which 1 inch = 1°2θ. Adularia and LiF peak centers were located with a comparator near peak tops, and absolute 2θ values for LiF were calculated for $CuK\alpha_1$ (λ = 1.54051Å) radiation.

The structural state of any alkali feldspar polymorph is largely a function of Al-Si distribution among tetrahedral lattice positions. The degree of Al-Si ordering can be approximately determined from X-ray diffraction data using the three-peak method of Wright (1968). In the three-peak method, 2θ values for the $\bar{2}04$ and 060 reflections of alkali feldspars are plotted against one another and compared directly with established trends representing synthetic alkali feldspar solid-solution series (Fig. 3). Furthermore, feldspars with anomalous unit-cell dimensions are predicted if measured 2θ values for $\bar{2}01$ disagree with $\bar{2}01$ values contoured on the $\bar{2}04$-060 plot.

Values for the adularias from Bodie are plotted on the $\bar{2}04$-060 diagram shown in Figure 3. For comparison, a vein adularia from Switzerland (Spencer B) and a synthetic sanidine (SynSanShaw) are also plotted. It is apparent from Figure 3 that Bodie adularias have the highly disordered monoclinic structural configuration usually associated with high sanidine. Both adularia samples of this study have $\bar{2}01$ values of 20.99° 2θ, suggesting unit-cell dimensions that are slightly anomalous. The highly disordered structural state of Bodie adularia, in contrast to the Spencer B adularia (Fig. 3), probably reflects more rapid cooling during and after crystallization of the Bodie feldspar. The unit cell dimensions suggest a higher proportion of the Ab component (about 30 mol. percent) from Fig. 4A of Kroll and Ribbe (1983) than that indicated by chemical analysis (4.7 mol. percent, Table 2).

Unit-cell parameters for Bodie adularias (Table 1) were calculated by least-squares refinement of X-ray diffraction data using a computer program by Appleman and Evans (1973). Initial unit-cell parameters for the refinement were those given for sanidine in Borg and Smith (1969, Table 34).

Unit-cell parameters for two other alkali feldspars are included in Table 1 for comparison with the adularias from Bodie. Cell dimensions for B-270 and RC-D1B are similar to those of synthetic sanidine but are distinctly different from those of Spencer B adularia. This tends to confirm the high structural state of hydrothermal adularia of the Bodie type and suggests that adularia may have a wide range in triclinicity depending on the thermal history of the mineral. Adularia from a large number of Tertiary and Mesozoic fissure vein Au-Ag deposits in the Great Basin exhibit structural states that vary between high sanidine and intermediate microcline (M. L. Silberman, unpub. data, 1978). Only a few of these exhibit the high sanidine structural state, a conclusion also reached by Cerny and Chapman (1986) in their study of adularias from a variety of other deposits.

Table 1. Unit-cell parameters for adularia from Bodie and other alkali feldspars

[Standard errors in brackets refer to last decimal place]

Unit-cell parameter	B-270	RC-D1B	SynSanShaw[1]	Spencer B[2]
a (Å)	8.591(1)	8.590(1)	8.606(2)	8.554(1)
b (Å)	13.008(1)	13.008(2)	13.018(2)	12.970(2)
c (Å)	7.170(1)	7.177(1)	7.172(1)	7.207(1)
α	90°	90°	90°	90°
β	116°03.3(5)'	116°03.4(8)	116°02.6(8)'	116°00.4(6)'
γ	90°	90°	90°	90°
Volume ($Å^3$)	719.86(9)	720.49(15)	721.86(16)	718.65(13)

[1] Sanidine, Or=100, synthesized by Shaw (1963); X-ray data from Wright and Stewart (1968).

[2] Adularia from St. Gothard, Switzerland; 3-inch crystal described by Spencer (1937); X-ray data from Wright and Stewart (1968).

Table 2. Major element composition of adularia sample B-270

Oxide[1]	Weight percent
SiO_2	65.82
Al_2O_3	17.65
Fe_2O_3	.00
MgO	.00
CaO	.03
Na_2O	.56
K_2O	15.54
$H_2O\pm$	.06
TiO_2	.01
P_2O_5	.006
MnO	.00
Total	99.68
Weight percent of compounds:[2]	
Or	91.8
Ab	4.7
An	.05
Qz	3.4 (by difference)

[1] X-ray fluorescence analysis, analyst: B.P. Fabbi

[2] A structural formula calculated on the basis of 8 oxygens is:
$(K_{0.92}Na_{0.05}Ca_{0.002})_{\Sigma 0.972}\ Al_{0.96}\ Si_{3.04}\ O_8$.

If adjusted for 3.4 weight percent quartz:
$(K_{0.95}Na_{0.05})_{\Sigma 1.00}\ Al_{1.00}\ Si_{3.00}\ O_8$ (Cerny and chapman, 1986)

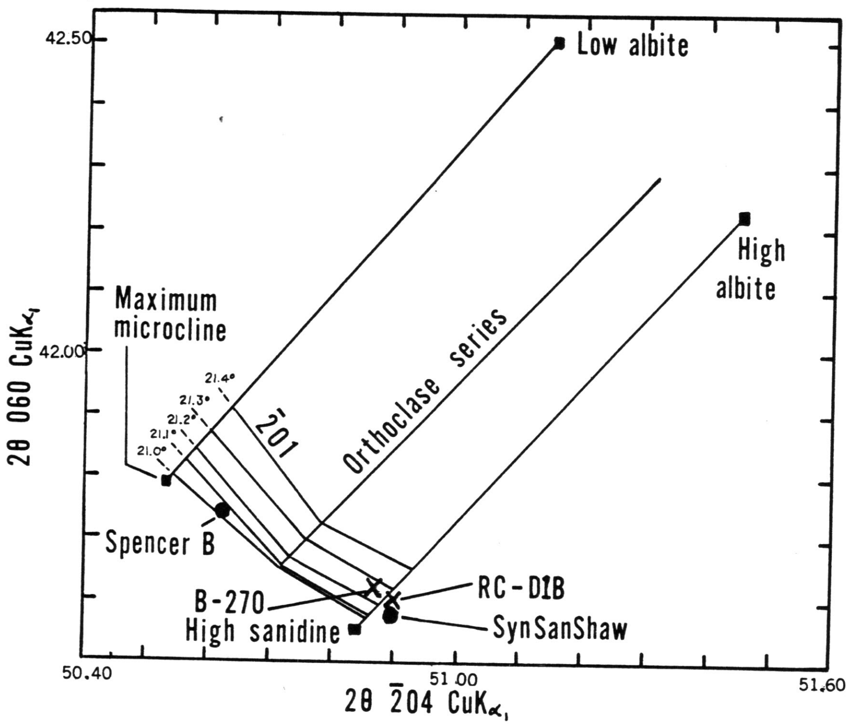

Figure 3.--Plot of 2θ (060) against 2θ (204) with 201 contours (modified from Wright, 1968). Connecting lines for three complete alkali feldspar solid solution series are constructed from data of Orville (1967) and Wright and Stewart (1968). X-ray data for Spencer B adularia and synSanShaw from Wright and Stewart (1968). Both adularias from Bodie have 2θ (201) values of 20.99°.

CHEMISTRY

A chemical analysis for the vein adularia B-270 is shown in Table 2. SiO_2, Al_2O_3, and K_2O account for more than 99 percent of the sample, but calculation of proportions of feldspar end members (Table 2) indicates an excess of SiO_2 beyond the amount required to balance Ca, Na, and K. This excess SiO_2 may represent contamination from fine-grained quartz intergrown with adularia, an occurrence found in many epithermal vein deposits and difficult to completely remove by mineral separation procedures. When the chemical analyses are corrected for the amount of SiO_2 assumed to be present as free quartz, the composition of adularia B-270 becomes $Or_{95}Ab_5An_{<0.1}$.

X-ray fluorescence analyses for K, Rb, and Sr of the two adularias from Bodie are given in Table 3. Also listed in Table 3 are K, Rb, and Sr values for two dacitic volcanic rocks, one completely replaced by quartz and adularia, the other unaltered. Sample OD7604 represents the end product resulting from intense potassium-silicate alteration in the Bodie mining district. Table 3 shows that strong K + Rb enrichment and Sr depletion occur during alteration, and values may approach those of adularia in progressively more altered rocks.

Rb and Sr values for adularias from Bodie are consistent with those for hydrothermal K-feldspars from epithermal ore deposits in the Basin and Range province of the western United States (M.L. Silberman and B.P. Fabbi, unpub. data). In general, Bodie adularias have higher Rb contents and lower K/Rb ratios than volcanic and plutonic feldspars (Dodge and others, 1970; Noble and Hedge, 1970). The K/Rb ratio is typical of those found in pegmatites and hydrothermal deposits (Shaw, 1968). The low K/Rb ratios of hydrothermal feldspars probably reflects a low K/Rb ratio in hydrothermal waters (Ellis and Mahon, 1964). Present-day hot-spring waters near Bodie, which are isotopically similar to the Bodie ore fluids, have K/Rb ratios in the same range as the adularias. These relationships suggest that a K- and Rb-rich fluid of meteoric origin was responsible for potassium-silicate alteration in at least part of the Bodie district.

Detailed stable isotope, fluid inclusion, chemical analyses and K-Ar isotopic age determinations at Bodie, reported by Silberman and others, (1972); O'Neil and others, (1973); Silberman and Berger (1985); and Koski and others, (1978) demonstrated that precious-metal mineralization at Bodie occurred about 8 m.y. ago, during waning stages of volcanic activity within and near the district, during the formation and evolution of a surface-venting hot-spring system whose fluid composition appears to be very similar to current geothermal waters in the region.

SUMMARY

During late Miocene time intermediate volcanic rocks in the Bodie mining district were subjected to hydrothermal alteration, principally by potassium metasomatism. Potassium-rich, highly disordered monoclinic adularia crystallized as a stable phase in the potassium-silicate alteration zone which coincides with the zone of economic precious-metal deposition. As replacement of host rock approached completion, its Rb and Sr contents and K/Rb ratio approached those of vein adularia (Table 3). Adularia from Bodie apparently crystallized in open conduits connected to an underlying epithermal hot-springs environment, from waters of dominantly meteoric composition similar to water in presently active thermal springs near the mining district. Adularia was the single most important mineral present whose chemistry, isotopic systematics, and stable isotope ratios led to deciphering the conditions and timing of the process of mineralization.

Table 3. K, Rb, Sr, and Au contents of adularia, altered dacite, and unaltered dacite from Bodie mining district

Sample	K (Percent)	Rb (ppm)	Sr (ppm)	Rb/Sr	K/Rb	Au[3] (ppm)
B-270	12.97	800	94	8.5	162	8[4]
RCD1B	12.09	610	245	2.5	198	0.10
OD7604[1]	11.08	520	153	3.4	213	N/A
855-40[2]	2.59	83	890	0.1	312	<.02

Chemical data and sample descriptions from O'Neil and others (1973). Analyses except Au by X-ray fluorescence. Analysts: B.P. Fabbi and L.F. Espos.

[1] Sample is altered dacite, almost completely replaced by adularia and quartz.
[2] Sample is unaltered porphyritic biotite dactie.
[3] Analyses by atomic absorption, analyst: R. Hanson
[4] Analyzed whole vein sample, before adularia separation.
N/A not analyzed.

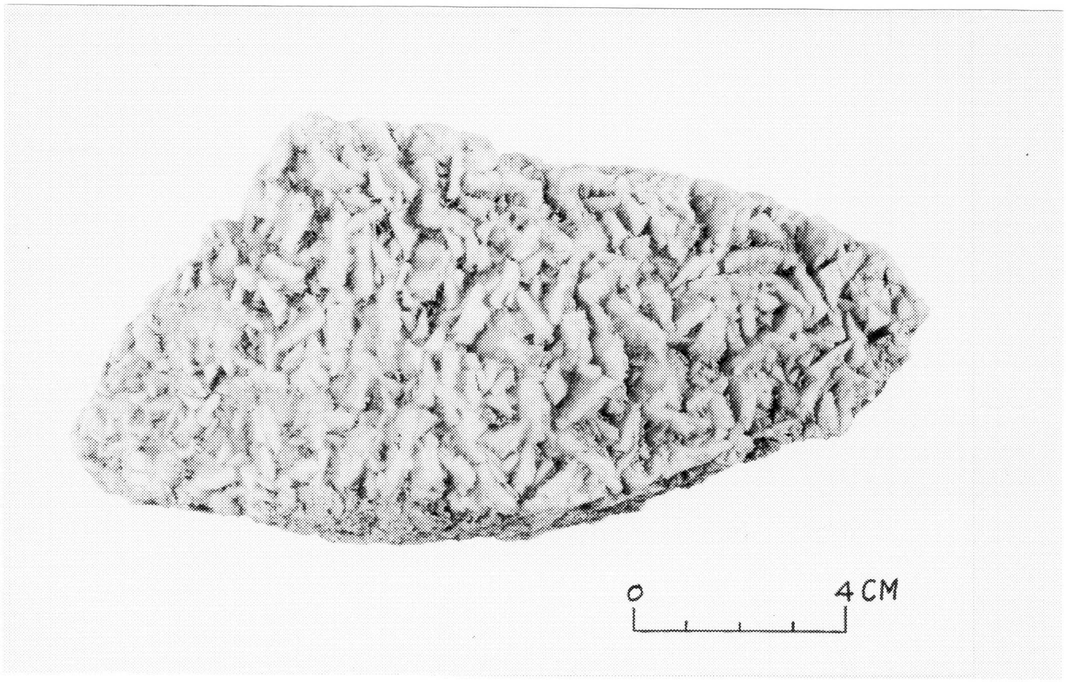

Plate 1. Coarse-grained adularia, sample B-270, from Standard Hill. Crystals line cavity in hydrothermally altered dacite. The adularia, intergrown with minor fine-grained quartz, contained 8 ppm Au.

Plate 2. The Roseclip open pit, on Standard Hill, showing sheeted quartz-adularia veins, cutting hydrothermally altered dacite. These veins are generally fine grained, and contain the adularia in bands. They are near the upper part of the Bonanza ore zone, which was stoped just below the level of this photo.

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Richard C. Erd, Jr., Victoria R. Todd, George W. Walker, Eugene Foord, Peter Modreski, and John Antweiler reviewed earlier versions of this manuscript and made helpful suggestions for improving its content. R. C. Erd also provided instruction for the unit-cell determinations.

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ROSCOELITE IN COLORADO TELLURIDE ORES

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The dioctahedral vanadium mica, roscoelite, is commonly associated with epithermal (shallow, low temperature) gold-silver telluride mineralization in Colorado and western North America. It is well known from the Boulder County telluride district, Cripple Creek, La Platas, and Central City. Other worldwide occurrences include; the Emperor mine, Fiji; the Spotted Horse mine in the Judith Mountains, Montana; Belle of Baker, Mammoth and North Pole mines, Baker county, Oregon; and the Kalgoorlie district, Australia. All of the above occurrences of roscoelite are associated with telluride ores. The type locality, the Stucklager mine in Columa, California, shows the association roscoelite, native gold, minor tellurides, and Cr mica (mariposite). Probably the most well-known occurrence of roscoelite is with the sedimentary uranium-vanadium deposits of the Colorado Plateau.

In the telluride deposits of Colorado, roscoelite is typically an early-stage gangue mineral in the veins and always appears before tellurides in the paragenetic sequence. The Tertiary age epithermal telluride deposits of Boulder County frequently show an assemblage of quartz, pyrite, roscoelite, tellurides, and iron carbonate with occasional fluorite. In general, the roscoelite encrusts the earliest stage of quartz in the veins.

Roscoelite is very similar in appearance to chlorite, and consequently may be more common than originally thought. In hand specimen, roscoelite appears in various shades of green to rare clove-brown. It typically has either a drusy or rosette habit when encrusting quartz, but may occur as massive felted aggregates intergrown with tellurides. In thin section it is greenish-brown to pale green and displays either a fibrous or fine-grained scaley habit. Scanning electron microscopy shows habits ranging from rosettes, blades, and fibrous bundles, to flakes (stacked and random). A comparison of microprobe data to these habits indicates a trend toward more complex rosette configuration with higher vanadium content (20-26 weight % V_2O_3). As the vanadium content decreases, more micaceous characteristics, structurally and chemically, appear. From our preliminary data, there appears to be a complete compositional range from vanadian muscovite to high vanadium roscoelite. This range is most likely due to a substitution of vanadium for aluminum in the octahedral sites of the mica. The cause of the vanadium variability is not well understood, but appears to be a strong function of the specific ore environment and ore solution.

Based on the chemistry of vanadium-transporting solutions in Colorado Plateau uranium deposits and in several Colorado telluride deposits, fluids were low temperature (about 200° C), dilute, near neutral pH, and relatively oxidizing. The source of vanadium is poorly constrained, but its absence in associated lead-zinc-silver and tungsten veins in the same wall-rock suggests that the telluride ore fluids were much more oxidizing than is typical of the other ores. The presence of V-rich mafic minerals which are altered and oxidized adjacent to the telluride veins suggests a probable wall-rock source for the vanadium.

Several possible exploration applications can be suggested based on this preliminary work. The frequent association of roscoelite, tellurides, and fluorite in telluride vein deposits associated with alkalic intrusions indicates that the elements V, K, Te, and F would be a good element suite for geochemical exploration. For the greenstone/serpentinite-hosted native gold deposits like the northern Mother Lode, the association of roscoelite with mariposite suggests that K, V, and Cr would be a good element suite for exploration.

MINERAL DISTRIBUTIONS IN THE GOLD HILL MINING DISTRICT, BOULDER COUNTY, COLORADO

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INTRODUCTION

The Boulder Telluride Belt is an area of epithermal precious metal mineralization, at the northeast end of the Colorado Mineral Belt, which includes the Boulder County districts of Gold Hill, Jamestown, Magnolia, and Sugarloaf. The Telluride Belt extends roughly 23 km from north to south and about 8 km from east to west. The center of the belt lies in the Gold Hill mining district about 10 km northwest of Boulder, Colorado (Fig. 1). Based on limited production figures (Goddard, 1940; Koschmann and Bergendahl, 1968; Kelly and Goddard, 1969), I estimate that the Gold Hill district proper produced roughly 14.0 metric tons (450,000 tr. oz.) of gold, worth just under $15 million at the time of production (Lovering and Goddard, 1950), or over $200 million in today's dollars. This is the largest amount of gold-telluride production in the Colorado Mineral Belt by at least a factor of two.

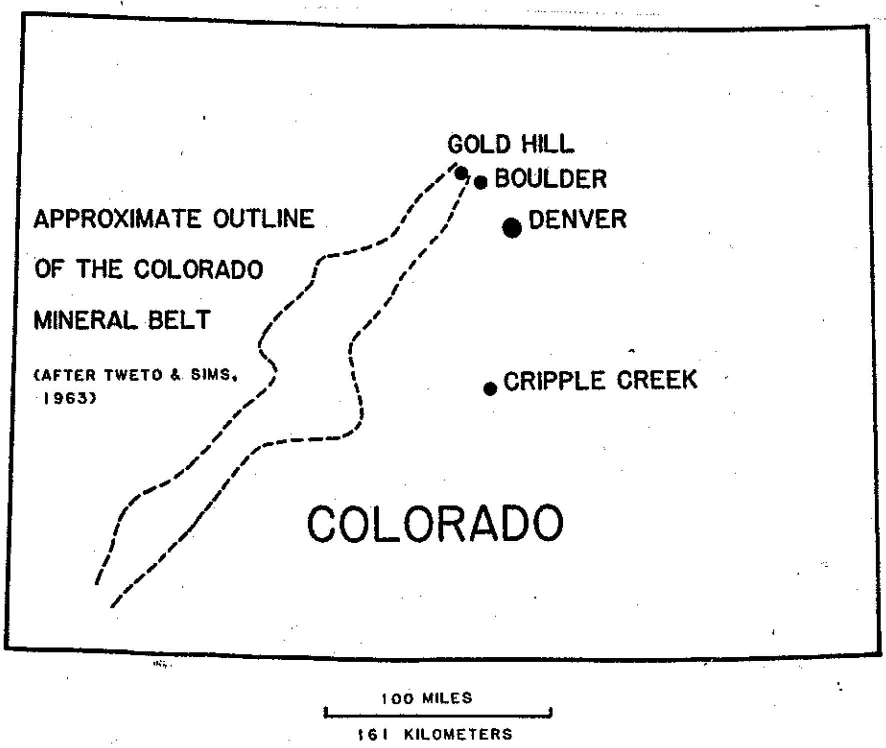

Figure 1. Map illustrating the location of the Gold Hill district.

Syenite plugs and their related rhyolite dikes west of Gold Hill are the best candidates for generating the telluride mineralization at Gold Hill (Geller et al., 1988). There is a fair chance that syenitic stocks exist below the Gold Hill district either as distinct plugs, or as satellitic cupolas of the Sunset stock to the west. Most major telluride veins at Gold Hill dip steeply to the west, which lends further support for the proposed source for the mineralized fluids at Gold Hill. Another less favored telluride source at Gold Hill is a northeast-southwest belt of bostonites, (alkalic, K-spar-rich, Laramide intrusions) that crop out discontinuously from Bald Mountain, southwest of Gold Hill, northeast under Gold Hill, and then east of Jamestown.

ECONOMIC GEOLOGY

Economic mineralization is hosted principally by steeply-dipping veins that occupy sheared and/or brecciated zones in the Proterozoic (1700 Ma) Boulder Creek Granodiorite and to a lesser extent, Proterozoic schists and gneisses formerly called the Idaho Springs Formation. A few veins are moderately- to gently-dipping. Better deposits are located near the intersections of northwest-trending faults with younger northeast-trending faults (Fig. 2). The host rocks are often noticeably foliated near the faults, reflecting the fact that some veins follow Precambrian shear zones. Pay zones average a few centimeters to a meter in width, but widen at most fault intersections, and may extend hundreds of meters along strike and down dip. The veins are commonly displaced by younger faults.

Grades were erratic but frequently reached >1000 ppm Au and >2000 ppm Ag. Average grades for Gold Hill were probably about 11 ppm Au, 40 ppm Ag, plus trace to minor amounts of Cu, Pb, Zn, and W (Lovering and Goddard, 1950; Geller and Atkinson, 1987). These figures depended largely on the type of deposit being mined.

Gold Hill contains several types of ore deposits, notably telluride deposits, pyritic-gold deposits, bonanza silver/base metal deposits, and rarely tungsten deposits. A given vein generally contains only one type of ore, with rare exceptions, such as the Logan vein which produced telluride, pyritic-gold, and tungsten ores from superimposed mineralization. Within the Logan mine, this vein intersects a bonanza silver vein. Nonetheless, telluride ores commonly contained recoverable base metal by-products, as in ores from the Cash, Slide, Rex, Horsfal, and Prussian mines. A common practice was exploitation, by a given mine, of intersecting veins containing different ore types (e.g., the Slide mine had telluride and pyritic-gold veins).

MINERALOGY

Minerals in the telluride deposits are fine-grained and intergrown, in tiny joints and vugs. They commonly include pyrite, sphalerite, chalcopyrite, galena, tetrahedrite-tennantite, arsenopyrite, electrum, and over a dozen different Ag, Au, Pb, Bi, Hg, and Ni tellurides (Geller and Atkinson, 1987). Frequency of occurrence of telluride minerals (not modal abundances) according to my preliminary data and Kelly and Goddard (1969) is in the following order (from most common to least common): 1. Sylvanite $AgAuTe_4$, 2. melonite $NiTe_2$, 3. petzite Ag_3AuTe_2, 4. altaite PbTe, 5. coloradoite HgTe, 6. native tellurium Te; 7. hessite Ag_2Te, 8. krennerite $Au_{0.8}Ag_{0.2}Te_2$, 9. calaverite $(Au>>Ag)Te_2$, 10. empressite AgTe, and 11. stuetzite $Ag_{5-x}Te_3$.

Mines which produced more Au than Ag at Gold Hill contain at least one Au-rich mineral such as: calaverite, electrum, krennerite, sylvanite, or auriferous pyrite. This appears to be supported by ore petrographic studies (Geller and Atkinson, 1987).

Gangue is mostly comprised of quartz, carbonates, roscoelite (V-mica), adularia, and uncommon to rare barite (Kelly and Goddard, 1969). Much of the quartz is very fine-grained chalcedonic material termed "horn quartz" by the miners. The remaining quartz has a cockscomb texture. Paragenetic sequences include several major stages: 1) barren quartz, pyrite and marcasite, 2) base metal sulfides and sulfosalts, 3) precious metal tellurides, and 4) barren quartz and carbonates. Alteration occurs in zoned envelopes with a sericite-adularia zone adjacent to the veins and a peripheral montmorillonite zone. Propylitic alteration is generally weak or absent.

The pyritic-gold deposits (e.g., the Grand Republic mine and the Klondike vein in the Slide mine) consist of fine-grained auriferous pyrite disseminated in vein walls; chalcopyrite with minor free gold, galena, sphalerite, and tetrahedrite; in a gangue of quartz, sericite, chlorite, roscoelite, and late barren ankerite.

The bonanza silver-base metal deposits (e.g., the Yellow Pine, Victoria, Goldsmith Maid, and at least seven other mines) were characterized by moderately coarse-grained galena, sphalerite, pyrite, chalcopyrite, silver-rich tetrahedrite-tennantite, Ag- sulfosalts, and, less commonly, bornite, stromeyerite, electrum, arsenopyrite, and covellite in a gangue of quartz, adularia and ankerite.

The tungsten deposits (e.g. the Grandview, Logan, Interocean, and several other mines) contain wolframite in horn quartz with minor pyrite and occasionally arsenopyrite (Goddard, 1940; Lovering and Goddard, 1950; Kelly and Goddard, 1969). Recent research in the Tungsten mining district, southwest of Gold Hill, indicates depositional conditions below 200 °C, hydrostatic pressure corresponding to depths of <200 meters, low to moderate salinities, and boiling as the inferred depositional mechanism. These deposits appear to be zoned from a Mn-poor Fe-rich wolframite (ferberite) center at depth, to distal

Mn-rich wolframite (approximating huebnerite) upward and outward (Hudson and Atkinson, 1988). The Tertiary hornblende-monzonite dikes centered around Hurricane Hill (2.4 km, or 1.5 miles, northeast of Nederland) are the suggested source of these deposits (Hudson, pers. communication).

A late crustiform pitchblende occurs in sparse amounts in the northwest part of the Gold Hill district, and may have been remobilized from Precambrian pegmatites.

In at least one property containing both telluride and Ag-base metal mineralization (the Mineral Point mine), the paragenetic sequence suggests that the sulfides and sulfosalts preceded Au-telluride mineralization. My proposed scenario for mineralization at Gold Hill is: 1. Ag-base metal introduction primarily along the Hoosier and Fortune 'reefs'; 2.Telluride mineralization, generally in northeast-southwest vein sets cutting 'reefs'; 3.ferberite introduction preferentially along the Poorman 'Reef', and in a belt from Logan Mountain northeast to Sunshine; and 4.pitchblende input late in the sequence in the northwest part of the district, which is indeterminately timed with respect to the ferberite (Geller and Atkinson, 1987).

The telluride deposits at Gold Hill can be classified as Te-rich epithermal deposits similar to those at Cripple Creek, Colorado; Vatukoula, Fiji; and Nagyag, Rumania, with some major differences. The Gold Hill deposits lack the prominent explosive volcanism characteristic of all the other districts, and include bonanza silver-base metal and tungsten mineralization that other telluride districts lack. Likewise, the high diversity of telluride minerals from a given property at Gold Hill (the average is about six telluride minerals) is unique among the world's telluride deposits (Kelly and Goddard, 1969).

The Boulder Telluride Belt has been studied by mineralogists and geologists for over 114 years (Silliman, 1874). Early efforts focused on mineral identification, whereas 20th century research has emphasized structural geology and its control on vein localization. Present investigations are concentrating on genesis of the deposits. Work under way includes studies of trace-element distribution, vein petrology, fluid inclusions, chemistry of transport and deposition, and radiometric dating by $^{39}Ar/^{40}Ar$. Four theses are in progress; a Ph.D. study by Bruce Geller and M.S. studies by Ann Hudson, Ward Kane, and Avrom Howard. The goal of our combined efforts is to better understand the nature of the deposits in Boulder County and to propose genetic models for the various districts in light of other similar epithermal deposits throughout the world.

MINERAL DISTRIBUTION

Polished sections of over 235 specimens were studied in reflected light in this ore petrology investigation. These specimens were obtained from collections at the University of Colorado, the Denver Museum of Natural History, and the Colorado

School of Mines. In addition, many were self-collected from mine dumps and certain underground workings. To this data, published reports of ore petrology at Gold Hill (Eckel, 1961; Kelly and Goddard, 1969) were added to create maps of mineral distributions in the district.

Out of the 130 or so properties at Gold Hill with reported ore production, specimens or published petrologic descriptions for approximately half of the productive properties were obtained. Curiously, in a district known worldwide for its diverse telluride mineralization, only about three dozen properties displayed visible telluride mineralization that could be studied. It is entirely possible that additional properties contain telluride mineralization, but specimens from them were unavailable to the author.

Telluride mineralization occurs throughout most parts of the Gold Hill district. In terms of productive centers, I agree with Kelly and Goddard (1969) that the Sunshine area contains the highest concentration of telluride producing mines in the district. Strangely, this area is not immediately adjacent to any of the major shear zones (or 'breccia reefs') previously credited with being the sources of mineralizing fluids by earlier researchers.

Twenty mineral distribution maps produced in this study indicate several important points. First, telluride, sulfide, and sulfosalt mineralization occurs throughout most of the Gold Hill district, and for the most part, does not appear to cluster in distinct areas. Second, ferberite only occurs in two belts; a southwest-northeast belt from Logan Mountain northeast to Sunshine, and a west-east belt along the Poorman shear zone. Third, the five minerals that can be found in over half of the 63 properties studied are pyrite, sphalerite, chalcopyrite, galena, and sylvanite. Fourth, minerals that usually occur in large amounts per individual specimen are arsenopyrite, ferberite, hessite, krennerite, marcasite, pyrite, and native tellurium, which would tend to make them easy to spot (although field identification of telluride minerals in this district is exceedingly difficult). Fifth, minerals that rarely occur in large amounts per individual specimen are altaite, chalcopyrite, coloradoite, covellite, galena, melonite, sphalerite, and tetrahedrite/tennantite, which makes them difficult to examine in the field, and sometimes under the microscope. Sixth, minerals such as electrum, petzite, Ag-sulfosalts, and sylvanite tend to occur either very abundantly or very sparingly per individual specimen. Seventh, identification of calaverite is nearly impossible, even with microscopic methods, and its reported occurrence in the district should be scrutinized. It usually is misidentified krennerite, or rarely, untwinned sylvanite. Eighth, sphalerite with "chalcopyrite disease" is not restricted to the proximity of the Hoosier shear zone, but occurs from north of Salina--west to Gold Hill, and possibly correlates with a set of Laramide dikes in this area. Ninth, natural amalgam (with chemical analysis approximating $Au_{80}Hg_{20}$, J. W. Drexler personal communication) has been observled in at least two properties at Gold Hill. Tenth, the average telluride-bearing property at Gold Hill identified in this study is more likely to contain altaite, calaverite(?), electrum, hessite, krennerite, melonite, petzite, and sylvanite than an average property from a gold mineralizing center identified in an earlier study (Geller and Atkinson, 1987), whereas the average gold-mineralizing center is more likely to contain coloradoite and native tellurium. Eleventh, silver mineralizing centers appear to be enriched in pyrite, sphalerite, galena, chalcopyrite, tetrahedrite/tennantite, Ag-sulfosalts, and covellite, compared to average properties in this study. Twelfth, marcasite and electrum are much more likely to be found in mines containing tellurides than in non-telluride mines.

ACKNOWLEDGEMENTS

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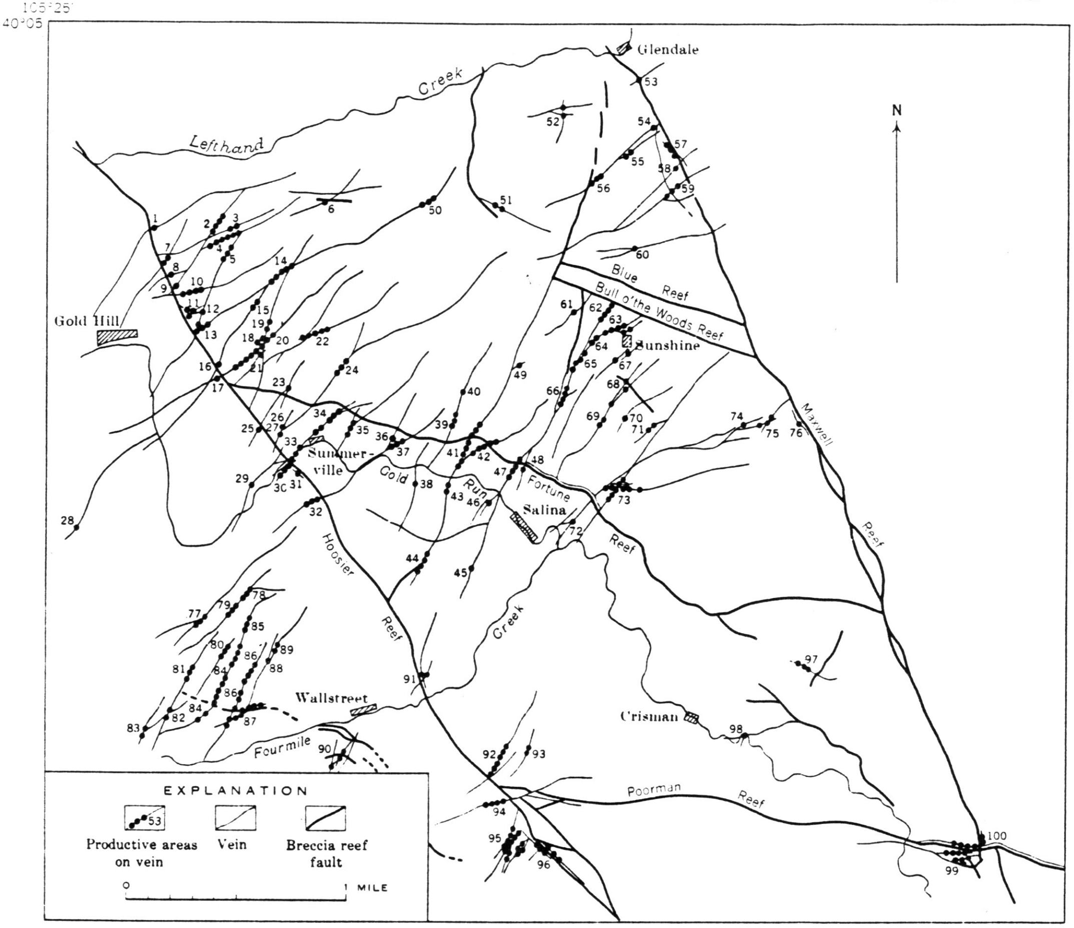

SKETCH MAP SHOWING RELATION OF PRODUCTIVE VEINS OF THE GOLD HILL DISTRICT TO BRECCIA REEFS

Fig. 2

LIST OF MINES

1. New Discovery
2. Prussian
3. Twin
4. Klondike
5. Slide
6. Helena
7. Cold Spring and Red Cloud
8. Alturas
9. Gold Ring
10. Alamakee
11. Times
12. Winona
13. White Cloud
14. Horsefal
15. Columbus
16. Who Do
17. Bellvue
18. Cash group
19. Mack
20. St. Joe
21. Ready Cash
22. Black Cloud
23. Atlanta
24. Big Horn
25. King
26. First National Bank
27. Morning Glory
28. Myrtle
29. Tammany
30. Evans
31. Dana
32. Grant
33. Goldsmith Maid
34. Victoria
35. Scotia
36. Valley Forge
37. Belle
38. Golden Eagle
39. Fairfax
40. Minneapolis
41. Richmond
42. Ingram
43. Three Brothers
44. Melvina
45. Critic and Railroad Boy
46. Baron
47. Sunshine
48. Atchison
49. Sussex
50. Snowbound
51. Belle of Memphis
52. Delaware group
53. St.Louis
54. Washington Irving
55. Cleveland
56. Tillie Butzel
57. Sun and Moon
58. Hidden Treasure
59. Nil Desperandum
60. Dolly
61. Gillaspie
62. American
63. Interocean
64. Oceola
65. White Crow
66. Grand View
67. Washburn
68. White Eagle (Archer)
69. Golden Harp
70. Richard
71. Plough Boy
72. Home Sweet Home and Little Johnny
73. Emancipation group
74. Minnie Bell
75. New York-Union
76. Pilot
77. Sakhrat
78. Gold Lode
79. Great Britain
80. Lucky Star
81. Emerson
82. Concord
83. Forest
84. Franklin
85. Gillard
86. Gray Copper
87. Wood Mountain group
88. Last Chance
89. Doss
90. Gladys
91. Temborine
92. Dime
93. Evening Star
94. Grand Republic
95. Logan
96. Yellow Pine
97. King
98. McKnight Placer
99. Poorman group
100. Bell

HIGHLIGHTS OF COLORADO GOLD AND SILVER OCCURRENCES

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An important part of our mining and mineral heritage is recaptured in museum exhibits of prized precious metals. Colorado is recognized as one of the leading specimen producing states. Most of the gold and silver crystals, nuggets, or attractive pieces in collections can be traced to the classic mining districts on the Colorado Mineral Belt or the San Juan Mountains.

There are 10 Colorado counties with a total production of over 1 million ounces of gold since 1859. For most of the years, between 1860-1954, Colorado mines yielded 100,000 ounces of gold annually. The State was ranked second in the nation in accumulated gold production in 1965 with a total of 40,775,923 ounces (Koschmann and Bergendahl, 1968). Nearly one-half of this total came from Cripple Creek and Victor mines, in Teller County.

Counties leading in ounces of gold produced up to 1959 include: Teller (19,100,867), Gilpin (4,255,000), San Miguel (3,837,000), Lake (2,983,000), Clear Creek (2,400,000), Ouray (1,911,000), San Juan (1,665,000), Park (1,364,430), Boulder (1,048,200) and Summit (1,010,670).

U.S. Bureau of Mines figures show that gold production in Colorado between 1960-1979 totaled approximately 873,771 ounces. The highest annual yield during this period was 72,668 ounces in 1977. The lowest output, of 13,850 ounces, occurred in 1979.

By the 1980's mining and mineral explorations were greatly reduced, or had ceased altogether. The principal underground operations, such as the Camp Bird, Idarado, Sunnyside and Eagle mines, closed for the first time in decades. Traditional methods of underground mining were replaced with surface cyanide leaching operations; in 1987 there were about 15 such heap-leach plants recycling gold from old dumps or tailings piles.

In 1986 there was a dramatic rise in gold output, mainly due to a large new gold mine at Summitville, Rio Grande County, operated by Galactic Resources Inc. of Vancouver, British Columbia, Canada. This open-pit, heap-leach operation reported 54,714 ounces of gold in 1986, making it Colorado's largest gold producer; Summitville again led in gold production in 1987 with 88,207 ounces. The Sunnyside mine, in San Juan County, operated by Echo Bay Mines Ltd., of Edmonton, Alberta, Canada, (recently reorganized into a joint venture with Silver King Mines, Inc., and Pacific Silver Corporation, both of Salt Lake City, Utah) ranked second with approximately 47,093 ounces of gold derived from underground workings in 1987. The U.S. Bureau of Mines reported 179,916 ounces of gold recovered from Colorado in 1987, an increase from 120,347 ounces in 1986.

Summitville has an interesting history dating back to 1870 when placer gold was discovered in Wightman's Gulch. By 1873 permanent mining and a town site were well established on the high alpine upland located some 25 miles south of Del Norte. From 1873-1887 over $2 million in gold and silver came from the rich, near-surface, oxidized ores on South Mountain. A second period of production was initiated by a famous bonanza strike on the Little Annie vein where over $500,000 was recovered from some 860 tons of hand-sorted ore found in the "Pickins lode." Peak production was in the 1930's when the Summitville Consolidated Mines, Inc. was recovering high grade ore from South Mountain. Gold production from 1873 to 1957 totaled 257,600 ounces. The district has been the focus for geological studies and mineral exploration for several years, especially by the U.S. Geological Survey, by ASARCO, and Anaconda. Galactic Resources Inc., acquired the property in 1984. Summitville is once again alive with activity as a large open pit is being carved into the eastern slope of South Mountain.

Summitville is particularly famous for the "Gold Boulder of Summitville", a 141.5 pound rounded mass of quartz breccia that contained an estimated 17-20 percent of free gold. The extraordinary specimen was discovered in 1975 by Bob Ellithorpe, a contract worker for ASARCO, Inc. at the Summitville mine. The boulder, a piece of float, lay unrecognized along the side of a mine access road behind a small pine tree until Ellithorpe saw a glint of gold color from a 1 inch vein that cuts through the boulder. The specimen was trimmed to 114 pounds and donated to the Denver Museum of Natural History by the landowners, the Reynolds Mining Company, and the property lessees, ASARCO, Inc. It is on display in the Museum's Coors Mineral Hall.

Other large gold specimens attract our attention and have intriguing histories. "Tom's Baby" is Colorado's largest known solid mass of gold. The eight and one-half pound specimen is on display in the Denver Museum of Natural History. It has a flat, platter-like shape and consists of intergrown crystallized gold leaves embedded in a dark brown limonite matrix; it is 8-1/2 inches wide and averages about 1 inch in thickness. The gold was found while mining at the Gold Flake mine on Farncomb Hill, 4-1/2 miles east of Breckenridge, in Summit County. It was discovered on Thursday, July 23, 1887; the local newspaper, the "Daily Journal" told of how two miners, Tom Groves and Harry Lytton, discovered a bonanza pocket containing an abundance of free gold with the largest single piece weighing 160 troy ounces. The big gold was soon named because, "Tom was so elated and fondled the find so affectionately that the boys declared that it was `Tom's Baby'." It was originally noted that two pieces were broken off, leaving the big specimen at a total of 136 troy ounces.

The subsequent history of "Tom's Baby" had been the subject of several articles since the gold was missing for nearly 50 years. In 1972 it was "rediscovered," in two pieces, with a total weight of 102.4 ounces, in the vault of a Denver bank where it had been stored for security reasons by officials of the Denver Museum of Natural History. It is now well established that "Tom's Baby" belonged to John F. Campion, who donated his large collection of Breckenridge gold to the Denver Museum where it has been on continuous exhibit for 85 years.

Of all Colorado gold occurrences, Farncomb Hill is certainly the source for some of the most exquisite specimens. The gold, which occurs in thin veinlets in shale adjacent to a Tertiary intrusion, is easily identifiable as being from this locality. It forms well developed octahedral and cubo-octahedral crystals and thin delicate crystallized leaves. On the west side of the deposit, at the "wire patch," it occurs in masses of intergrown wires. The shiny luster of the gold, the intriguing surface patterns, and aesthetic forms make Farncomb Hill gold a choice collector's item.

A prize-winning Colorado specimen is a vein of nearly solid gold weighing 17 pounds that was donated to the Denver Museum of Natural History in 1977 by the Colorado Scientific Society. The gold vein, in quartz, is from the famous Smuggler-Union mine, Telluride District, San Miguel County. It was originally given to the Colorado Scientific Society by John A. Porter. The mass was cut into two pieces and polished to enhance its appearance. The rich specimen won medals of recognition at the 1893 Columbian Exposition in Chicago and at the Paris Exposition of 1900.

The state's largest known placer gold nugget, the doorknob-size "Penn Hill" nugget, is named for the place from which it was recovered, on Pennsylvania Mountain, west of Fairplay, Park County. The attractive, flattened mass weighs 12 troy ounces and can be seen at the Denver Museum of Natural History.

Colorado is not well known for large nuggets like other states; however, there is an abundance of small, attractive gold nuggets which have been panned or dredged from alluvial deposits across the State for 130 years. One of the finest known collections consists of about 25 variously sized pieces totaling more than 6 troy ounces. These were panned by Henry Schutz and his sons from the Cache Creek placers, west of Granite, in Chaffee County. These attractive nuggets reflect the efforts of Colorado's pioneer prospectors who first settled remote areas in search of mineral deposits. Henry Schutz came to the United States from Frankfort, Germany, in 1870, then traveled by covered wagon to Colorado in 1871. He successfully panned for gold at Cache Creek and opened a general store in Granite in 1881.

Significant Colorado gold specimens are seen in many other museums. The Harvard Mineralogical Museum displays one of Colorado's finest gold specimens, a thick, 4-1/2 inch-long mass of intergrown and curving wires from the Ground Hog mine, Gilman District, Eagle County. Fine examples of crystallized wire gold from the Ibex mine, at Leadville, are on display at the American Museum of Natural History in New York City. Gold from Breckenridge, Cripple Creek, Telluride, Central City and other localities can be seen in museum displays in Los Angeles, San Francisco, Dallas, Chicago, Pittsburgh and Washington D.C. The museum at the Colorado School of Mines, in Golden, displays a variety of fine gold crystals, nuggets and high-grade ore from famous Colorado deposits. Noteworthy specimens at the Colorado School of Mines are in a collection compiled in the early 1900's by Frank C. Allison of Cripple Creek; this collection was donated by Charles Boettcher and his son, Claude K. Boettcher in 1937.

Colorado is known as the "Silver State" and mining camps such as Georgetown, Silver Plume, Caribou, Leadville and Aspen grew at a rapid rate in the 1860's and 1870's following the rush for gold. By 1879 Leadville was the second largest city in the state and the unmatched leading source for Colorado silver. In 1961 there was a total of 768,408,372 ounces of silver credited to the state, which was ranked third in the nation for silver production.

Counties leading in ounces of silver produced through 1960 include: Lake (239,890,000), Pitkin (101,340,000), Eagle (61,000,000), Mineral (57,860,000), Clear Creek (56,000,000), and San Miguel (56,300,000).

Silver production in Colorado from 1960-1979 totaled some 56,695,100 ounces. The highest annual yield during this period was 4,663,496 ounces in 1977, a reflection of the high production in the 1970's from the Bulldog Mountain mine of Homestake Mining Company at Creede, in Mineral County. Silver mining has been on the decline during the 1980's, particularly after silver prices plunged in 1981-82. High grade ore producers, such as the Bulldog, Lake County's Sherman and Black Cloud mines, the Eagle mine at Gilman in Eagle County, and the Sunnyside in San Juan County, struggled to keep open until the mid-1980's when nearly every major operation closed except for the Summitville and Sunnyside mines. Silver production in 1986 from Summitville was approximately 50,000 ounces and in 1987 it totaled some 79,000 ounces. At the Sunnyside mine, 446,330 ounces of silver were recovered in 1987. The total amount of silver produced in Colorado in 1987 equals 860,562 ounces.

Many exciting native silver specimens have been preserved from Colorado's deposits. Aspen and Creede have long been recognized as leading sources for fine crystallized masses, leaf silver, and wires or delicate threads. Newspaper reports and a photograph in the Denver Museum of Natural History record the discovery of a single "nugget" of silver in the Smuggler mine, at Aspen, in 1894, that weighed 1,840 pounds. It was sent to the smelter where it yielded $13,000 worth of silver. An excellent intergrown mass of native silver crystals up to 2 inches in length from the Smuggler mine is on display in the Museum's Coors Mineral Hall. Other classic Aspen mines such as the Mollie Gibson and Della S. are known to have produced beautiful specimens of wire or "rams horn" silver.

Creede, with its lively history and unforgettable characters, is an enduring silver mining area. From the 1889 discovery of the Holy Moses mine, and the subsequent strikes along the 2-mile trend of the Amethyst vein system, the Creede mines yielded fantastic profits until prices plunged in 1893. The Commodore, Bachelor, Last Chance, and Amethyst mines are among the famous properties of this early era. In the 1920's many of the mines were consolidated under the Emperius Mining Company. Excellent specimens of silver, sphalerite, galena, barite and amethyst quartz from this era are preserved and grace private and museum collections. During the 1970's, fine silver specimens were also discovered in the Bulldog Mountain vein.

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THE MINERALOGY OF GOLD AND SILVER

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The mineralogy of gold is quite simple. Twenty-two minerals are reported by Fleischer (1987) to contain gold as an essential constituent. These can be classified as native elements (1), metal compounds and alloys (9), tellurides (7), and sulfides, selenosulfides, and selenides (5). Native gold and electrum are by far the most common naturally occurring forms of gold. They are not considered separate mineral species; electrum is defined as gold which contains greater than 20 atomic percent silver. Most mineral specimens and the largest part of the world's gold production are from gold solid solution and electrum. Gold mineralogy, with the exception of two phases, can be simply depicted on six triangular composition diagrams.

Four tellurides (calaverite, krennerite, petzite, and sylvanite) constitute the major ore minerals in the gold-telluride epithermal environment, which may constitute 5% to 10% of world gold production. Assemblages of tellurides with electrum can provide the most important geochemical interpretative tools of gold mineralogy, and numerous phase equilibrium studies have been undertaken to provide a quantitative basis for these interpretations. In many deposits, tellurium and precious metal mineralization was superimposed over prior sulfide mineralization, although the tellurium stage can also occur independently. Within the tellurium stage, mineralization frequently starts with native tellurium and progresses to lower-tellurium assemblages. Temperatures and the chemical activities of sulfur and tellurium can be determined by careful study of such samples.

The unusual mineral nagyagite is the last of the "common" gold minerals, as it has been reported from many gold-telluride epithermal deposits. It was considered as a sulfide in the account given above, although it has a significant metallic-compound component. Of the 16 remaining gold minerals, 9 are reported from only one locality, and the other 7 are found in only several places. Fourteen of the 16 are known only from electron microprobe studies, meaning that they have been described from several grains whose sizes are measured in microns. Clearly, gold mineralogy is dominated by the first 6 minerals.

With respect to geologic occurrences, native gold and electrum occur in extremely diverse environments, from the magmatic to the surficial. No summary of these environments will be made here, as examples will be the topic of numerous presentations of this symposium.

Four rare gold-mercury minerals of the metal alloy classification are reported occurring with native gold in ultramafic stocks, two from Russia and two from China.

Gold samples are readily available to the collector at understandably steep prices. The tellurides are scarce, whereas the remainder are unobtainable.

Silver mineralogy is overall quite different than gold mineralogy. Furthermore, in contrast to the several prior syntheses or compilations of gold minerals, none exists for silver. We will present a convenient classification of silver minerals, and discuss several aspects of this interesting and diverse group.

The first category consists of minerals containing both silver and gold, and these have been covered in the prior discussion. The second classification consists of silver alloys and native silver itself. Native silver is normally cubic, but two rare hexagonal polytypes, silver-2H and silver-4H, have also been reported. Five of the 11 alloy minerals consist of varieties of amalgam, that is, silver combined with mercury.

Silver-antimony compounds form two minerals, of which dyscrasite is the most common.

The next category of silver mineralogy consists of 26 species of simple sulfides, selenides, and tellurides (omitting regular sulfosalts), beginning with acanthite and argentite. Included here are several Se or Te equivalents of sulfosalts, for instance, the matildite analogues bohdanowiczite and volynskite, respectively. Sixteen of these minerals are extremely rare and may be limited to single localities. Common atomic substitutions are copper for silver and selenium for sulfur.

Rare-element silver sulfides and sulfosalts comprise the next group, consisting of 11 minerals containing germanium, thallium, tin, or manganese. They are all extremely rare; argyrodite, canfieldite, and hocartite are found at several localities each, and the others are reported from only one place. Uchucchacuaite, a rare manganese sulfosalt, was discovered in 1984 from an epithermal deposit in southern Peru.

The next mineralogical group is the silver sulfosalts. There are over 40 of these, and several constitute important ores of silver, namely tetrahedrite and the ruby silvers. The best way to quickly understand and depict the chemical relationships between these minerals is to consider silver-bearing binary, ternarary, and quaternary systems within the Cu_2S-Ag_2S-PbS-As_2S_3-Sb_2S_3-Bi_2S_3 system. The Cu_2S-Ag_2S-As_2S_3-Sb_2S_3 system produces most of the world's silver, largely in the form of argentite and freibergite (silver-bearing tetrahedrite). Small, high-grade ore shoots may be largely ruby silver and related phases in this system. It also produces fabulous crystallized mineral specimens such as proustite, pyrargyrite, stephanite, tetrahedrite, and argentite, to name a few. Finally, the Ag-Cu and As-Sb solid solutions provide tools to measure chemical activities, with the tennantite-tetrahedrite solid solution having been called "the cadillac of reciprocal solid solutions".

Another system of great mineralogical interest is Ag_2S-PbS-Sb_2S_3-Bi_2S_3. The galena-stibnite join alone contains 9 minerals; the more common silver-bearing ones include andorite, aramayoite, owyheeite, and others. Several other systems are also of mineralogical interest; however, most of the phases are extremely rare.

These very complicated silver-bearing sulfosalt systems will continue to present mineralogists with many fascinating problems in the future. New minerals within these systems are being described yearly. At the same time, the true nature of families along certain chemical joins has become suspect, and certain phases may be only superstructures of other minerals, thus reducing the number of valid species. Numerous scientists are involved in using these mineralogical curiosities as petrologic tools in ore deposit studies, and this is often aided by the presence of coexisting quartz in the epithermal environment upon which fluid inclusion studies can be made.

The final family of silver minerals consists of 9 species, and are the silver secondaries. Five of these are halides, with chlorargyrite, silver chloride, being by far the most common. There are two complex halides, boleite and bideauxite, chlorohydroxides of lead and silver. And finally, we have argentojarosite (silver-bearing jarosite) and stetefeldtite, a rare silver-antimony oxy-hydroxide from Nevada.

This compilation and review of silver mineralogy reveals the diversity and complexity of the group. Silver is widespread in the western U.S.A. and it is highly sought. Its geochemical affiliates are reflected in its mineralogy.

THE SILVER CONTENT OF GALENA AND SULFOSALT MINERALS FROM HYDROTHERMAL ORE DEPOSITS IN PERU, COLORADO, AND NEW MEXICO

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Introduction

Silver values in the primary minerals of hydrothermal ore deposits commonly reside in galena plus a variety of sulfosalts--the latter referred to by such terms as "black sulphurets" by the mining industry of the previous century. This report is a survey and comparison of the silver concentrations in galena, tetrahedrite-tennantite, and several other copper- and lead-bearing sulfosalts from a variety of ore deposits. A modern instrumental method of analysis ("KEVEX" energy-dispersive X-ray fluorescence) was used, which makes possible the rapid and nondestructive determination of silver and other trace metals in mineral samples. The results provide a range of information otherwise not readily obtainable and can serve as a starting point for more detailed mineralogical and geochemical studies on specific specimens and localities.

Samples from Colorado, New Mexico, and Peru were studied because of their availability and because of the general similarity in mineralogy and geologic environment of many of the Peruvian and Colorado igneous-related, Tertiary age, polymetallic hydrothermal vein deposits. The samples examined include some collected by the author, some loaned by various persons, and a large number (identified by DMNH catalog numbers) from the collection of the Denver Museum of Natural History.

Silver Mineralogy

In silver-containing ore deposits, silver can reside in several types of mineral hosts:

1) minerals in which silver is an essential component. These commonly include argentite/acanthite (Ag_2S); silver sulfosalts (of which some of the most common are proustite, Ag_3AsS_3; pyrargyrite, Ag_3SbS_3; pearceite, $Ag_{16}As_2S_{11}$; polybasite and antimonpearceite, $(Ag,Cu)_{16}Sb_2S_{11}$; stephanite, Ag_5SbS_4; and matildite, $AgBiS_2$); and silver/gold tellurides.

2) silver as an alloyed component in gold, electrum, or amalgam.

3) minerals which contain silver as a minor (but mineralogically and economically significant) substituent replacing lead or copper, principally in primary (hypogene) minerals such as galena, tetrahedrite-tennantite, several other sulfosalts, and less commonly in sulfides such as sphalerite and chalcopyrite (Hall and Heyl, 1968; Nishiyama and Kusakabe, 1986.)

4) secondary silver or silver-bearing minerals formed under near-surface conditions of oxidation and secondary enrichment, commonly including native silver, silver halides (chlorargyrite/bromargyrite), plumbojarosite/argentojarosite, anglesite, cerussite, and silver-bearing manganese oxides (Heyl and others, 1973). These minerals plus those listed in (1) above constituted the main ores of the "bonanza" silver deposits of the nineteenth century.

In most methods of analysis for trace components, inclusions of unwanted mineral impurities may affect the results. The method employed here (see appendix) is particularly susceptible to this because many of the crystals or mineral grains examined were in matrix and had not been purified by hand-picking or other separation methods. The results, therefore, need to be interpreted with care. Table 1 is a summary of the analytical results; the observed purity and associated ore minerals are noted.

Impurities in the analyzed specimens can be of several types. Bulk amounts of other intergrown ore minerals would affect the analyses the most. If galena is associated with silver-rich minerals such as argentite or silver sulfosalts, the apparent silver values will have no relevance to the composition of the galena itself. The analyses will still, however, provide a useful indication of the composition of the overall ore and may provide clues as to the presence of inconspicuous silver-bearing minerals that might otherwise escape notice. Some of the specimens analyzed here contain galena in a matrix of sphalerite, chalcopyrite, or pyrite; in most cases these can still provide a valid analysis of the silver content of the galena, computed from the Ag:Pb ratio, because these other sulfides normally contain a negligible amount of silver (sphalerite can be an exception). Gangue mineral impurities such as quartz, barite, siderite, and rhodochrosite normally would not affect the interpretation of the galena and sulfosalt analyses, although, for example, the presence of pyrite or iron-bearing gangue minerals would make it impossible to determine the Fe content in tetrahedrite, using this method. Minerals present as inclusions within galena will inevitably be included in the analysis and in some cases can account for much of the observed content of Ag, plus associated elements such as Bi and Sb. In many cases, these included elements are actually a true indication of the composition of the galena as it originally crystallized, prior to exsolution of sulfosalt phases upon cooling. Minerals present as products of alteration or of deposition of secondary minerals may introduce unexpected levels of silver or other trace elements into the analysis; in the present study, this can only be controlled by close examination of the sample and careful interpretation of the analytical results. A complete understanding of the geochemistry of silver in each sample requires examination of polished sections, followed by microprobe and X-ray diffraction analyses; the present analyses are a useful supplement but not a replacement for this type of detailed study.

Results: Galena

The galena samples analyzed here range in silver content from below the limit of detection (about 0.005 wt.% Ag) to as much as 4.8 wt. % Ag. The median value is 0.12 % Ag (= 1200 ppm = 35.0 oz/ton). Elsewhere, galena has been reported to contain as much as 3-10 wt. % Ag, together with as much as 18 wt. % Bi (Chapman and Stevens, 1933; Heyl and others, 1973; Foord, this volume; Foord and others, 1988; Foord and Shawe, in press). Galenas with less than about 0.4 wt.% Ag may be homogenous (Karup-Møller, 1977), but those with higher amounts of silver typically contain tetrahedrite or silver sulfosalts as exsolved phases. The simple substitution of silver for lead in galena ($2Ag^+ = Pb^{2+}$) occurs only to a very limited extent; most highly argentiferous galena contains Ag via coupled substititions requiring the presence of bismuth or antimony: $Ag^+ + Bi^{3+} = 2Pb^{2+}$, or $Ag^+ + Sb^{3+} = 2Pb^{2+}$. Foord and others (1988) refer to galena showing solid solution toward matildite ($AgBiS_2$), and containing more than 0.5 wt. % combined metals other than Pb as galena solid solution (PbS_{ss}). Malakhov (1968) gave analyses of both Bi and Sb in galena; he concluded that a high Bi:Sb ratio appeared to correlate with higher temperature and greater depth of formation. Fleischer (1955) summarized earlier studies of the trace element composition of galena and other sulfide minerals.

The limit of detection for silver in galena in this study, 0.005 wt.% Ag (= 50 ppm) corresponds to 1.458 troy oz/ton. This would constitute a significant but subeconomic grade of ore; currently, grades on the order of 10 oz Ag/ton would be considered mineable ore; by comparison, high-grade vein ore produced in Colorado in the 1880's often contained >100 oz Ag/ton (100 oz/ton = 0.34 wt. %). By way of comparison with typical bulk ore grades, the median (50th percentile) content of silver in 75 polymetallic vein deposits is 0.082 wt. % (820 ppm), and the 90th percentile deposit (i.e., as rich as 9 out of 10 such deposits) would have a grade of 0.47 wt.% Ag (4700 ppm) according to the grade-tonnage model of Bliss and Cox (1986).

Of the highest silver values found in the present study, two (4.8 and 2.3 wt. % Ag) are from portions of a galena sample from the Calliope mine, Ouray County, Colorado. It probably contains some intergrown tetrahedrite or other silver-bearing minerals, although none could be recognized in an X-ray diffraction pattern of the sample. The galena sample from the Yellow Pine mine, Boulder County, showing 3.5 % Ag and only minor Sb and Bi, almost certainly contains other silver minerals. Only one sample in the present study (Bedrock Creek, La Plata Mountains, Colo.) was notably high in Bi, with 2.5 wt. % Bi and only 0.26 wt. % Ag; further study would be needed to confirm whether the Bi in this sample is in fact contained in the galena. The next highest sample showed 0.8 wt. % Bi. Eight of the galena samples analyzed contain between 1.0 and 7.5 wt. % Sb; this antimony is most likely present as included tetrahedrite. Galena samples from several fluorite-barite-galena deposits in New Mexico (Blanchard, Galena King, and Mex-Tex mines) show very low silver contents, as would be expected for these deposits which are related to Mississippi Valley-Type deposits. Three samples from Precambrian deposits in Colorado were included; two from metamorphosed stratabound sulfide deposits (West McCoy Gulch, Cotopaxi, and Betty mine, Guffey), and one from a granite-related greisen (Boomer mine). The latter two of these show high silver. Two samples analyzed allow a comparison of silver content of primary galena and the dominant cerussite (with trace anglesite) alteration product derived from it. One sample (Capitol City mine) shows just a slight loss of Ag in the fine-grained, laminated cerussite surrounding the galena (0.13 wt. % Ag, vs. 0.16 % in the original galena); the other (Gates mine) shows a large depletion of Ag (0.01 % vs. 0.38 %) in coarsely crystalline cerussite rimming the galena. In addition to the elements reported in Table 1, the Bard Creek mine, Empire, Colo. sample showed about 0.8 wt. % Mo, suggesting the presence of molybdenite; the Bulldog mine, Creede, sample CR-1 also showed 0.2 % Mo. The Sweet Home mine sample DMNH-12488-B showed about 4.0 wt. % As, indicating intergrown tennantite.

Tetrahedrite-Tennantite

Aside from the intrinsic silver-bearing minerals, the tetrahedrite-tennantite series is the main carrier of silver in most ore deposits, especially of the igneous-related, polymetallic-base-metal, hydrothermal-vein type typical of both Colorado and Peru. The mineral series can ideally be described by the formula $Cu_{12}Sb_4S_{13}$-$Cu_{12}As_4S_{13}$ (where $Cu_{12} = Cu^{1+}{}_{10}Cu^{2+}{}_2$). However, in most natural tetrahedrite-tennantite the two atoms of divalent copper are largely replaced by a variety of metals, and the mineral series can better be represented by the general formula $(Cu,Ag)_{10}(Zn,Fe,Cd,Hg,Cu)_2(Sb,As,Bi)_4S_{13}$ (Patrick and Hall, 1983). Freibergite is the silver-dominant end member of the group, $(Ag,Cu)_{10}(Fe,Zn)_2(Sb,As)_4S_{13}$. This name was earlier used loosely for any silver-bearing members of the series, but in recent years true freibergites with atomic Ag>Cu have been recognized (Riley, 1974), although they are rare. Silver is more commonly enriched in the Sb-dominant member of the series; argentotennanite, $(Ag,Cu)_{10}(Zn,Fe)_2(As,Sb)_4S_{13}$, from the U.S.S.R. was just described as a new mineral in 1988 (see Am. Min., v. 73, p. 439). Of 78 tetrahedrite-tennantite analyses tabulated by Palache and others (1944), Araya and others (1977), Wu and Petersen (1977), and Yui (1971), 48 are tetrahedrites (atomic Sb>As) with between 0.0 and 17.71 wt. % Ag (median value = 1.21 %), and 30 are tennantites (atomic As>Sb) with between 0.00 and 13.65 wt. % Ag (median value = 0.25 %). Ideal end-member freibergite, $Ag_{10}Fe_2Sb_4S_{13}$, would contain 51.51 wt. % Ag; 50:50 freibergite-tetrahedrite, $Ag_5Cu_5Fe_2Sb_4S_{13}$, would contain 28.80 wt. % Ag.

Of the 23 tetrahedrite-tennantites analyzed here, none appear to be true freibergites, including one "freibergite" from the Sweet Home mine which proves to have only about 1 wt. % Ag, and one "freibergite" from Cerro de Pasco, also with about 1 wt. % Ag. The highest measured silver contents are in a massive specimen of argentian tetrahedrite (DMNH-8929) from the Bachelor mine, Ouray County, Colorado, with 26 wt. % Ag, and another (DMNH-8446) from Dunton, Colorado that contains 21 wt. % Ag. The inferred molecular compositions of these two samples are approximately freibergite$_{38}$-tetrahedrite$_{56}$-tennantite$_6$, and frei$_{34}$-tetr$_{61}$-tenn$_5$, respectively. Examination via polished section or microprobe is needed to confirm that the silver in these samples is all contained in the tetrahedrite and not in other silver minerals; SEM examination does confirm that these are apparently homogenous argentiferous tetrahedrites. Of the 23 total samples, 14 are tetrahedrites with a range of 0.5-26 wt. % Ag (median 4.55 % Ag), and 9 are tennantites with 0.09-1.8 wt. % Ag (median = 0.6 % Ag).

Enargite

Eight analyses of enargite show silver contents of between 0.02-0.6 wt. % Ag (median = 0.07 %). The six analyses given by Palache and others (1944) show no silver; the present samples need to be rechecked by polished section and microprobe to verify whether it is the enargite that hosts the silver. One sample of luzonite, the tetragonal dimorph of enargite, shows 0.14 wt. % Ag.

Other Sulfosalts

Several lead-bearing sulfosalt minerals were analyzed because they were available in large crystallized specimens suitable for the present technique. Four specimens of bournonite, $PbCuSbS_3$, from Peru show trace or no silver (0.0-0.3 wt. % Ag, +/- 0.1 wt. %). One specimen each of gratonite, $Pb_9As_4S_{15}$, from Peru, and boulangerite, $Pb_5Sb_4S_{11}$, from Colorado both show 0.00 wt. % Ag. A specimen of massive zinkenite, ideally $Pb_9Sb_{22}S_{42}$, from the Brobdignag mine, Colorado, shows 0.36 wt. % Ag and also contains some As. Sulfosalts which contain silver as an essential component were not examined in this study, because their silver content is known *a priori*. However, two samples of Pb-Ag-Bi sulfosalts from Leadville, Colorado, were examined because of interest in their mineral identity. A specimen of lillianite(?) (DMNH-5946) from the Lillian mine shows approximately 5 wt. % Ag, and a second specimen (an old ore sample supplied by H. Bachman, from an unidentified mine in Leadville) of a massive, silvery-gray Pb-Ag-Bi sulfosalt, which in polished section appears to be homogenous, shows about 13 wt. % Ag and gives an X-ray diffraction pattern resembling ourayite (in addition to the elements reported in Table 1, this sample also shows 2% Mn and 0.3% U; it is slightly radioactive). Ideal lillianite is $Pb_3Bi_2S_6$, but a number of closely related silver-bearing minerals exist, including heyrovskyite, schirmerite, ourayite, and others (see Foord, this volume). The exact mineralogical identities of these two samples are yet to be determined.

Conclusions

The determination of silver content in galena from a variety of mines provides a preliminary look at the range of distribution of this metal from many deposits, some of which are no longer accessible. The trace element chemistry of the galena can be a guide to the presence of included or exsolved minerals, and may be of use in correlating types of deposits or conditions of formation. The presence of high amounts of uncommon trace elements (such as Sn or Te) in some samples invites further examination for the presence of unusual minerals or for possible indications of a distinctive environment of mineralization. Silver in the tetrahedrite-tennantite series, in agreement with other published work, tends to be more commonly enriched in the tetrahedrite-rich members of the series. The silver content of the other investigated lead sulfosalts tends to be quite low; a tentative order of abundance of Ag in the investigated minerals is tetrahedrite > tennanatite > zinkenite $\geqslant$ luzonite $\geqslant$ enargite $\geqslant$ bournonite > boulangerite = gratonite. A study of the partitioning of silver and other metals between sulfide and sulfosalt phases in a given deposit has much potential value for providing information about the chemistry, temperature, source, and depositional history of the fluids which formed the deposit.

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TABLE 1 DESCRIPTION OF SAMPLES, AND ANALYSES (WEIGHT PERCENT)

GALENA

	Ag	Cd	Sn	Sb	Te	Bi
Atlantic Cable mine, Rico, CO, DMNH-8453; massive w/cpy, sphal	0.03	0.01	-	0.05	-	0.2
Bachelor mine, Ouray Co., CO, DMNH-8929; 1-5 mm cleavages w/barite, cpy, tetrahedrite	0.50	-	-	0.60	-	-
Bard Creek mine, Empire, Clear Creek Co., CO, DMNH-5091; cleavages w/pyrite, sphalerite	0.62	P	0.22	0.30	-	-
Bedrock Creek, La Plata Mtns., CO, DMNH-370; 1-cm cleavages in rock matrix	0.26	0.02	-	0.05	-	2.5
Betty mine, Guffey, Park Co., CO, DMNH-13674; cleavages w/cpy in calc-silicate schist	1.0	-	-	1.2	-	0.3
Black Cloud mine, Leadville, CO, BC-2; granular band in sphalerite-pyrite-siderite ore	0.05	-	-	0.09	-	0.1
Black Cloud mine, Leadville, CO, BC-3; 5-mm cubic crystals w/pyrite, siderite	0.12	-	-	0.08	-	-
Boomer mine, Badger Flat, Park Co., CO, DMNH-15375; massive cleavages	0.70	-	-	0.05	-	0.2
Bulldog mine, Creede, CO, CR-1; massive 2-cm vein w/chalcopyrite crystals	0.95	P	-	0.50	-	0.2
Bullion mine, Montezuma, Summit Co., CO, DMNH-6412; massive cleavages	0.08	-	-	0.03	-	-
Calliope mine, Ouray, CO, DMNH-8457; solid granular mass; [A] - fine-grained (<1 mm)	4.8	-	-	1.4	-	0.3
" " " " " " [B] - coarser-grained area (3-4 mm)	2.3	-	-	1.0	-	0.1
Camp Bird mine, Ouray Co., CO, DMNH-14524; 5-mm cubo-octah. xls w/chalcopyrite, sphalerite	0.39	P	-	0.64	-	0.07
Capitol City mine, Hinsdale Co., CO, DMNH-2392; [A] 1-3 cm cleavages surr. by cerussite	0.16	-	-	0.21	-	0.4
" " " " " " [B] chalky, fine-grained, laminated cerussite	0.13	-	-	0.11	-	0.2
Commodore mine, Creede, CO, CR-2; disseminated in breccia w/minor chalcopyrite	0.03	0.02	-	0.11	0.15	0.2
Commodore mine, Creede, CO, CR-3; in vuggy breccia w/sphalerite	0.03	P	0.01	m	0.08	0.1
Creede, CO, DMNH-14947; 2x3-cm cleavage with chalcopyrite	0.03	-	-	-	-	0.2
Creede, CO, PJM-2539; 1-cm cubo-octah. crystals w/minor chalcopyrite, quartz	0.01	-	-	0.01	-	-
Eagle mine, Gilman, CO, DMNH-9652; 5-10 cm cubo-oct. xls on sphalerite, pyrite	0.015	0.12	-	0.07	-	0.1
Eagle mine, Gilman, CO, DMNH-10416; 3-9 mm, cubo-oct. xls atop sphalerite	0.05	-	-	0.13	-	0.1
Eagle mine, Gilman, CO, DMNH-11498; 1-2 cm cubic crytals atop sphalerite	0.08	-	-	0.12	-	-
Gates mine, Leadville, CO, DMNH-9410; [A] residual 1-cm cleavages surr. by cerussite	0.38	-	-	0.04	-	0.1
" " " " [B] coarsely crystalline cerussite surrounding galena	0.01	-	-	0.02	-	-
Hayseed mine, Central City, CO, #88-6-7-4; cleavages w/minor pyrite, sphalerite	0.08	-	-	0.07	-	0.2
Iowa Tiger mine (?), Silverton, CO, DMNH-6463; mass. cleavages w/cpy, sphal	0.06	-	-	0.07	-	-
Julia Fisk mine, Leadville, CO, DMNH-11331; 3-5 mm cubo-oct. xls on rhodochrosite	0.11	-	-	0.17	-	-
Keystone mine, Crested Butte, Gunnison Co., CO, DMNH-11282; cubo-oct. xls w/py, qtz, sid	0.21	-	-	0.23	-	0.1
Last Chance mine, Creede, CO, GR-4; 5-10 mm crystals in banded vein w/amethyst	0.12	-	-	0.28	-	nm
Mendota-Frostberg mine, Silver Plume, Clear Creek Co., CO, DMNH-12860; cubo-octah. xl	0.11	-	-	0.12	-	0.2
Monarch dist., Chaffee Co., CO, DMNH-368; single 3x5 cm cleavage cube	0.30	-	-	0.5	-	-
Neuman mine, Aspen, CO, DMNH-14943; 3-cm cleavage w/sphalerite	0.01	-	-	0.02	-	0.1
Ophir, San Miguel County, CO, DMNH-375; mass of 1-cm cubic crystals	1.0	0.03	-	3.6	-	0.1
Osceola mine, Silverton, CO, DMNH-11010; 1-cm xls w/sphalerite, quartz	0.03	0.07	-	0.09	-	0.1
Patch mine, Central City, CO, PGH-2; cleavages filling breccia w/sphalerite, quartz	0.16	-	-	0.03	-	0.2
Patch mine, Central City, CO, PJM-1701; 1-cm etched (rounded) cubic crystal	0.14	-	-	0.11	-	0.1
Rex mine, Gold Hill dist., Boulder Co., CO, DMNH-15570; w/pyrite, sphal., ?tenn., ?HgTe	0.8	0.05	-	7.5	0.4	-
San Antonio mine, Red Mtn. Pass, San Juan Co., CO, DMNH-9357; cleavages w/selenite	0.00	-	-	0.12	-	0.1
Silver Plume (?), Clear Creek Co., CO, DMNH-2382; etched/rounded 2-3 cm xls on quartz xls	0.12	-	-	0.29	-	0.2
Smuggler mine, Aspen, Pitkin Co., CO, DMNH-14944; massive, fine-grained	0.13	0.05	-	0.08	-	0.1
Star mine, Taylor Park, Gunnison Co., CO, DMNH-15620; 1-2 mm cleavages in barite	0.45	-	-	0.43	-	0.1
Sunnyside mine, Silverton, CO, SU-1; granular (1-mm) cleavages in qtz vein w/trace py, cpy	0.05	-	-	0.12	-	-
Sunnyside mine, Silverton, CO, SU-2; massive, granular w/chalcopyrite, pyrite	0.15	-	-	0.35	-	-
Sweet Home mine, Alma, Park Co., CO, DMNH-12465; clvgs w/quartz, cpy, pyrite, ?tetrah	0.48	P	-	0.50	-	0.8
Sweet Home mine, " " DMNH-12488; 2-5 mm cubo-oct. xls w/py, cpy, sphal. [A]	0.27	P	-	0.7	0.13	0.4
" " " " " " [B] - surface of crystals; [A], above, - interior]	0.26	P	-	1.3	0.21	-
Troublesome mine, Geneva Creek, Park Co., CO, #88-6-7-3; 1-3 cm cleavages w/pyrite	0.68	-	-	1.0	-	0.1
Yellow Pine mine, Boulder Co., CO, DMNH-15370; massive, fine-grained w/sphalerite	3.5	P	-	0.16	-	0.0
West McCoy Gulch, Cotopaxi, Fremont Co., CO, DMNH-13641; 1-5 mm cleavages in rock	0.03	-	-	0.15	-	-
White Raven mine, Ward dist., Boulder Co., CO, DMNH-12921; 2-7 mm, complex xls on siderite	0.04	0.01	-	0.14	-	-
White Raven mine, Ward dist., Boulder Co., CO, DMNH-14945; 1-mm xls on siderite stalactite	0.09	P	-	0.07	-	0.6
Wilfley mine, Kokomo, Summit Co., CO, DMNH-14946; cubo-octah. xls w/quartz, pyrite	0.07	-	-	0.10	-	0.3
Blanchard mine, Hansonburg dist., NM; cubic xls in fluorite-barite-quartz ore [avg. of 3]	0.02	-	-	0.02	-	-
Galena King mine, Bernalillo Co., NM, GKM-1; 2-cm cleavage in blue fluorite	0.00	-	-	0.02	-	-
Groundhog mine, Grant Co., NM; 3-5 mm cubic crystals with chalcopyrite	0.25	-	-	-	-	0.5
Mex-Tex mine, Hansonburg dist., NM; cubic xls in fluorite-quartz-barite ore [avg. of 2]	0.015	-	-	-	-	0.2
Huaron, Peru, P-15; intergrown w/minor sphalerite, chalcopyrite, ?tetrahedrite	0.27	-	-	0.29	-	nm

P - present due to contamination by another mineral; m - masked by another element; nm, not measured; (-) - below limit of detection; mineral abbreviations: cpy - chalcopyrite; py - pyrite; qtz - quartz; rhodoc - rhodochrosite; sid - siderite; sphal - sphalerite; tenn - tennantite; tetrah - tetrahedrite

TABLE 1, continued

TETRAHEDRITE-TENNANTITE

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi	End-members Tetr	Tenn	Frei
Bachelor mine, Ouray, CO, DMNH-8929; massive in barite vein w/minor cpy, galena	9	25	5	0.9	26	0.2	m	25	-	3	-	56	6	38
Calhoun mine, Central City dist., CO, DMNH-14692; xls in alt. rock w/py, sphal, galena	4	40	P	5	0.5	0.2	m	26	0.1	1	-	76	23	1
Central City, Gilpin Co., CO, DMNH-583; intergrown 1-3 cm xls w/pyrite & oxidized surf.	5	30	4	3	2.2	0.1	m	25	-	0.5	-	80	16	4
Contention mine, Lake City dist., CO, DMNH-12953; 2-mm xls w/pyrite, quartz, barite	2	38	5	2.8	4.1	0.1	m	27	-	0.3	-	80	14	6
Dunton, San Miguel Co., CO (Tellur. Mines Dev. Co.), DMNH-8446; mass. w/cpy, sphal, rhodoc	4	24	P	0.8	21	m	m	27	-	6	-	61	5	34
Idaho Springs, Clear Creek Co., CO, DMNH-8682; massive w/pyrite, cpy, galena, sphal	P	30	P	<2	11	P	m	29	-	P	-	>75	15	<10
Longfellow mine, Red Mtn., San Juan Co., CO, DMNH-11118; 3-6 mm xls, on sphal, pyrite	4	40	2	15	0.6	0.3	-	4	0.3	0.1	-	13	86	1
Marshall Basin, San Miguel Co., CO, DMNH-577; 3-5 mm xls on quartz xls	4	35	4	1.2	1.5	0.1	m	28	-	0.1	-	89	9	4
McDonnell Claim, Hall Valley, Park Co., CO, DMNH-11348; massive w/cpy, gal in qtz-barite	3	40	3	6.5	5	0.2	m	28	-	P	0.9	66	27	7
Sweet Home mine, Alma, Park Co., CO, DMNH-12176; 1-2 mm xls w/quartz, huebnerite, galena	4	45	P	15	0.09	0.4	-	-	-	P	-	<1	>99	0
Sweet Home mine, Alma, Park Co., CO, DMNH-12467; "freibergite", 1-10 mm xls w/quartz	2	45	4	14	1.2	0.1	m	6.5	0.5	0.2	-	20	78	2
Vermont mine, Capitol City, Hinsdale Co., CO, DMNH-2360; solid mass w/minor cpy, sphal	3	30	5	1.8	6	0.2	m	28	-	0.3	-	79	10	11
Casapalca, Peru, P-6; sharp 1-2 cm xls w/pyrite, galena	3	40	6	5	6	-	m	25	-	3	-	72	20	8
Casapalca, Peru, P-13; sharp xls to 2.5 cm w/pyrite, galena, calcite	2	40	6	5	6	-	m	25	-	2	-	67	25	8
Casapalca, Peru, P-19; large, complex crystals on quartz w/pyrite	3	40	5	15	1.2	-	m	13	-	-	-	33.5	65	1.5
Cerro de Pasco, Peru, DMNH-6349; intergrown 5-15 mm crystals w/sphalerite, cpy	2	40	4	12	1.3	0.1	m	16	-	0.1	-	43	55	2
Huancavalica, Peru, P-1; crystals in rhodochrosite	6	32	5	3.5	1.6	-	m	25	-	-	-	78	19	13
Morococha, Peru, DMNH-7225; intergrown to free 1-cm crystals w/quartz, minor chalcopyrite	2	60	0.3	18	0.10	-	0.4	2.6	-	0.1	-	8	92	0
Pachapaqui, Peru, P-5; crystals with kutnahorite	5	40	5	10	1.8	-	-	15	-	1	-	55.5	42	2.5
Pachapaqui, Peru, P-14; 3-mm tetrahedral xls w/quartz, pyrite, galena	5	40	6	19	1.1	-	-	1.6	-	-	-	3.5	95	1.5
Pachapaqui, Peru, P-17; crystals w/sphalerite, pyrite, galena, quartz	P	40	P	15	0.6	P	-	8	-	P	-	24	75	1
Pasto Bueno, Peru, P-7; crude 2.5-cm crystals on quartz	1	40	6	3.6	0.64	-	-	25	-	-	-	79	20	1
Pasto Bueno, Peru, P-18; intergrown 6-mm crystals	6	45	3	19	0.15	0.1	0.15	0.7	0.1	0.1	-	2	98	0
ideal tetrahedrite	-	45.8	-	-	-		-	29.2	-	-	-	100	-	-
ideal tennantite	-	51.6	-	20.3	-		-	-	-	-	-	-	100	-

ENARGITE, Cu_3AsS_4

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
Summitville, Rio Grande Co., CO, DMNH-10988; crust of 1-2 mm crystals w/pyrite	2	50	-	15	0.10	-	0.18	1	0.3	-	-
Willis Gulch, Gilpin Co., CO, DNMH-611; massive intergrown enargite blades, w/pyrite	0.4	50	-	14	0.25	-	-	2.4	-	0.05	-
"New Mexico", DMNH-2334; massive intergrown blades	0.3	48	-	13	0.03	-	0.13	0.3	0.06	0.1	0.1
Cerro de Pasco, Peru, DMNH-6348; 1-2 cm crystals w/oxidized surface coating	4	50	-	17	0.06	-	0.27	1.2	0.14	0.2	-
Cerro de Pasco, Peru, DMNH-7456; crust of 1-2 mm crystals	-	50	-	14	0.02	-	0.4	3	0.1	-	-
Cerro de Pasco, Peru, DMNH-7526; massive enargite w/chalcopyrite-pyrite-?luzonite	4	35	-	10	0.07	-	0.8	5	0.04	0.1	-
Morococha, Peru, DMNH-6572; intergrown crystals w/pyrite, cpy, qtz, ?tetrah, gypsum	1.5	48	-	14	0.08	-	0.2	1.8	-	-	-
Morococha(?), Peru, DMNH-9347; 2-5 cm crystal blades, coated by quartz	0.3	48	-	13	0.61	-	-	3	-	0.1	-
ideal enargite	-	48.4	-	19.0	-	-	-	-	-	-	-

LUZONITE, Cu_3AsS_4

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
Reynolds Tunnel, Summitville, CO, DMNH-11100; solid, sl. vuggy mass w/qtz, trace pyrite	1	50	-	17	0.14	-	0.3	1.4	0.6	0.2	-
ideal luzonite	-	48.4	-	19.0	-	-	-	-	-	-	-

TABLE 1, continued

BOURNONITE, $PbCuSbS_3$

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
La Oroya, Julcani dist., Peru, P-2; intergrown crystals	-	12	-	8	0.1	-	-	18	-	40	0.5
La Oroya, Julcani dist., Peru, P-16; intergrown crystals	-	12	-	8	0.1	-	-	18	-	40	nm
Pachapaqui, Peru; P-12; crystals on quartz, with sphalerite	2	14	P	11	0.3	-	-	23	-	40	nm
Quiruvilca, Peru, P-11; single crystal	-	15	-	4	0.0	-	-	27	-	40	nm
ideal bournonite	-	13.0	-	-	-	-	-	24.9	-	42.4	-

BOULANGERITE, $Pb_5Sb_4S_{11}$

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
Poverty Gulch, Baxter Basin, Gunnison Co., CO, DMNH-579; fibrous mass	0.4	-	-	-	0.00	-	-	22	-	55	-
ideal boulangerite	-	-	-	-	-	-	-	26.0	-	55.2	-

GRATONITE, $Pb_9As_4S_{15}$

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
Cerro de Pasco, Peru, DMNH-7437; cluster of 2-4 mm crystals	0.3	-	-	20	0.00	-	0.2	0.2	-	70	-
ideal gratonite	-	-	-	11.3	-	-	-	-		70.5	-

LILLIANITE GROUP, $Pb_3Bi_2S_6$

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
Lillian Mining Co., Leadville, CO, DMNH-5946; massive silvery-gray w/pyrite, cpy	P	3	-	-	6	0.4	-	0.14	0.5	60	14
Leadville (?), CO, LE-2; solid silvery-gray mass with pyrite	6	3	0.7	-	13	0.08	-	0.09	0.14	40	29
ideal lillianite	-	-	-	-	-	-	-	-	-	50.5	33.9

ZINKENITE, $Pb_9Sb_{22}S_{42}$

	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
Brobdignag mine, San Juan Co., CO, DMNH-546; solid mass	-	3	-	18	0.36	-	-	24	-	32	0.1
ideal zinkenite	-	-	-	-	-	-	-	45.5	-	31.7	-

Appendix: analytical methods

Samples were analyzed using a KEVEX energy-dispersive, X-ray fluorescence spectrometer. With this technique, samples are exposed to radiation from an artificial radioisotope source, and the spectrum of X-ray energies emitted from the sample is counted and displayed. Table 2 gives the typical analytical uncertainties and limits of detection for those elements that were present in detectable amounts. Analytical sensitivity is lowest for Fe and highest for the elements Ag-Cd-Sn-Sb-Te; sensitivity for Bi in galena and other lead-rich samples is relatively poor because the Bi X-ray emission lines lie close to those of Pb and are partly masked by them.

Table 2

Analytical uncertainty in determination of metals in galena and sulfosalts

element	Fe	Cu	Zn	As	Ag	Cd	Sn	Sb	Te	Pb	Bi
error (wt. %)	0.03	0.04	0.01	0.04	0.005	0.007	0.01	0.015	0.006	0.01	0.10

Normally, quantitative data on the KEVEX system are obtained on powdered samples, or pressed pellets, of silicate-dominant rocks. In the present study, however, the metal sulfide-rich sample compositions differed considerably from those for which the system is normally calibrated. In addition, most samples were analyzed nondestructively, using (insofar as was possible) relatively clean and monomineralic broken crystal surfaces or crystal faces. The method permits the nondestructive examination of crystallized museum specimens, and makes it easy to analyze and compare several different areas or surfaces of a specimen. When used in this mode, because of the irregular surface and variable matrix composition of the material analyzed, absolute concentrations of elements were not determined directly; rather, ratios between elements were measured (such as Ag:Pb for galena, and Cu:As:Sb:Ag for tetrahedrite-tennantite), and the results were recalculated to a weight percentage basis according to the known or inferred bulk composition of the mineral being analyzed. Instrumental response was calibrated by analyzing powdered reference samples of several artificially prepared mixtures of reagent-grade chemicals, including compositions close to those of tetrahedrite, tennantite, enargite, and galena, containing known additions of Fe, Zn, As, Ag, Sb, and Bi. Also used as a standard was a reference sample of galena high in Ag and Bi (containing 0.75 wt.% Ag and 1.35 wt.% Bi, from the Pequea silver mine, Pa.), previously analyzed by E.E. Foord (see Foord and others, 1988). The results presented here are semiquantitative and are accurate to an estimated +/-20% of the amount present, though admixed impurities may cause larger errors. Elements such as Ca, Mn, Sr, and Ba, though detected in some samples, were normally present as components of associated gangue minerals, and are not reported here.

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