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Geologic setting of the Leadville mining district, Lake County, Colorado

by

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PREFACE

This geologic summary of the Leadville, Colorado, mining district is part of an interagency agreement between the U.S. Geological Survey (USGS) and the Environmental Protection Agency (EPA) related to the California Gulch Superfund Site in Leadville, Colorado. Under the agreement, the USGS provides expert, objective geologic input regarding the geology and mineral deposits of the Leadville mining district. The report, a summary based upon the published literature and the author's first-hand experience in the area, provides a general foundation and framework for the agreement and Superfund project.

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GENERAL SUMMARY

The Leadville mining district, in Lake County, Colorado, contains one of the largest lead-zinc-silver deposits in the world. Discovered in 1858, the district has produced more than $5 billion worth of metals.

The ore deposits formed approximately 39 million years ago at a depth of more than five kilometers. The largest deposits formed where hot fluids carrying metals and sulfur ascended faults, dissolved carbonate rocks, and deposited the metals as sulfide minerals. Many of these orebodies formed where the fluids were impeded by impermeable layers and forced to dissolve the underlying carbonate rocks to form thin but laterally extensive deposits of sulfide minerals. Ore minerals also were deposited along the faults to form veins.

After a series of geologic events, the ore deposits were eventually exposed at the surface where the sulfide minerals in the upper part of the deposit were converted into lead carbonate and zinc carbonate minerals that are stable at the surface. The deposits were eventually buried by sediments, then partially uncovered during relatively recent glaciation. Gold eroded from the newly exposed deposits washed into California Gulch to form placer deposits. Miners that worked the gold placers eventually discovered the nearby lead-zinc-silver deposits in the carbonate rocks.

Just prior to the discovery of the ore deposits, the eventual site of the district was a high, windswept, tree-covered area underlain largely by gravels and in part by exposures of ore and the rocks that contained the ore. Modern, unmined analogs for that deposit type and in a similar setting may exist but have not yet been discovered. Predictive modeling, using knowledge of geologic and geochemical processes, would probably provide the best estimates of the pre-mining conditions at Leadville.

INTRODUCTION

The mineral deposits of the Leadville mining district, located at about 10,000 feet in Lake County, Colorado (fig. 1), comprise one of the world's largest polymetallic replacement deposits. Since the discovery of placer gold in the California Gulch drainage in 1858, more than $5.4 billion (1989 metal prices; Thompson and Arehart, 1990) of gold, silver, lead, and zinc have been extracted from the several square miles that constitute the district.

As with any highly mineralized area, the Leadville district has been the focus of numerous geologic studies, commencing with the early work by S.F. Emmons (Emmons, 1886; Emmons and others, 1927) and including later studies by Behre (1953), Tweto (1968), Thompson and Arehart (1990), and Thompson and Beaty (1990). These geologic studies have dealt with a wide variety of topics, ranging from general geology to more detailed investigations of mineralogy, alteration, geochronology, and isotope geochemistry. Coupled with geologic work in the surrounding area, the resulting literature provides a fairly complete understanding of the geology and genesis of the mineral deposits.

This paper summarizes the geology of the Leadville mining district, based upon the published literature and this writer's geologic experience in and around the district. A wealth of details is available in publications referenced in this paper, and the reader should consult those reports for any additional information required.

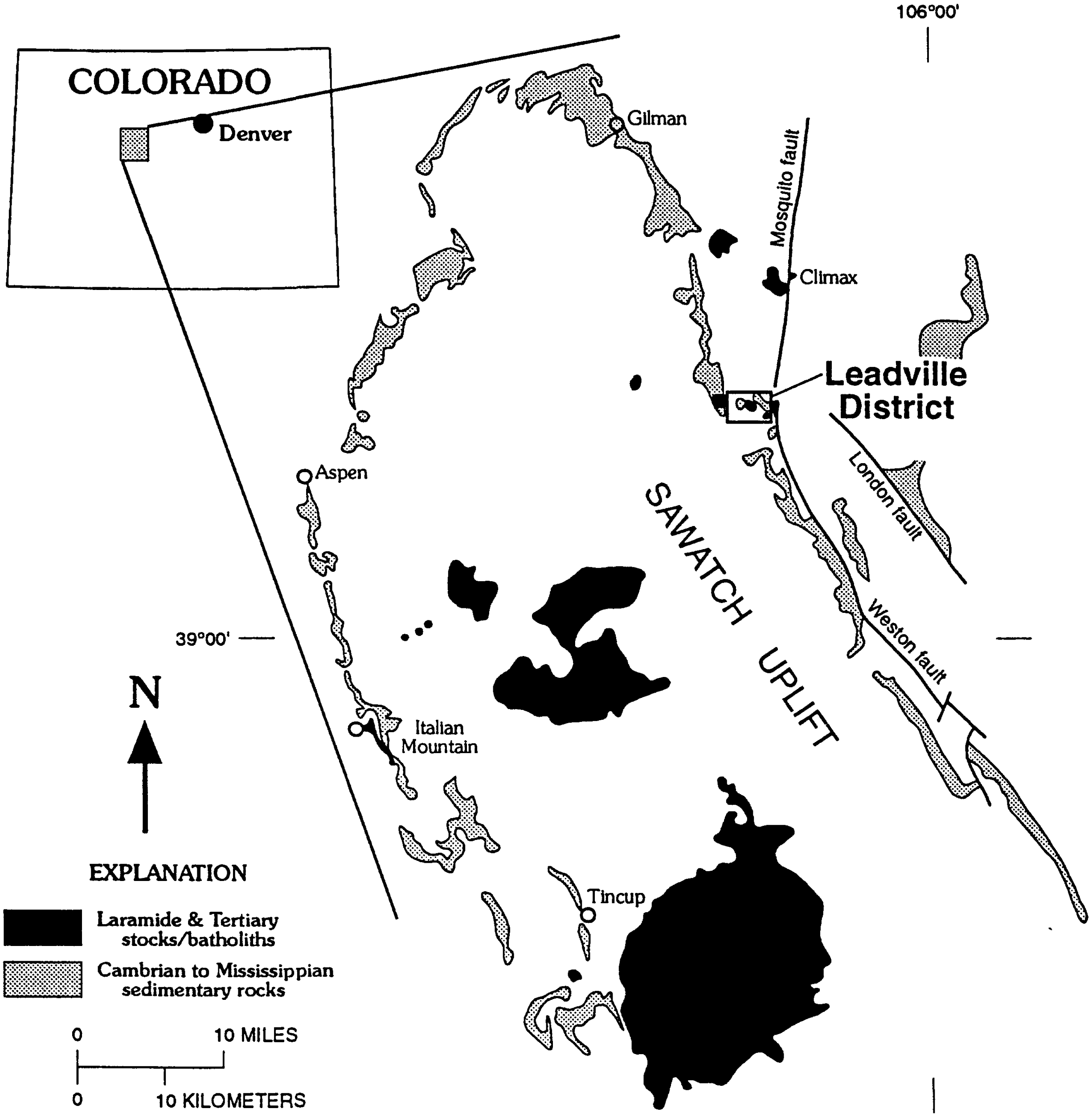

Figure 1. Location map, showing the Leadville district and other mineral deposits in the area.

The purpose of this summary is to provide a geologic foundation for hearings regarding the Environmental Protection Agency's CERCLA project in the California Gulch area in specific and the Leadville district in general. The report does not focus specifically on the California Gulch area, but rather places that part of the district in a larger geologic framework. Where necessary, specific aspects of the California Gulch area are noted as they pertain to the overall geologic scenario. Because this paper is intended to provide detailed technical information, it is written in scientific language rather than for a lay audience. The *Glossary of Geology* (Bates and Jackson, 1987) should be consulted for definition of terms; a geologic time scale is provided as Appendix A.

BRIEF HISTORY OF MINING

The history of mining in the Leadville district describes a series of booms and busts. Prospectors working their way up the Arkansas River drainage discovered gold in stream gravels along California Gulch in 1860, precipitating a robust but short-lived boom, and the first lode gold deposit was discovered on Printer Boy Hill along the upper flanks of California Gulch in 1868. The placer operations were plagued by a heavy, apparently worthless mineral that, when finally analyzed, turned out to be argentiferous lead carbonate. This revelation led to the discovery of outcrops of lead-silver ore in the upper part of the California Gulch drainage in 1874. Additional orebodies were discovered, either by design or blind luck, throughout much of the rest of the present-day district. Rich zinc ores were recognized in 1909, leading to a zinc boom that lasted until after World War I. Financial panics in 1893 and 1907-08, as well as a protracted labor strike in 1896-97, precipitated sudden declines in production in the district. Activity declined until 1935, with the discovery of veins in the eastern part of the district near the Resurrection mine, and, after World War II, in a downfaulted block in the vicinity of Breece Hill. The Sherman and Black Cloud mines were opened in the 1970's, but only one, the Black Cloud, is still open.

Early mining exploited the relatively shallow oxidized ores which were amenable to fairly simple metal extraction. As the mines became deeper, non-oxidized sulfide ores, which required more complex smelting techniques, were encountered. With increased depth the mines also were forced to deal with increased amounts of ground water, and, as a result, several long tunnels were excavated to penetrate the deeper workings and drain the water. In addition to draining the deeper mines, these tunnels were designed to penetrate stratigraphic intervals that experience had shown to be favorable sites for mineralized rock. The Yak tunnel extends from California Gulch northeastward beneath Breece Hill, and the Leadville tunnel extends southeastward from the Arkansas River valley north of the town of Leadville.

REGIONAL GEOLOGIC SETTING

The geologic history of central Colorado spans more than 1.8 billion years, commencing with the Early Proterozoic accretion of volcanic arc and back-arc complexes to the southern margin of the Archean Wyoming craton. These rocks were complexly deformed and intruded by large Early and Middle Proterozoic batholiths. During Paleozoic and Mesozoic time, the Proterozoic basement complex was buried beneath several kilometers of marine and continental sediments, and it was partially exhumed during Pennsylvanian orogenic uplift. Subduction-related alkalic-calcic magmatism and uplift affected the region during the Late Cretaceous-early Tertiary Laramide orogeny. Post-subduction Oligocene and younger extension generated the north-trending Rio Grande rift zone, which was accompanied by bimodal magmatic activity.

Most of the mineral deposits in the central Colorado mineral belt are associated with Oligocene subduction-related magmatism or later rift-related activity. Laramide deposits are relatively small, and a few carbonate-hosted deposits may be of Mississippian age.

ROCK UNITS

The Leadville district lies on the west flank of the Mosquito Range at the head of the Arkansas River valley, a deep graben that was created during the Late Tertiary development of the generally north-trending Rio Grande rift. Rifting exposed Paleozoic sedimentary rocks which overlie Proterozoic granites and which were intruded by Late Cretaceous and younger igneous rocks (fig. 2). Orogenic sediments were deposited in the graben during uplift and erosion of the adjacent Sawatch and Mosquito ranges. Quaternary glaciation further modified the landscape and locally redistributed the orogenic sediments in the district.

Proterozoic Rocks

According to Tweto and others (1978), the oldest rocks exposed in the Leadville district are granites of the Middle Proterozoic (about 1,400 Ma (million years old)) St. Kevin Granite. Some of these rocks, however, actually are part of the older 1.7-Ga suite of plutonic rocks (E.H. DeWitt, personal commun., 1993). The unit is composed principally of peraluminous two-mica granites. Surface exposures are relatively limited within the district, but they are more common to the east and south and in the Sawatch Range to the west. The St. Kevin was encountered in many of the deeper workings in the district.

Paleozoic Sedimentary Rocks

Shallow marine Paleozoic limestones, dolomites, sandstones, and quartzites overlie the St. Kevin Granite in the Leadville district. The combined Paleozoic and now-absent Mesozoic stratigraphic section exceeded 11,000 meters, but Tertiary uplift, faulting, and erosion have reduced that total to, at most, 7,000 meters and, locally within fault blocks, to less than a hundred meters.

The lower part of the stratigraphic section at Leadville is composed principally of quartzite with subordinate amounts of carbonate rocks and shale; units include the Sawatch Quartzite, Peerless Formation, Manitou Dolomite, and Parting Sandstone, ranging in age from Late Cambrian to Late Devonian, with a total thickness of about 265 meters (fig. 3). Overlying these units are roughly 150 meters of predominantly carbonate rocks, including the Late Devonian Dyer Dolomite ("White Limestone" of the older literature), Early Mississippian or Late Devonian Gilman Sandstone, and the Early Mississippian Leadville Dolomite ("Blue Limestone" of the older literature). The Leadville was exposed and partially eroded during the Pennsylvanian, creating a karst-like topography and a regolith known as the Molas Formation. These units are capped, principally to the north and northeast, by sandstone, shale, and minor limestone of the Pennsylvanian Belden and Minturn Formations ("Weber Shales and Grits," respectively, of the older literature).

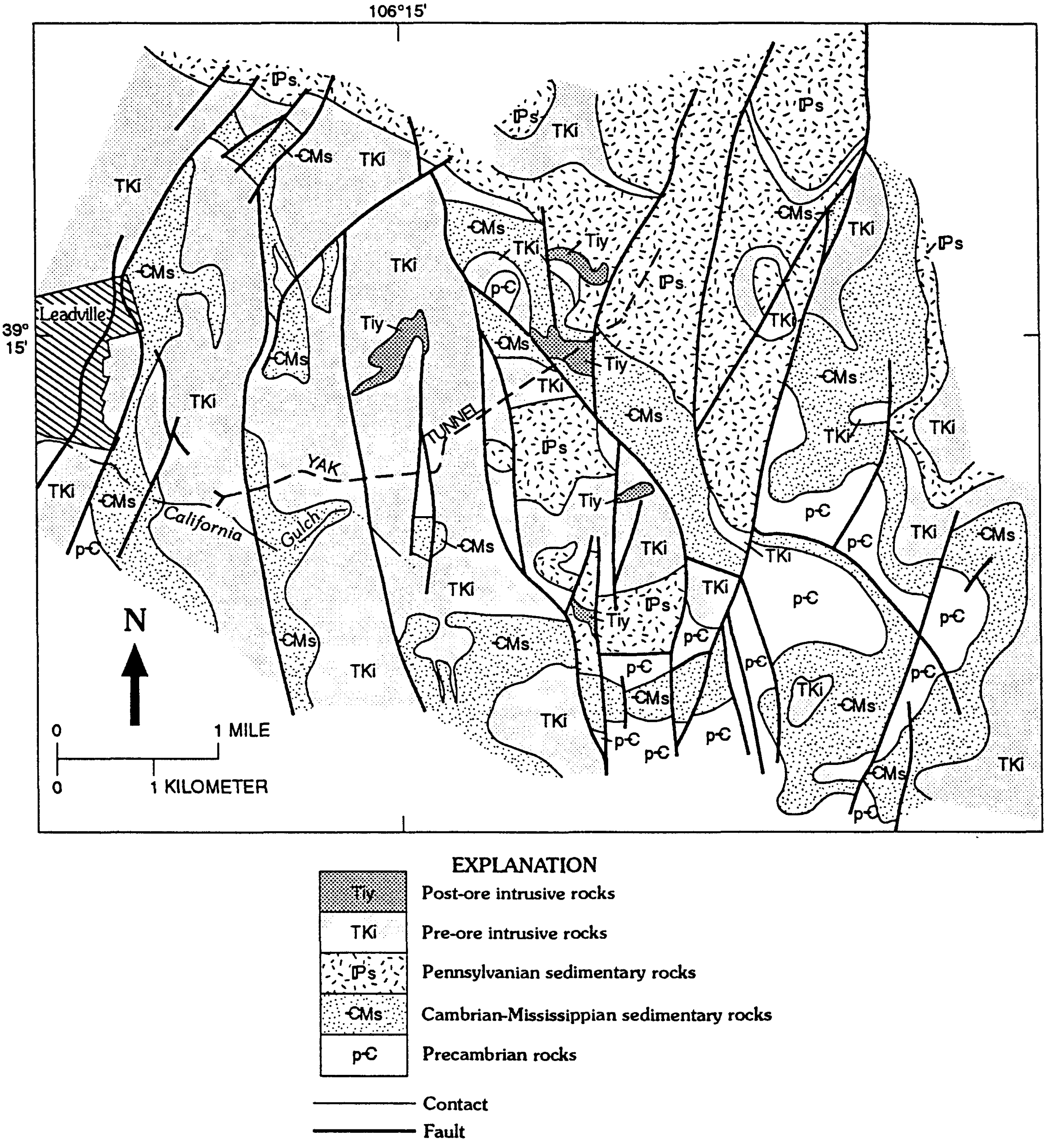

Figure 2. Basement geologic map of the Leadville mining district. Modified from Thompson and Arehart (1990).

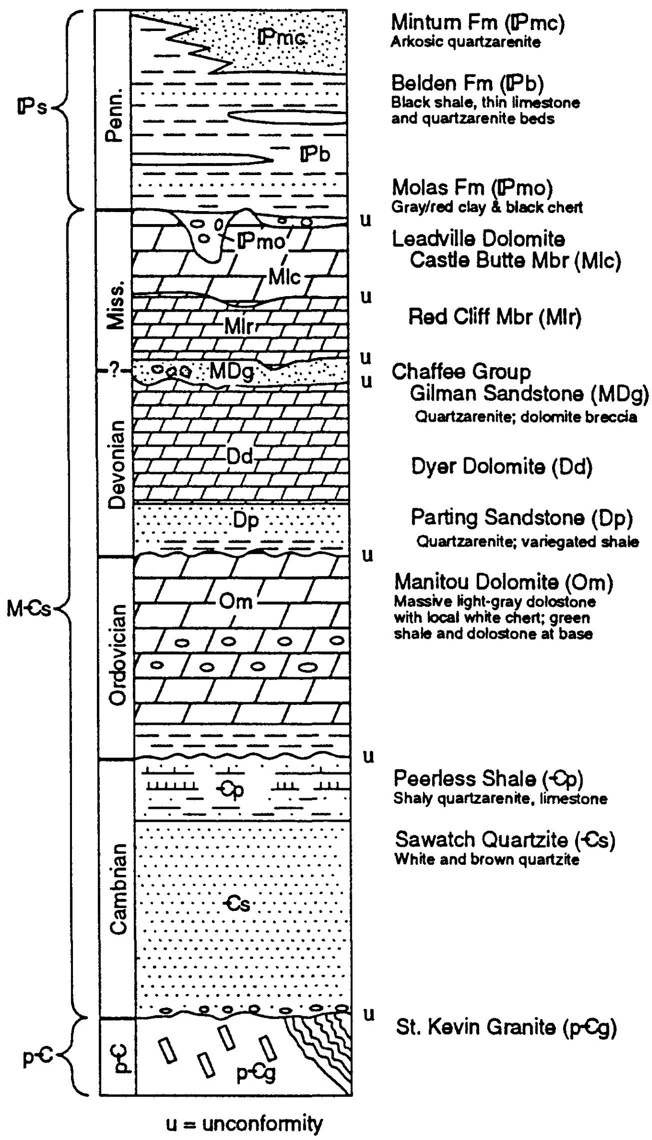

Figure 3. Pre-Tertiary stratigraphic section of the Leadville district. The replacement ore deposits of the district occur principally in the Leadville Dolomite and the Dyer Dolomite. Modified from Thompson and Arehart (1990).

Late Cretaceous and Tertiary Igneous Rocks

Central Colorado was subjected to major intrusive events in Late Cretaceous-early Tertiary time (approximately 72-64 Ma) and again in the middle Tertiary (43 to 39 Ma). Within the Leadville district and nearby areas, the intrusive activity produced sills, dikes, and small stocks of granodioritic to monzogranitic composition (Bookstrom, 1990). Many magmas werecontacts between sedimentary units, especially between the Belden and Leadville (the "first contact" of Emmons, 1886), but intrusive bodies commonly cut across the stratigraphic section. Magmas invaded many faults, including shallow-dipping Laramide thrust faults and high-angle younger faults, forming structurally controlled dikes.

The early literature (Emmons, 1886; Emmons and others, 1927) divided the intrusive rocks into two major pre-ore groups: the White Porphyry and the Gray Porphyry (table 1). The White Porphyry is now referred to as the Pando Porphyry, which was emplaced at about 72 Ma (recalculated from Pearson and others, 1962). The Gray Porphyry includes igneous rocks formed during several early to middle Tertiary intrusive events; units include (from oldest to youngest) the Lincoln (66 Ma), Evans Gulch, Sacramento, and Johnson Gulch porphyries. Within the Leadville district, the Johnson Gulch porphyry is the most widespread intrusive rock; it is exposed at Breece Hill, and forms numerous laccolithic sills and crosscutting dikes. The age of the Johnson Gulch porphyry is equivocal, but all field and geochronologic evidence indicate that it is of early to middle Tertiary age and was emplaced before the 39-Ma ore-forming event.

The thermal center of the Leadville district was centered on the Breece Hill area, and geologic and isotopic evidence indicate that the magmatic source for the mineralizing system was an unexposed igneous body beneath the Breece Hill stock (Thompson and Arehart, 1990; Thompson and Beaty, 1990). Two igneous units were emplaced shortly after mineralization, a 38.5-Ma rhyolite porphyry and a fragmental porphyry ("rhyolite agglomerate" of Emmons and others, 1927). These igneous units are centered around the Breece Hill stock, and both clearly cut the Leadville orebodies. Thompson and Arehart (1990) note that minor veins cut the fragmental porphyry, suggesting that the units were emplaced during the waning stages of intrusive activity and related mineralization.

Tertiary Sedimentary Rocks

Post-middle Tertiary uplift of the Sawatch and Mosquito Ranges and formation of the Arkansas River valley induced erosion of the rising ranges and deposition of orogenic sediments into the graben. At Leadville, erosion exposed many orebodies, which consequently became oxidized during prolonged surface exposure. This initial erosion of mineralized rocks probably removed an unknown quantity of sulfide and partially oxidized ore, which was transported as sediments into the graben to the west. As sedimentation in the graben continued during the late Tertiary, the orebodies, and probably much of the area of the modern Leadville district, were progressively covered by the orogenic sediments. These poorly consolidated sediments, known as the Dry Union Formation (the "lake beds" of the early literature), are composed of sandy silt and interbedded sand and gravel layers. Where the sediments have not been totally stripped by subsequent erosion, total thickness varies from a few to several hundred meters; in the Arkansas River valley west of Leadville, the thickness exceeds a kilometer (Tweto and others, 1978).

Much of the ridge east from Carbonate Hill to Bald Mountain is directly underlain by bedrock with a thin veneer of rocky soil ("wash" of Emmons and others, 1927), and it is unknown if this ridge was at one time covered by the Dry Union Formation. A remnant of the Dry Union Formation is exposed at the northeast flank of Carbonate Hill, and the unit extends east along the

Table 1. PRINCIPAL PHANEROZOIC IGNEOUS ROCKS, LEADVILLE MINING DISTRICT

Unit Name	Age (Ma)*	Former Nomenclature
Fragmental porphyry	<38.5	Rhyolitic agglomerate
Rhyolite porphyry	38.5	Late White Porphyry
Johnson Gulch Porphyry	43.1	Gray Porphyry
Sacramento Porphyry	43.9	Gray Porphyry
Evans Gulch Porphyry	47.0	Gray Porphyry
Lincoln Porphyry	66.0	Gray Porphyry
Pando Porphyry	74.0	White Porphyry Mt. Zion Porphyry Early White Porphyry

* Geochronology from Pearson and others (1962; ages recalculated using new standards), Cunningham and others (1977), and Thompson and Arehart (1990).

ridge between California Gulch and Iowa Gulch; both areas are topographically lower than the Carbonate Hill-Bald Mountain ridge, suggesting that the ridge may have remained uncovered during Dry Union sedimentation.

Quaternary Deposits

Three periods of glaciation significantly modified the topography of the Leadville district during the Pleistocene, carving deep, U-shaped valleys and creating thick terminal and lateral moraines. Although no modern work has been done on the glacial geology of the Leadville district, the earlier descriptions by Behre (1953) and Emmons and others, (1927) provide at least a sense of the distribution of the glaciers and their deposits.

Major glaciers occupied the Evans Gulch and Iowa Gulch valleys during the glacial periods, transforming pre-existing valleys into the deep, U-shaped valleys visible today. Older glaciers of pre-Bull Lake age extended farther west, depositing gravels over much of the area within and west of the present town of Leadville (Tweto, 1974). Bull Lake and Pinedale glacial till was deposited in lateral moraines along high flanks of the valleys and in terminal moraines which formed at the maximum downstream extent of the glaciers. As the glaciers retreated, a few tens of meters of till and outwash material were deposited in the valley bottoms. The resulting materials are composed of unconsolidated, poorly sorted subangular fragments ranging in size from silt to boulder.

The thicknesses of the moraines vary considerably and generally thicken to the west (Behre, 1953). No depth-to-bedrock map has been compiled for the district, although estimates can be gleaned from cross sections in Emmons and others (1927). In the Fryer Hill area north of Carbonate Hill (fig. 2), which is underlain in part by the terminal moraine of the Evans Gulch glacier, glacier deposits are at least 30 meters thick. In the Downtown district beneath the town of Leadville, cross-sections show a total cover exceeding 200 meters (Tweto, 1974; Emmons and others, 1927) that thins eastward over an irregular paleosurface to between 10 and 30 meters (Tweto, 1974). At Printer Boy Hill, the thickness of the lateral moraine along Iowa Gulch is about 10 meters but increases to the west (Behre, 1953).

Not all drainages in the Leadville area were occupied or influenced by glaciers. California Gulch and Stray Horse Gulch, on the south and north sides of Carbonate Hill, respectively, are relatively young V-shaped drainages.

STRUCTURAL GEOLOGY

Stratified rocks of the Leadville district dip moderately to the east, forming a homocline that, prior to Neogene rifting, once formed the eastern flank of the Sawatch uplift. This homocline is cut by a complex network of faults, most of which dip steeply, but a few of which, as noted by Thompson and Arehart (1990), are low-angle thrusts that presumably formed during the Laramide.

Trends of the principal faults in the district are about N15°E and N20°W, consistent with the trends of major regional faults in the district (Tweto, 1960, 1968). Movement was complex: individual faults show evidence of both normal and reverse movement both laterally and sequentially during reactivation. The amount of displacement also varies considerably, ranging from a few tens to hundreds of meters. The earliest faults demonstrably formed prior to intrusion of the Pando Porphyry; these faults were variously reactivated, and new faults formed, during intrusion of the different igneous bodies during the Paleogene. Tweto (1960) was able to show that virtually all of the major faults in the district formed prior to mineralization.

The mineralized rocks of the district owe their exposure in large part to formation of the Rio Grande rift, a major intracontinental rift that extends northward from west Texas into at least central Colorado. At the latitude of Leadville, rift-related processes produced broad regional doming (Eaton, 1986) and concomitant downdropping of the longitudinal axis of the dome to form what is now the Arkansas River graben. In effect, the rift severed the Sawatch uplift to form the Sawatch Range to the west and the Mosquito Range, including the Leadville district, to the east. Within the district, the major effect of the regional doming and rifting was twofold: (1) to raise the mineralized zones from a depth of several kilometers to a near-surface position, and (2) to segment the orebodies along rift-related normal faults. The normal faults, which trend north-northwesterly and dip steeply, progressively raised the east-dipping rocks and orebodies to the east. As noted by Tweto (1968), this process fortuitously placed the orebodies progressively higher to the east, generally parallel to the eventual topography and thereby kept the orebodies in a relatively economic position to be exploited.

ORE DEPOSITS

Most of the ore deposits in the Leadville district formed during a major mineralizing event at about 39 Ma, by wholesale replacement of the Paleozoic carbonate rocks by silver-, lead-, zinc-, and gold-rich sulfide minerals. These orebodies were exposed during the early formation of the Arkansas River valley, at which time supergene oxidation and enrichment of the sulfide ores took place. Orogenic sediments of the Dry Union Formation eventually blanketed the Leadville area, which remained covered until Quaternary glaciation and erosion, at which time the placer gold deposits of California Gulch formed. As a result, the deposits can be discussed in three broad categories: primary, secondary (supergene), and placer.

Primary Deposits

As defined by Thompson and Arehart (1990), primary ore deposits of the Leadville district generally fall into three categories: (1) magnetite-serpentinite deposits around the Breece Hill stock, (2) carbonate-hosted barite-silver deposits ("Sherman-type" of Behre (1953), and (3) carbonate-hosted silver-lead-zinc deposits ("Leadville-type"). The Leadville-type ores are by far the most widespread and economic of the types and are the focus of this discussion. However, the other two were economically significant in certain parts of the district.

The magnetite-serpentinite deposits formed during intrusion of the Breece Hill stock and are present within 200 meters of the stock. In addition to magnetite and serpentinite, which were used as smelter flux for several decades, the deposits contain locally economic concentrations of gold and silver.

The "Sherman-type" deposits, named for the ores at the Sherman mine east of the main Leadville district, are open-space fillings in paleokarst in the Leadville Dolomite. The deposits typically contain barite and very little pyrite, and they are considerably more silver rich than those of the "Leadville type." The origin of the deposits is controversial: Landis and Tschauder (1990) call upon fluid migration and mineralization during the Pennsylvanian, whereas Johansing and Thompson (1990) attribute the ores to a Late Cretaceous-early Tertiary mineralizing event.

The predominant type of ore deposits of the Leadville district are the "Leadville type," which are primarily replacement bodies ("blanket" or "manto" in some of the literature) in the Paleozoic carbonate rocks, as well as veins in all rock types. The most important host rock for the mineral deposits is the Leadville Dolomite, but other carbonate units, such as the Dÿer and Manitou Dolomites, as well as some of the quartzites, also host ore deposits.

The principal structural control of mineralization for the Leadville-type ores was the contact between an impervious layer, such as a shale, quartzite, or intrusive rock, and an underlying

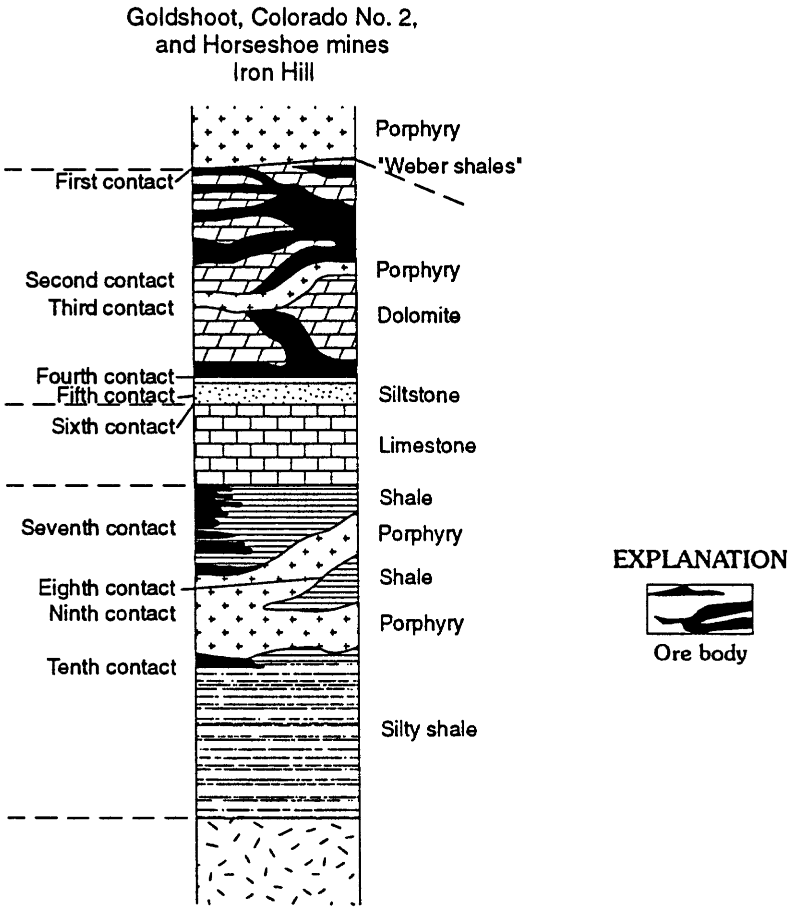

Figure 4. Vertical section at Iron Hill, showing "contacts" and stacked orebodies. From Emmons and others (1927).

carbonate rock, such as the Leadville or Dyer Dolomite. Mineralized horizons were called "contacts" by the miners and early geologists. A vertical stratigraphic section could contain as many as eleven such contacts, all of them having ore in an underlying carbonate unit (fig. 4; Emmons and others, 1927). The most important contact was that between Late Cretaceous and Tertiary dikes and sills and underlying Paleozoic carbonate rocks, especially the Leadville Dolomite. The dikes and sills impeded the ascent of hydrothermal fluids, channeling them instead into the more reactive carbonate rocks. The carbonate units were replaced, commonly entirely, by sulfide minerals, whereas the igneous rocks were essentially unmineralized. In many parts of the district, sills and dikes were emplaced at several stratigraphic horizons in the section, and the intervening Paleozoic rocks have been completely replaced by sulfide minerals.

Faults in the district served as conduits for the ascending fluids and were mineralized as well to form veins. Many veins terminate upward at replacement deposits, whereas others pass through the replacement orebodies and continue upward. Few, if any, veins extend up into the Belden and younger formations. According to Tweto (1968), veins tend to have more copper, gold, and silver than the replacement ores. Numerous quartz-pyrite-gold veins and veinlets cut the Breece Hill stock; the intervening sedimentary rocks contain disseminated ore of similar mineralogy (Thompson and Arehart, 1990). In places, such as at the Antioch and South Ibex mines on Breece Hill, the high density of mineralized fractures permitted open-pit mining techniques.

Replacement orebodies have irregular shapes and dimensions, some extending for as much as a kilometer in length or as narrow as less than a hundred meters. Fluid pathways during replacement were controlled by numerous, often subtle factors, including grain size, porosity, permeability, and percentage of interbedded shale. As a result, orebodies grade gradually to abruptly into unmineralized carbonate rocks. Proximity to conduits was also important, and many potentially favorable carbonate rocks were not replaced by sulfide minerals for lack of a nearby conduit for mineralizing fluids.

Alteration, Mineralogy, and Zoning

Although the igneous rocks in most places do not contain economic quantities of ore, they are weakly to strongly altered, especially adjacent to orebodies. Common alteration minerals include chlorite, sericite, iron-manganese carbonates, and quartz. In a sense, the wholesale replacement of the carbonate rocks by sulfide minerals also can be considered a form of alteration. The carbonate rocks are also silicified adjacent to the orebodies.

Pyrite (iron sulfide), galena (lead sulfide), and sphalerite (zinc sulfide) are the most common sulfide minerals in the replacement deposits of the Leadville district, with relatively minor amounts of chalcopyrite (copper sulfide), tennantite-tetrahedrite (copper-arsenic-antimony-sulfosalt), and magnetite (iron oxide), which is abundant in the magnetite-serpentinite skarns (table 2). Numerous other sulfide and non-sulfide minerals have been identified, but few are present in more than trivial amounts; these include various bismuth, tungsten, tellurium, and mercury minerals (Emmons and others, 1927; Thompson and Arehart, 1990). Silver principally is in argentite (silver sulfide), with some argentiferous tetrahedrite, and gold is in its native form (Tweto, 1968). Manganosiderite (manganese-iron carbonate) and quartz (mostly as fine-grained jasperoid) are the principal non-sulfide gangue minerals.

The primary ores of the Leadville district are mineralogically and geochemically zoned around the Breece Hill stock (Emmons and others, 1927; Thompson and Arehart, 1990). The most pronounced feature of this zonation is an increase in the silver:gold ratio progressively outward from the stock; gold values decrease outward with a concomitant increase in silver. The gold-rich core includes the Printer Boy vein in California Gulch, the first gold-quartz vein found in the

TABLE 2. PRINCIPAL PRIMARY AND SECONARY MINERALS IN THE LEADVILLE DISTRICT

Primary Minerals:
Magnetite (iron oxide)
Sphalerite (zinc sulfide)
Galena (lead sulfide)
Pyrite, marcasite, pyrrhotite (iron sulfide)
Chalcopyrite (copper sulfide)
Tetrahedrite-tennantite (copper-iron-antimony/arsenic sulfide)
Bismuthinite (bismuth sulfide
Scheelite (calcium tungstate)
Wolframite (iron tungstate)
Native gold
Native silver
Argentite (silver sulfide)
Arsenopyrite (iron arsenic sulfide)
Electrum (gold-silver alloy)
Rhodochrosite (manganese carbonate)
Dolomite (calcium magnesium carbonate)
Siderite (iron carbonate)
Manganosiderite (manganese-iron carbonate)
Calcite (calcium carbonate)
Serpentine (hydrous iron-magnesium silicate)
Barite (barium sulfate)
Quartz (silicon oxide)
Sericite (potassium aluminum silicate)

Secondary Minerals:
Melanterite (hydrated iron sulfate)
Limonite, goethite (hydrous iron oxide)
Jarosite (hydrated potassium iron sulfate)
Psilomelane (hydrogen manganate)
Smithsonite (zinc carbonate)
Minium (lead oxide)
Cerussite (lead carbonate)
Anglesite (lead sulfate)
Native copper
Chalcocite (copper sulfide)
Chrysocolla (hydrated copper silicate)
Cerargyrite (copper chloride)
Native gold
Native silver

Leadville district. Manganese also increases outward, primarily reflecting more manganiferous carbonate minerals in orebodies in the distal portions of the district.

Secondary Deposits

Uplift and erosion related to the late Tertiary development of the Rio Grande rift in the Leadville area exposed the primary ore deposits and lowered the ground water table. As a result, the sulfide ores near the surface were oxidized by descending meteoric water, and the constituent metals and sulfur were variably remobilized and reprecipitated at depth. The depth to which oxidation extended beneath the paleosurface varied throughout the district, depending upon local permeability and the depth of the ground water table, but in most areas exceeded a hundred meters and was a much as 300 meters (Tweto, 1968). In some vertical sections, all of the ore was oxidized, whereas other zones contained intervals of both oxidized and primary ore.

The mineralogy of the primary ore strongly influenced the results of oxidation. Oxidation of galena produced cerussite, a lead carbonate that is extremely insoluble and chemically immobile in oxidizing conditions. In contrast, the oxidation products of sphalerite are very soluble under oxidizing conditions, and zinc was transported to and deposited at or below the ground water table as the zinc carbonate smithsonite or as zinc-rich clays. As a result, ore in the oxidized zone was enriched in lead by the removal of zinc and other elements, and the ore zones at depth were enriched in zinc and other elements as a result of remobilization and deposition. Silver remained in the oxidized zone, in the form of argentite and other minerals, creating the rich lead-silver orebodies that were exploited in the early days of the district; some ore contained many hundreds of ounces of silver per ton. Pyrite was oxidized to form a number of secondary minerals that were intimately intermixed with the lead-silver and zinc carbonate ores. Copper typically is very mobile in the oxidizing environment, forming secondary sulfide deposits below the ground water table, but the general paucity of primary copper minerals precluded the formation of major secondary copper deposits in the district. However, Tweto (1968) reported secondary copper sulfides in many of the veins.

POST-MINERALIZATION WEATHERING AND EROSION

The primary ore deposits of the Leadville district formed at about 39 Ma at a depth of more than five kilometers (Thompson and Arehart, 1990; Thompson and Beaty, 1990). As described above, progressive development of the Rio Grande rift in the late Oligocene and early Miocene eventually exposed the ore deposits, inducing weathering, oxidation, and supergene enrichment. Erosion continued, and the upper part of the original ore deposit was undoubtedly removed and transported out into the developing Arkansas River valley, although how much was removed is unknown. The erosion and weathering processes continued until, in probable middle to late Miocene time, the thickness of the Dry Union Formation reached the point that orogenic sediments were deposited over much, if not all, of the ore deposit. As the sediments thickened, the ground water table rose to eventually stop oxidation of the primary ores.

Normal faults which were reactivated during rifting offset the orebodies. How much movement occurred after primary mineralization but prior to oxidation is unknown. Tweto (1968) showed that significant movement occurred along a number of faults after oxidation, based upon displacement of the boundary between oxidized and sulfide ore.

Glaciation during the Pleistocene created large glaciers that filled the Evans and Iowa Gulch valleys. The glaciers widened and deepened the valleys, depositing lateral moraines on the flanks of the valleys, terminal moraines at the points of maximum glacial advance, and till along the valley bottom as the glaciers retreated. The terminal moraine of the Evans Gulch glacier blanketed the Dry Union Formation and the underlying ore deposits in the vicinity of Little Stray Horse Gulch and Fryer Hill, and outwash from the glacier was deposited on top of the Dry Union north of California Gulch and west of present-day Leadville. The glaciers cut deeply into the north and south flanks of the ore deposit, locally exposing oxidized ore and, rarely, primary sulfide ore. Fragments of mineralized rock were undoubtedly incorporated into the glacial till, although in relatively trivial quantities compared with the amount of till generated in the valleys as a whole.

Quaternary erosion removed whatever materials covered the central part of the mineralized area, again exposing and eroding the orebodies along the newly formed east-trending ridge between Carbonate Hill and Ball Mountain. Non-glaciated drainages such as California Gulch and Little Stray Horse Gulch began to develop, cutting through the Dry Union and glacial deposits and into the oxidized zone of the ore deposits. California Gulch cut into both the gold veins of the Printer Boy Hill area, as well as the rich lead-silver oxidized ore, and the gold and cerussite washed down the gulch to form the placer deposits that first attracted prospectors to the area.

Post-glacial surface weathering has created a veneer of soil, talus, and colluvium that covers virtually all of the Leadville district, with the obvious exception of sparse outcrops. This surficial deposit varies considerably in depth, but everywhere is less than a few tens of centimeters.

PRE-MINING SETTING OF THE LEADVILLE DISTRICT

Even a cursory glance at the Leadville mining district reveals that the extent of anthropogenic surface disturbance is extreme. Mine dumps and piles of smelter slag cover large tracts of the district, and the town of Leadville itself, with its many buildings, paved streets, and gardens, obscures the original surface. However, some points can be made regarding the pre-mining geologic conditions in the area, based upon the published literature, field studies in the district, and comparison with nearby, undisturbed areas.

Physiographically, the pre-mining site of the Leadville district was essentially the same as it is today, with the Carbonate Hill-Ball Mountain ridge flanked and incised by Evans, Iowa, and California Gulches. Many similar ridges underlain by identical bedrock and surrounded in part by the Dry Union and glacial deposits are present on the west flank of the Mosquito Range. However, the delimiting factor is the presence of the enormous orebodies at Leadville.

Of the area that was actually mined, approximately one-half to two-thirds of the district was directly underlain by late Tertiary and younger sediments that, for all intents and purposes, were devoid of mineralized rock. These sediments concealed, in places to significant depths, the oxidized ores. The remainder of the district, entirely along the Carbonate Hill-Ball Mountain ridge, was underlain directly by bedrock, including some of the ore deposits (fig. 5). The relative percentage of ore versus non-ore originally exposed at the surface in this area is unknown, but historical accounts of the slow discovery of ore deposits at the surface suggests that exposures were limited. In part, however, this might be a function of poor exposure, which is typical of bedrock in the upper Arkansas River valley, rather than relative absence of ore exposed at the surface. Comparison of Figures 2 and 5, shows that, of the bedrock exposed between Carbonate Hill and Ball Mountain, most of it is composed of intrusive rocks *beneath which* orebodies were encountered. As a result, considerably less than a quarter of the mining district likely contained actual ore exposed at the surface.

The silver-lead-zinc-gold deposits of the Leadville mining district constituted one of the largest base- and precious-metal concentrations in the world. Geologic processes concealed or had not yet exposed much of the anomaly, and the Tertiary oxidation rendered the exposed ore relatively stable in the surficial environment. Most sulfide minerals, especially pyrite, had been

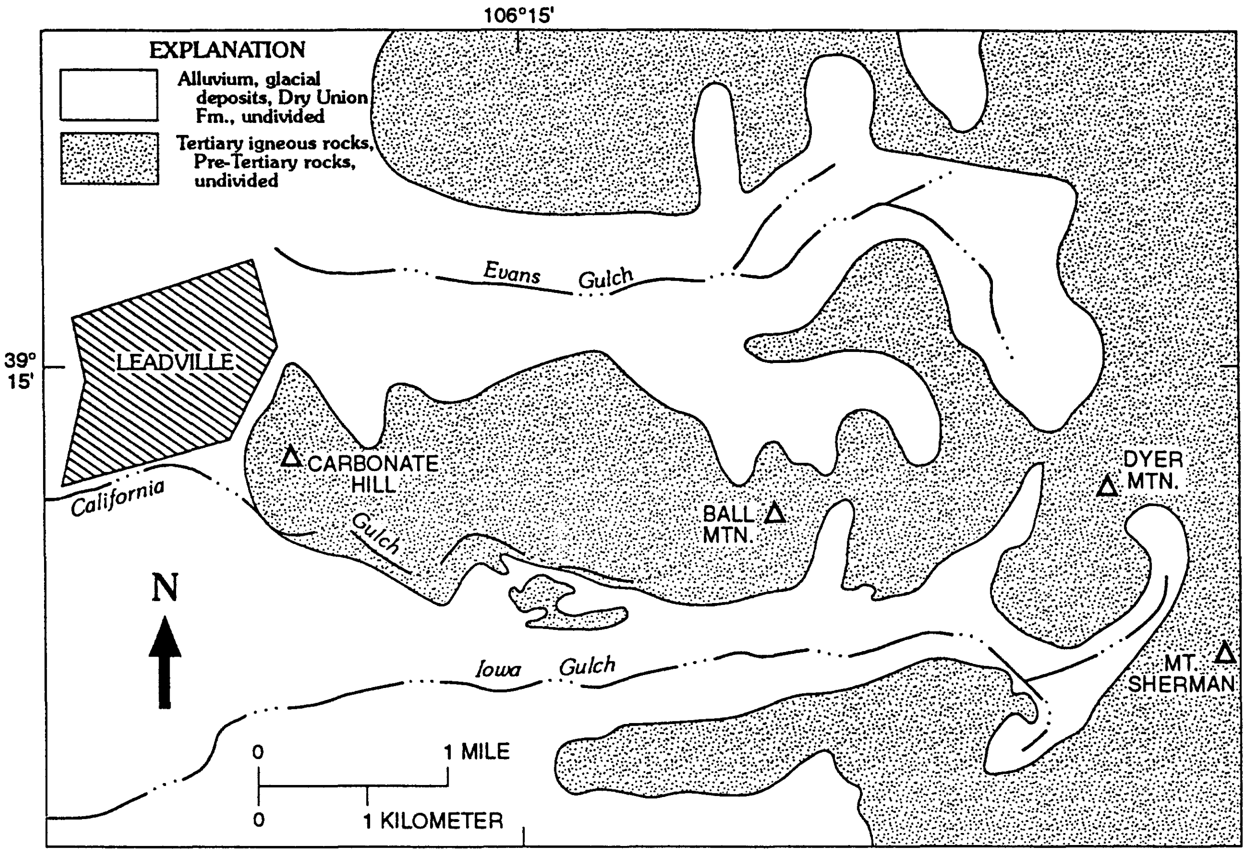

Figure 5. Map showing extent of bedrock exposures (Tertiary intrusive rocks and pre-Tertiary igneous and sedimentary rocks; stippled pattern) and unconsolidated sediments of the Dry Union Formation and Quaternary glacial and alluvial deposits (unpatterned area). Area west of Leadville and west of map area is underlain entirely by unconsolidated sediments (Tweto and Case, 1972). Modified from Behre (1953).

destroyed in the upper parts of the orebodies, and the natural production of sulfuric acid in the oxidizing environment therefore was negligible in the mid-1800's; minor sulfide-bearing veins were exposed along Iowa Gulch. Nevertheless, the areas of exposed bedrock, including that with subeconomic grade, contained anomalous amounts of lead, iron, gold, silver, and sulfur, as well as possible arsenic, antimony, mercury, and bismuth. Native gold and cerussite eroded from the bedrock were concentrated in placers along California Gulch.

Prior to mining, much of the district was covered by trees, primarily conifers such as Douglas fir and Ponderosa pine. Photographs in the early literature (Emmons, 1886; Emmons and others, 1927) show abundant tree stumps where the forest had been cut down for fuel and lumber. As a result, the forested areas likely had a several-centimeter-thick surficial cover of duff composed of pine and fir needles. Biogeochemical studies on duff above mineralized areas show that it contains significant amounts of metals, particularly lead, due to uptake of the metals by the trees (Curtin and others, 1971). Therefore, a natural metal anomaly may have been present in the duff along the Carbonate Hill-Ball Mountain ridge where trees were growing directly above mineralized rock. This layer clearly was disturbed during mining.

Placer gold led to the eventual discovery of the lead, zinc, and silver deposits. Had the mineralizing system been devoid of gold, or had the central gold zone not been exposed, the other orebodies may have lain undiscovered for many decades. As a result, mining probably would have progressed in a very different fashion using, from the outset, technology that was not used in Leadville until well into the life of the district. Without placer mining of gold along California Gulch, the condition of that drainage might have developed very differently than it did.

SEARCH FOR AN UNDISTURBED ANALOG

One question that arises repeatedly is if there is a modern, undisturbed analog to Leadville that can be used for various baseline investigations. Considering the size and degree of exposure of the Leadville deposits, it is highly unlikely that a similar orebody, in a similar climatic setting, lies exposed but undiscovered in the conterminous United States. Undiscovered deposits may be exposed elsewhere in the world, especially in some countries with large, remote regions that have not been well explored. Regardless, each possible deposit must match the characteristics and conditions at Leadville to be a viable analog. Some of these requirements are:

* Similar history of formation, including deep oxidation and subsequent preservation, followed by partial exhumation. Had the deposit not undergone the original secondary oxidation, or if Late Tertiary and younger uplift and erosion had been more vigorous and completely stripped away the oxidized ores, the modern situation at the surface would have been very different. Similarly, had Quaternary erosion not exposed part of the deposit, the Leadville ores might never have been exposed, and a search for an analog for this particular CERCLA project would be a moot point.

* Similar host rocks and ore (both primary and secondary) mineralogy. For instance, the carbonate rocks provide a chemical buffer in the modern surficial environment, and the composition of the primary ores affected the eventual mineralogy of the secondary ores. Also, the relative absence of sulfide minerals at the surface limited the amount of natural sulfuric acid production at the surface.

* Similar climate, during both original oxidation and modern exposure. Mineral deposits weather very differently in different climates, so weathering of a Leadville-type deposit in the arid Sonoran desert, the jungles of Venezuela, or the tundra of northern Alaska would produce very different end results.

Probably the best analog is Leadville itself, simply because it meets all but one of the requirements for an analog, the one being the fact that it has been mined. This exception is not an insurmountable obstacle, as geologic and geochemical modeling techniques, coupled with knowledge of the geology, mineralogy, and geochemistry of the mineral deposits of the Leadville district, could be used to make predictive models of the conditions prior to mining.

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GEOLOGIC TIME CHART

Terms and boundary ages used in this report

EON	ERA	PERIOD		EPOCH	BOUNDARY AGE IN MILLION YEARS
Phanerozoic	Cenozoic	Quaternary		Holocene	0.010
				Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late Middle Early	205
		Triassic		Late Middle Early	~ 240
	Paleozoic	Permian		Late Early	290
		Carboniferous Periods	Pennsylvanian	Late Middle Early	~ 330
			Mississippian	Late Early	360
		Devonian		Late Middle Early	410
		Silurian		Late Middle Early	435
		Ordovician		Late Middle Early	500
		Cambrian		Late Middle Early	~ 570[1]
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				3800?
pre-Archean[2]					4550

[1] Rocks older than 570 m.y. also called Precambrian, a time term without specific rank.

[2] Informal time term without specific rank.

Appendix. Geologic time chart.