RESOURCE SERIES 42

Geology and Mineral Resources of Lake County, Colorado

By James A. Cappa and Paul J. Bartos

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By James A. Cappa and Paul J. Bartosharr

Harris D. Sherman, Executive Director,
Department of Natural Resources

Vince Matthews,
State Geologist and Division Director
Colorado Geological Survey
Denver, Colorado
2007
The Colorado Department of Natural Resources is pleased to present the Colorado Geological Survey Resource Series 42, *Geology and Mineral Resources of Lake County, Colorado*. Its purpose is to describe the geological setting and the various mineral deposits of Lake County. The report discusses known precious- and base metal deposits, molybdenum deposits, and industrial mineral and construction material deposits. The report contains a single 1:50,000 scale geological map of the county. James A. Cappa and Paul J. Bartos wrote this report in 2001 and 2002.

The objective of this publication is to provide geological information to resource developers, government planners, and interested citizens.

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James A. Cappa  
Chief, Minerals and Energy Section

Vince Matthews  
Division Director and State Geologist
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PLATE

Geologic map of Lake County, Colorado .................................................................pdf file

APPENDIX I

Selected mineral and mine descriptions from:

Geology and Ore Deposits of the Leadville Mining District, Colorado:
U.S. Geological Survey Professional Paper 148 .................................................................pdf files

Geology and Ore Deposits of the West Slope of the Mosquito range:
U.S. Geological Survey Professional Paper 235 .................................................................pdf file
This report describes the geology and mineral resources of Lake County; it includes a 1:50,000-scale geologic map of the county that was compiled from published source materials of various scales (pl 1). The report describes the geologic setting, stratigraphy, and structure of Lake County. The section on Mineral Deposits includes descriptions of the mining districts of Lake County. Lake County boasts two of the most important mining districts in Colorado, the Leadville district and the Climax district. These two districts have played major roles in the history and economic development of the state. Other mining districts of lesser economic importance are also described, as well as areas of potential industrial mineral and construction material deposits.

There is no record of any oil and gas drilling in Lake County. There are no recorded geothermal sites in Lake County, nor any formations known to host coal deposits. No new field investigations of mining districts were made in the course of this study.

Part of this report contains transcriptions of mineral and mine descriptions from the two important U.S. Geological Survey Professional Papers on the Leadville district (Emmons and others, 1927; Behre, 1953; see Appendix 1). The CGS has chosen to preserve these descriptions as originally written.
SUMMARY
Lake County is one of Colorado’s smallest counties, it has an area of 384 square miles—only Gilpin and Denver counties are smaller. The County is in the heart of Colorado’s Rocky Mountains and has elevations ranging from 8,935 ft to 14,433 ft at Mount Elbert, the highest peak in Colorado. Lake County is surrounded by mountain ranges, the Sawatch Mountains and Collegiate Range in the west and the Mosquito and Ten Mile Range in the east (Figures 1 and 2).

The Arkansas River originates in Lake County and is the county’s principal waterway. The Arkansas River and its tributary, Tennessee Creek, occupy the wide central valley between the Sawatch Range and the Mosquito Range.

For convenience, the relatively low lying part of Lake County is referred to as the Arkansas River Valley; this geographic area includes the lower reaches of Tennessee Creek and other tributaries in addition to the Arkansas River itself.

Figure 1. Location map of Lake County.
Leadville is the only city and is the county seat. According to the 2000 census, the population of Lake County is 8,393.

The western half of Lake County consists primarily of the Precambrian igneous and metamorphic core of the Sawatch Range (Figure 2). The Sawatch Range is a structural antiformal uplift. Well-exposed Paleozoic sedimentary rocks dip generally eastward along the eastern part of the uplift in the Leadville and Tennessee Pass areas of Lake County. The same Paleozoic sedimentary rocks encircle the Sawatch uplift and dip generally to the west along the western part of the uplift. Paleozoic rocks are important ore hosts in the mining districts of Gilman, Aspen, and Tincup.

Lake County falls within the broad region known as the Colorado Mineral Belt (Figure 3). This northeast-trending belt is developed over a zone of shearing of Precambrian age (Tweto and Sims, 1963). The Colorado Mineral Belt is defined by numerous porphyritic intrusive rocks of Laramide and Tertiary age that contain or are related to precious- and base-metal deposits. Figure 4 is a simplified geologic map of the County with the mining districts located on it.

The Paleozoic rocks of Lake County contain strata of Cambrian through Pennsylvanian age and Mesoproterozoic to paleoproterozoic igneous and metamorphic rocks. (Figures 4 and 5). Sedimentary rocks of Mesozoic age probably were deposited over the paleozoic rocks, but if so, they have been eroded and are no longer in Lake County. Tertiary continental sedimentary rocks of Miocene to Pliocene age are abundant in the southern part of the County adjacent to the Arkansas River valley.

Figure 2. Geological features of Colorado and Lake County.

Figure 3. Colorado Mineral Belt showing location of major active and inactive mines. Lake County shown in black.
Intrusion of porphyritic igneous rocks began in Late Cretaceous time and continued through the mid-Eocene (Figure 5). During Oligocene time, magmatic activity consisted of the formation of the Grizzly Peak caldera in the southern part of the county and the intrusion of the Climax Stock in the northern part of the county. There are small exposures of Pliocene to Quaternary age volcanic rocks (not shown on geologic maps in this publication).

During the Pleistocene, much of this region was glaciated. Glaciers deposited sedimentary material of several ages in Lake County.
Figure 5. Generalized stratigraphic column of Lake County; thickness in feet; full thickness of Minturn Formation not shown.
**Precambrian Rocks**

**Overview**
Precambrian rocks in Colorado are composed of igneous and metamorphic rocks ranging in age from Paleoproterozoic to Mesoproterozoic. In Lake County, the oldest Proterozoic rocks are metamorphic; they primarily consist of biotite gneiss and schist and quartzites, predominantly of sedimentary origin, and hornblende and felsic gneiss of volcanic origin. The protoliths of these metamorphic rocks were deposited before the peak age of metamorphism, which was from 1,775 to 1,700 Ma (million years ago) (Tweto, 1980).

Three periods of igneous activity occurred during the Proterozoic in Colorado. Only the two oldest events are represented by rocks in Lake County. The Paleoproterozoic event occurred at about 1,750 to 1,650 Ma. The Paleoproterozoic rocks are variable in composition but are, for the most part, granitic. These rocks were emplaced around the time of peak metamorphism and are locally foliated. Early Mesoproterozoic igneous rocks consist primarily of granite and quartz monzonite ranging in age from 1,480 to 1,350 Ma. These rocks generally lack foliation and are discordant with the surrounding metamorphic rocks (Tweto, 1980).

The youngest Proterozoic igneous event produced the granite of Pikes Peak batholith in the late Mesoproterozoic at about 1,100 to 1,000 Ma. These rocks are not found in Lake County.

**Metamorphic Rocks**
Paleoproterozoic metamorphic rocks are found throughout Lake County, but are generally more widespread in the Sawatch Range. Limited exposures of metamorphic rocks are sparse in the Mosquito Range, which makes up the eastern portion of Lake County. The metamorphic rocks of the Sawatch Range and Mosquito Range are lithologically similar to the Paleoproterozoic metamorphic rocks of the Front Range. Rubidium–strontium age dates from whole-rock and feldspar samples indicate that regional metamorphism occurred about 1,750 Ma (Hedge and others, 1967).

Behre (1953) described three main types of metamorphic rocks of the Mosquito Range, which are generalized in the following to represent all the metamorphic rocks in Lake County. On plate 1, the Precambrian metamorphic rocks are consolidated into the biotite gneiss and schist unit.

**Biotite-Hornblende Gneiss**
Biotite-hornblende gneiss is dark gray, almost black, and is locally spotted with pink microcline crystals. Under the petrographic microscope, the rock consists of green hornblende, quartz, microcline, partly bleached brown biotite, and small quantities of oligoclase-albite. Accessory minerals include rutile, sphene, and apatite. Sericite and limonite are the most common alteration products. The hornblende, biotite, and quartz are intimately intergrown, but microcline occurs as scattered grains amongst the other minerals and in fine-grained veinlets that cut across the rock.

**Quartz-Biotite Gneiss**
Quartz-biotite gneiss is a fine-grained, medium-gray rock with a pronounced foliation that Behre (1953) ascribes to original bedding. The gneiss commonly appears as inclusions in the later Proterozoic granitic intrusive rocks. Most of these rocks consist entirely of quartz and biotite; whereas other facies may contain considerable amounts of feldspar. The quartz grains at some places are rounded, which suggests a sedimentary origin according to Behre (1953).

Locally, in some inclusions on Finnback Knob (near the eastern edge of Lake County, just south of Mount Sherman; plate 1), the quartz-biotite gneiss grades into an injection gneiss, which is characterized by numerous stringers of microcline and quartz, 0.5 cm thick or less, that follow schistosity. The veinlets and gneissic banding are minutely crinkled, and, in addition, the biotite is recrystallized to large (1.0 by 0.3 cm) mica tablets.

**Biotite-Sillimanite Schist**
The biotite-sillimanite schist occurs in isolated localities near Climax and in small but widely distributed masses in the Leadville area. The schist is a gray to black, medium-grained, banded rock that glistens on surfaces parallel to foliation. The bands consist of biotite-sillimanite schist and a more quartz-rich variety with biotite and sillimanite. The sillimanite forms slender, silvery laths as much as two centimeters in length. Plagioclase feldspar is a common accessory mineral.

Biotite-sillimanite schist also been mapped north of Twin lakes in the southern part of Lake County (fig. 1) (Howell, 1919). Here, small amounts of muscovite accompany with biotite. Abundant sillimanite forms radiating or fibrous bundles of prismatic crystals, elongate in the plane of schistosity, both between the quartz and the biotite crystals and within the biotite crystals. Near Mount Champion (southwestern Lake County; plate 1), small, pink to brown almandite garnets in the biotite sillimanite schist have a broken appearance.
Talc Schist
Small areas of talc schist crop out in the area north of Mount Champion (Howell, 1919). The schist is very fractured and is composed almost entirely of talc and quartz. The quartz appears to be both a primary and a secondary mineral. Field relationships of the talc schist and surrounding rocks are obscured by talus slopes of fractured talc schist; however, Howell (1919) suggested that the talc schist is an alteration product of mafic rocks that intruded as sills and dikes in other Precambrian rocks.

Igneous Rocks
There are two groups of Precambrian igneous rocks in Lake County. The earliest igneous rock complex was emplaced during Paleoproterozoic regional metamorphism at about 1,775 to 1,650 Ma. The second group of igneous rocks was emplaced in the middle Mesoproterozoic at about 1,400 Ma. The Precambrian igneous rocks are mapped as three units in plate 1; the fine divisions of the Paleoproterozoic igneous rocks mapped by Fridrich and others (1998) are not shown but are described here.

Paleoproterozoic Granitic Rocks
The early Paleoproterozoic granitic rocks consist of a diverse group of mainly gneissic granite and granodiorite with local bodies of more mafic rocks including diorite and possibly gabbro. The granite and granodiorite are often layered with biotite-rich and biotite-poor layers. Fridrich and others (1998) included detailed descriptions of these rock units, including geochemistry and age dates, in the central Sawatch Range of southwestern Lake County.

The Denny Creek Granodiorite is exposed in the western part of Lake County. The granodiorite is a dark grayish-brown to greenish-black, coarse-grained, equigranular to porphyritic, undeformed to strongly foliated biotite-rich granodiorite. The granodiorite consists of oligoclase, quartz, perthite, biotite, ilmenite, magnetite, and minor amounts of sphene, apatite, allanite, zircon, and chlorite. The granodiorite is distinguished by its abundance of biotite. The Denny Creek Granodiorite is mostly calc-alkaline to alkali-calcic in composition (Fridrich and others, 1998 p. 22–23).

A leucocratic phase of the Denny Creek Granodiorite is exposed in the area north of Lake Creek and south of Mount Elbert. This phase is a tawny-brown to brownish-gray, medium-grained, equigranular, and compositionally layered and foliated biotite granodiorite. It grades into and is chemically similar to the Denny Creek Granodiorite (Fridrich and others, 1998, p. 22).

In the area west of Mount Elbert, the Kroenke Granodiorite cuts the Denny Creek Granodiorite. The Kroenke is a light-gray, medium-grained, equigranular biotite granodiorite that is undeformed, but compositionally layered. It’s composition is alkali-calcic to calc-alkaline and mildly to strongly peraluminous (Fridrich and others, 1998, p. 20–23). The unit is distinctly sodium rich and has been classified as a trondhjemite (Barker and others, 1976).

The Kroenke Granodiorite in the Sawatch Range has been dated by rubidium–strontium methods. A recalculation of six whole-rock samples by DeWitt yielded an age of 1645 ± 5 Ma date (Fridrich and others, 1998, p. 20). Dikes of medium-grayish-green, medium-grained, equigranular to slightly porphyritic, well flow-foliated plagioclase-hornblende diorite commonly cut the Paleoproterozoic metamorphic rocks. The dikes are cut by Kroenke Granodiorite (Fridrich and others, 1998, p. 24). Howell (1919) described the Mount Champion quartz monzonite in the Twin Lakes district of southern Lake County. The map units of the quartz monzonite shown on Howell’s Plate I (1919) correspond to both early and middle Proterozoic intrusive complexes of this study. His rock description of the Mount Champion quartz monzonite is similar to the Denny Creek Granodiorite, rather than the conspicuous two-mica granites of Mesoproterozoic age.

Mesoproterozoic Granitic Rocks
In the Sawatch Range, the Mesoproterozoic granitic rocks are composed primarily of the St. Kevin Granite, a light-tan to pinkish-tan, fine- to medium-grained, equigranular biotite-muscovite granite. The St. Kevin Granite is mostly undeformed; however, locally it is flow foliated and has compositional layering. The granite consists of microcline, quartz, plagioclase, biotite, and muscovite and trace amounts of apatite, zircon, fluorite, and sillimanite. Pegmatite sills and dikes as thick as 35 ft are common (Fridrich and others, 1998, p. 16–17).

The St. Kevin Granite is well exposed in the Sugar Loaf and St. Kevin mining districts, south and north of Turquoise Lake, respectively (fig. 4). At these places, the rock is medium-grained, gray, granular two-mica granite. Locally, the grain size is coarse or fine grained. A few of the feldspar crystals are as long as 1 in. At places, the granite shows a distinct foliation due to dark films of biotite. Large areas of the St. Kevin Granite in the Sugar Loaf and St. Kevin districts have been hydrothermally altered, and the feldspars have been converted to clay minerals, the biotite has been bleached, and the rock is friable and crumbly (Singewald, 1955).

The St. Kevin Granite is alkali-calcic, mildly to strongly peraluminous, and potassic to normal. It has no apparent iron enrichment. In the northern Sawatch
Range, the St. Kevin Granite has a seven-point rubidium-strontium age of 1,420±100 Ma (Fridrich and others, 1998, p. 18).

In addition to the St. Kevin Granite, unnamed Mesoproterozoic granitic rocks are well exposed in the upper part of Iowa Gulch in the Leadville district (the east-central part of pl. 1). In Iowa Amphitheater, the oxidized Mesoproterozoic granitic rocks form a crumbly regolith and are unconformably overlain by the Sawatch Quartzite (Figure 6).

Ogden Tweto (1974b) divided the St. Kevin Granite into four subfacies: (1) The fine-grained facies consists of gray, even-grained, strongly to weakly foliated, two-mica quartz monzonite. (2) The normal facies consists of light-gray to light-pink, equigranular to porphyritic, two-mica granite and quartz monzonite. (3) The granodiorite facies is a gray, seriate, porphyritic, fine- to medium-grained, weakly foliated granodiorite. (4) The trachytoid hybrid facies consists of a coarse-grained, nonhomogeneous granite composed of closely packed parallel microcline crystals, 0.5 in. to 1 in. long, in a fine-grained matrix; this facies is common on the borders of the intrusion.

PHANEROZOIC SEDIMENTARY ROCKS

Cambrian Rocks

Paleozoic sedimentary rocks in Lake County consist of shelf carbonate rocks and siliciclastic sedimentary rocks; they lie unconformably upon Proterozoic igneous and metamorphic rocks in the Mosquito Range. Except near Tennessee Pass on the northern edge of Lake County, no Paleozoic sedimentary rocks are exposed in the Sawatch Range of the County. In the Leadville district, the stratigraphic thickness from the base of the Cambrian Sawatch Quartzite to the top of the Mississippian Leadville Dolostone is 507 ft (fig. 5). The Pennsylvanian Minturn Formation overlies the Leadville Dolostone and has a thickness of at least 2,450 ft in the Leadville district.

The Paleozoic section in central Colorado contains several disconformities and unconformities. The top of the Mississippian Leadville Dolostone is the most prominent unconformity; it represents an erosion surface and karst filling formed as the late Paleozoic seas withdrew from Colorado.

Sawatch Quartzite

Emmons and others (1927) described and named the Sawatch Quartzite in this region. Fossil collections described by Behre (1953) indicate a Late Cambrian age for the upper sandy beds of the Sawatch Quartzite. In Lake County, the formation mostly consists of orthoquartzite and a basal quartz conglomerate; the thickness varies from 100 to 150 ft. The Sawatch Quartzite unconformably overlies the Precambrian metamorphic and igneous rocks; in Lake County the contact is a remarkably flat surface (Tweto, 1974a; Behre, 1953). Elsewhere, however, the contact has been interpreted as an originally irregular topographic surface that is thought to have contributed to the significantly greater variations in thickness in some areas (Myrow and others, 2003).

The basal conglomerate unit is about 2 ft thick and consists of well-rounded pebbles of bluish-white or white quartz; the matrix is composed of fine-grained white quartz grains, which is locally somewhat micaeous or argillaceous. The lower 60 ft of the Sawatch Quartzite above the conglomerate consists of white, glassy orthoquartzite in beds averaging about 3 ft thick. Some of these beds weather to a pinkish color (fig. 6). The upper 40 ft of the Sawatch Quartzite consists of impure, gray, buff, or brownish-gray sandstone. Many of these darker beds have calcareous cement, and their weathered surfaces become pitted or honey-combed. The common interbedding of darker sandstone with white orthoquartzite gives the upper Sawatch Quartzite a distinctive striped appearance. The upper beds average about 1 ft thick and are commonly crossbedded. Glauconite is common in the upper part of the unit (Gerhard, 1972). A bed of purple or black quartzitic sandstone marks the top of the Sawatch Quartzite. This unit grades into the overlying Dotsero Formation (Myrow and others, 2003).
**DOTERO (FORMERLY PEERLESS) FORMATION**

Emmons and others (1927) called the shale unit above the quartzites of the Sawatch Quartzite the "transitional shales." Behre (1932) applied the name Peerless Formation to these shales, called the "red-cast beds," for exposures on Peerless Mountain, 7 mi south of Leadville. Myrow and others (2003) revised the Cambrian and Ordovician stratigraphy of central Colorado; they suggested the elimination of the name "Peerless" and included these rocks in the Dotsero Formation, a unit defined by Bass and Northrup (1953) in the White River uplift northwest of Lake County. The formation is about 50 ft thick in the Leadville area. Tweto (1974b) described thicknesses of as much as 110 ft in the Holy Cross quadrangle in northern Lake County. He further characterized the Dotsero (formerly Peerless) Formation as thin-bedded, buff, green, and maroon sandy dolomite, dolomitic sandstone, dolomite, and dolomitic shale. Gerhard (1972) described the Dotsero (formerly Peerless) Formation as having a Late Cambrian fauna. Myrow and others (2003) confirmed that the Dotsero Formation as exposed at Horseshoe Mountain about 500 ft east of the Lake-Park County line contains conodonts of the Eoconodontus Zone, which indicates a Late Cambrian age.

In the Mosquito Range, the lower part of the Dotsero Formation consists of thin-bedded shaly sandstone that contains a few quartzitic layers as thick as 1 ft. The upper part is mostly brick-red, impure sandy and shaly limestone as thick as 2 ft (Figure 7) (Behre, 1953).

**Ordovician Rocks**

**MANITOU DOLomite**

The Manitou Formation is a calcareous dolomite that averages about 110 ft in thickness. The Manitou Formation overlies the Dotsero Formation on a nonconformable contact. The older literature refers to the Manitou Formation as the "White limestone" (Emmons and others, 1927). Kirk (1931) correlated these beds with the Manitou limestone of the Front Range, and Behre (1953) called these beds the Manitou Dolomite, as they consist primarily of dolomite.

The Manitou Formation consists of uniform, finely crystalline, white, light-gray, or very faintly pinkish dolomite. In general, the lower 20 ft of the Manitou Formation consists of light-gray dolomite and intercalated layers of greenish-gray shale averaging about 2 in. thick. A 60-ft-thick section of light-gray, granular dolomite overlies the intercalated dolomite and shale unit. The gray dolomite beds are about 2 to 3 ft thick. White chert in discontinuous beds and nodules is common. The upper 30 ft of the Manitou Formation is similar to the gray dolomite, but contains distinctly lesser amounts of chert (Figure 8). The Manitou Formation is nonconformably overlain by the Parting Formation of the Chaffee Group (Behre, 1953; Myrow and others, 2003).

Microscopically, the Manitou Dolomite consists primarily of fine-grained dolomite, ranging from 0.02 to 1.0 mm in diameter. Some calcite surrounds the dolomite crystals. There are minor amounts of quartz and clay minerals.

In the Leadville district, the Manitou Formation typically has been strongly altered. The resulting crumbly and friable texture—commonly referred to as "sugar" texture—is a result of the dissolution of the calcite surrounding the dolomite crystals. Locally on Printer Boy Hill, which is east of Leadville between Iowa Gulch and California Gulch (pl. 1), the Manitou Formation has been altered to small grains of epidote, iron-stained quartz, and a fibrous, light-colored amphibole, possibly tremolite.

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*Figure 7. Outcrop of Peerless Shale in Iowa Ampitheater —well exposed outcrop is approximately 15 feet high.*

*Figure 8. Manitou Dolomite in Iowa Ampitheater. Hammer point is resting on a chert layer.*
Devonian Rocks

**CHAFFEE GROUP: PARTING FORMATION, DYER FORMATION, GILMAN SANDSTONE**

Three divisions of the Devonian Chaffee Group are recognized in Lake County. Campbell (1970) elevated the rocks of the Chaffee Formation to group status and defined two formations, and Tweto and Lovering (1977) included the Gilman Sandstone as the upper part of the Chaffee Group.

The lower unit in Campbell’s (1970) twofold stratigraphy is called the Parting Formation, and the upper unit is the Dyer Formation. The Parting Formation is a white to light-buff to pinkish-gray quartzarenite. Crossbedding is common. Quartz grains are not very well rounded; their mean diameter is 0.5 mm. There are sparse flakes of white mica. Silica is the most common cement. Calcareous cement is locally common; in some cases, the beds are sufficiently calcareous to be sandy limestones. The Parting Formation has variable thickness but averages 27 ft (Behre, 1953).

A 2-ft-thick brick-red to light-olive-green shale underlies the quartzarenite. However, the shale is as thick as 22 ft at Weston Pass south of Leadville.

The Dyer Formation is a light-gray or bluish-gray banded dolomitic limestone. In general, the carbonate is well crystallized. The average thickness of the Dyer Formation is 80 ft. A typical stratigraphic section of the Dyer Formation near Dyer Mountain east of Leadville is shown in Table 1.

<table>
<thead>
<tr>
<th>Bed no.</th>
<th>Lithology</th>
<th>Thickness (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Blue-gray, dense dolomitic limestone in massive beds; faintly banded</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Brown-spotted, gray dolomitic limestone, densely granular; weathers into beds about 1 in. thick</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>Light-blue-gray dolomitic limestone with platy fracture; weathers to a conspicuous ochre</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Light-gray, buff-weathering dolomitic limestone in massive beds</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>Light-buff, very sandy, crystalline dolomitic limestone; medium- to locally coarse-grained</td>
<td>14</td>
</tr>
<tr>
<td>1</td>
<td>Total</td>
<td>99</td>
</tr>
</tbody>
</table>

**Mississipian Rocks**

**LEADVILLE DOLOSTONE**

The Mississippian Leadville Dolostone, formerly known as part of the Blue Limestone of the Leadville mining district, was first named and described by Emmons (1882) and later modified by Kirk (1931) and Tweto (1949). In much of Colorado this unit is termed the Leadville Limestone because it is composed mostly of calcium carbonate. However, much of the original Leadville Limestone on the east side of the Sawatch uplift is now dolomite; therefore, for this report, this unit is termed the Leadville Dolostone (Behre, 1953; Beatty and others, 1988; Armstrong and others, 1992). The average thickness of the Leadville Dolostone in the Leadville mining district is 140 ft (Behre, 1953). The Leadville Dolostone (Figure 9) in the area of the Leadville mining district in Lake County was divided into three members by Nadeau (1972), in ascending order from the base: The Gilman Member was described by Tweto (1949), but later that unit was reassigned to formation status in the Devonian Chaffee Group (Tweto and Lovering 1977); the Redcliff Member was described for exposures near Red Cliff in neighboring Eagle County (the member name is one word, whereas the town name is two words); and the Castle Butte Member was named for exposures at Castle Butte on Aspen Mountain.

The Redcliff Member consists primarily of micrite and dolomicrite. The basal unit consists of very fine grained, tan to gray, dense dolomitic from 2 to 8 ft thick. Above the basal dolomicrite, the bedding becomes more massive and consists primarily of fractured micrite. Stromatolitic boundstones and intraformational breccias are common in the Redcliff Member. There is an unconformity between the Redcliff Member and the underlying Chaffee Group (Nadeau, 1972).

The Castle Butte Member marks a change in grain size from the fine-grained micrite of the underlying Redcliff Member to coarse-grained packstone, grainstone, and boundstone. Oolitic, pelletal, skeletal, and
composite packstones are found mostly in the lower part of the Castle Butte Member. Composite grainstone with rounded and disarticulated oolites and skeletal fragments is found only in the upper part of the Castle Butte Member (Nadeau, 1972).

Beaty and others (1988) discussed three problems in the Leadville mining district that arise when applying Nadeau’s (1972) “Leadville limestone” stratigraphy: (1) No type section of the Leadville exists, only reference sections for the Redcliff Member at Red Cliff and for the Castle Butte Member in Aspen. (2) Away from the reference section at Red Cliff, workers could not identify the unconformity separating the two members. (3) In the Leadville district, the “Leadville limestone” has been dolomitized, and the original texture is obscured; correlations based on texture are therefore meaningless.

Beaty and others (1988) revised the Leadville stratigraphy by using more than 50 drill cores taken for mineral exploration. A well-developed unconformity—the M-2 unconformity—was defined as the contact between the Redcliff Member and the Castle Butte Member. A lithostratigraphy using dolomite grain sizes was established, and a reference section for the Leadville Dolostone was established. Dolomitization of the carbonate rocks of the Leadville Dolostone in central Colorado is restricted largely to the eastern flank of the Sawatch uplift, essentially all of Lake County (fig. 3a). Many early investigators thought that the dolomitization was a direct result of the hydrothermal alteration associated with the mineralization on that flank (Thompson and others, 1983). Later workers (Horton and DeVoto, 1990; Armstrong and others, 1992) instead have interpreted that the limestone was converted to dolomite by essentially diagenetic and burial processes during the late Paleozoic.

The Redcliff Member has been altered from micrite to fine-grained dolomicroite. The Castle Butte Member is typically completely recrystallized. Zebra texture as illustrated by Horton and DeVoto (1990, fig. 8) is most common in the Castle Butte Member and is usually associated with sulfide mineralization.

Mississippian(?) and Pennsylvanian Rocks

Molas Formation

The Molas Formation was first recognized in southwestern Colorado (Cross and others, 1905) where it forms a karst residuum on the top of the Leadville Dolostone. In central Colorado near Minturn in Eagle County, it forms a unit of thin but variable thickness of red to yellow sericitic silty and clayey material, very fine grained sandstone, and fragmental chert (Tweto and Lovering, 1977, p. 32–33). In the Leadville district, Tweto (1968, table II) reported that the Molas Formation is 0 to 40 ft thick and consists of structureless red and yellow siltstone and mudstone containing abundant chert fragments. Armstrong and others (1992) suggested that the Molas Formation might be, in part, of Late Mississippian age.

Pennsylvanian and Permian Rocks

Belden Shale

The Belden Shale is composed of a series of dark-gray to black marine shales that contain thin interbeds of limey mudstone and wackestone and gray to brown, micaceous, fine-grained, feldspathic to arkosic sandstone. Brill (1942, 1944) originally described the Belden Shale. In the Leadville district, it has been previously described as part of the Weber Sandstone(?) (Emmons and others, 1927; Behre, 1953). The Belden Shale unconformably overlies the carbonate rocks of the Mississippian Leadville Dolostone and the Mississippian(?)—Pennsylvanian Molas Formation. The thickness of the Belden Shale varies from about 200 ft to nearly 800 ft in Lake County (Brill, 1944). The Belden Shale in the southern Mosquito Range (south of Lake County) thickens and changes facies across a distance of 35 mi to become more than 1,000 ft of fine-to coarse-grained arkosic sandstone and conglomerate (DeVoto, 1980).

Minturn Formation

The Minturn Formation is about 6,000 ft thick and is composed of dominantly gray, green, and brown lenticular beds of sandstone, siltstone, shale, conglomerate, and limestone stratigraphically above the dark shales of the Belden Shale (DeVoto, 1980). The Minturn Formation was named by Tweto (1949) for exposures along the Eagle River near Minturn in Eagle County. The Minturn Formation is described in detail north of Lake County in the Pando area by Tweto (1949) and in the Copper Mountain area by Widmann and others (2004). Tweto (1956) produced a detailed geologic map of the Tennessee Pass area, which includes the northern part of Lake County; however, for a full description of the Minturn Formation, he referred to his earlier work (1949) in the Pando area. Tweto (1956) recognized three dolomite marker beds in the Minturn Formation around Tennessee Pass: the Wearyman Dolomite Member, the Hornsilver Dolomite Member, and the Resolution Dolomite Member. On his geologic map, however, none of these dolomite members are shown in Lake County. Therefore, the thickness of the Minturn Formation in Lake County remains poorly defined.
**Tertiary Sedimentary Rocks**

**DRY UNION FORMATION**
The Dry Union Formation consists primarily of brown, sandy to pebbly, poorly cemented siltstone with local layers of gray to white sandstone, greenish-gray to pinkish-gray clay, brownish-gray gravel, and thin beds of volcanic ash. The thickness of the formation near Leadville is about 1,000 ft; near Malta it is 3,000 ft thick. Tweto (1961) named the Dry Union Formation for exposures in Dry Union Gulch about 5 mi south of Leadville. The units that make up the Dry Union Formation were previously described as “lake beds” by Emmons (1886) and redefined as more alluvial in origin by Capps (1909) and Emmons and others (1927). A complete description of the Dry Union Formation was completed about 30 mi south of the Dry Union Gulch in Chaffee County by Van Alstine (1969). Fossil vertebrate remains in this area indicate a Miocene to Pliocene age for the Dry Union Formation.

**Quaternary Deposits**

**OLDER GRAVELS AND ALLUVIUM**
The older Quaternary gravels and alluvium consist of terrace, outwash, and pediment gravel of pre-Bull Lake age. These gravel deposits include the “high level terraces” described by Behre (1953), Emmons and others (1927), Capps (1909), and renamed the Malta Gravel by Tweto (1961). The “high level terraces” consist of imperfectly stratified gravels, uniformly coarser toward the mountains and finer grained (pebble sized) closer to the Arkansas River Valley. The clasts are generally strongly weathered and in places have a coating of carbonate minerals (Capps, 1909). This gravel unit fills valleys and is of variable thickness. The maximum thickness is between 250 and 700 ft. Pre-Bull Lake deposits are dated at 400 to 500 ka (thousand years) (Nelson and Shroba, 1984).

**OLDER GLACIAL DRIFT AND GLACIAL DRIFT**
These drift deposits of unsorted boulders are of Pleistocene age. Older glacial drift deposits have a subdued morainal form or lack a morainal form and are probably of pre-Bull Lake age. These deposits are found in almost all the valleys in both the Mosquito Range and the Sawatch Range. Glacial drift deposits with well-developed morainal form are probably of Bull Lake (130 to 150 ka) and Pinedale age (15 to 30 ka) (Nelson and Shroba, 1984). More detailed descriptions of the Quaternary glacial and alluvial deposits are found in Capps (1909) and Nelson and Shroba (1984).

**PHANEROZOIC IGNEOUS ROCKS**

**Late Cretaceous and Early to Middle Tertiary Igneous Rocks**

**PANDO PORPHYRY (EARLY WHITE PORPHYRY)**
Tweto (1951, 1954) named the Pando Porphyry for exposures along the Eagle River south of Gilman, Eagle County. The Pando Porphyry includes the Early White Porphyry of Behre (1953) and Emmons and others (1927). It is the earliest of the Laramide-age intrusive rocks and has a potassium-argon age on biotite of 71.8 Ma, as reported by Pearson and others (1962) and recalculated by Cunningham and others (1994). The Pando Porphyry is especially well exposed in the Mosquito Range of the Leadville mining district where it forms conspicuous and extensive sills, which at Mount Sherman east of Leadville can attain a thickness of more than 1,000 ft (Figures 10 and 11). Sills are exposed along the crest of the Mosquito Range for distances of as much as 5 mi (Behre, 1953).

The porphyry is a white to very light gray granodiorite and has a fine-grained groundmass. Phenocrysts are sparse and generally consist of small crystals, about 0.25 cm, of quartz, plagioclase, and black pseudohexagons of biotite (fig. 10). Variations in the Pando Porphyry are due to grain-size variations in the groundmass. Coarser-grained groundmass minerals are generally found in thicker sills. In the

**Figure 10. Pando Porphyry in Iowa Ampitheater. Note black biotite phenocrysts in white felsic matrix.**
least altered rocks, the groundmass consists mostly of quartz, biotite, and rare orthoclase. Accessory minerals include magnetite, zircon, apatite, and hornblende. Phenocrysts are generally well formed—especially the quartz crystals, which generally have euhedral outlines. In contrast, later porphyritic rocks contain rounded and embayed quartz crystals. Quartz phenocrysts generally make up 1 to 2 percent of the rock; however, in some places their abundance can be 7 percent. Biotite phenocrysts constitute 1 to 2 percent of the rock. The scarce plagioclase feldspar phenocrysts are generally oligoclase. Alteration minerals in the Pando Porphyry consist of bluish-gray quartz crystals and sericite. Biotite is commonly altered to carbonate and sericite. Feldspar phenocrysts are commonly completely altered to sericite. Epidote and chlorite are also common alteration products (Behre, 1953).

The Late White Porphyry as described by Behre (1953) closely resembles his Early White Porphyry—the Pando Porphyry of this report. However, it contains larger phenocrysts, as long as 4.5 mm, of mostly altered plagioclase feldspar and rare phenocrysts of quartz and biotite. The most conspicuous feature is the amoeboid shape of the groundmass quartz crystals. Sericite is common in the groundmass. This rock resembles the rhyolite described by Emmons and others (1927) in the early report on the Leadville district and the later white porphyry described by Singewald and Butler (1931) in the Alma district of nearby Park County.

Early to Mid-Tertiary Porphyritic Rocks of the Leadville District

The early to middle Tertiary porphyritic rocks of the Leadville mining district were originally described as the Gray porphyries by Emmons (1886). The Gray porphyry group included all grayish-colored, distinctly porphyritic intrusive rocks younger than Precambrian. Later workers, including Emmons and others (1927) and Behre (1953), subdivided the Gray porphyries into several subunits. Table 2 lists the main characteristics of the subunits of the Gray porphyry group unit of Emmons. The Johnson Gulch Porphyry, which forms most of Breece Hill (the north side of California Gulch, pl. 1), is the most significant subunit because the area around Breece Hill contains most of the major ore deposits of the Leadville district. The Johnson Gulch Porphyry was emplaced at 43.1 Ma (Thompson and Arehart, 1990). The young zircon fission-track age of 34.8±4.9 Ma (Cunningham and others, 1994) shown in Table 2 for the Johnson Gulch Porphyry may represent later annealing caused by a younger intrusion underlying the Johnson Gulch Porphyry.

Other Middle Tertiary Porphyritic Rocks

Porphyritic igneous rocks similar to the Gray porphyry group crop out in other areas of Lake County. In the Climax district, rocks lithologically similar to the Lincoln Porphyry of the Leadville district described in Table 2 predate intrusion of the ore-bearing Climax Stock (Wallace and others, 1968). The Twin Lakes Quartz Monzonite Porphyry in the Twin Lakes district of southwestern Lake County was described and named by Howell (1919). His description of the Twin Lakes Quartz Monzonite Porphyry is similar to that for the Lincoln Porphyry of the Gray porphyry group. Fridrich and others (1998) mapped the Twin Lakes Quartz Monzonite Porphyry as the Twin Lakes pluton. A potassium-argon age on biotite of 42.7±1.2 Ma, a
zircon fission-track age of 45.5±5 Ma, and a rubidium-strontium age of 48.6±4.5 Ma are all listed as times for the intrusion of the Twin Lakes pluton (Fridrich and others, 1998), ruling out an affinity with the Lincoln Porphyry, which has an age of 64 Ma.

Porphyritic rocks similar in appearance to the Pando Porphyry are also found in the Sugar Loaf and St. Kevin mining districts of western Lake County. Plagioclase, biotite, and quartz are the most common phenocryst minerals. The plagioclase is altered to sericite. Biotite is altered and bleached. Groundmass minerals are quartz and orthoclase (Singewald, 1955).

**Middle Tertiary Climax Stock**

The Climax Stock is exposed along the east side of the Mosquito fault in northernmost Lake County (Figures 12 and 13). This stock is the host for the giant Climax molybdenum deposit. From about 33 to 18 Ma, the Climax Stock was intruded in four main phases (Shannon and others, 2006; Bookstrom, 1989; Bookstrom and others, 1988; Wallace and others, 1968): (1) the Alicante stock, formerly called the Southwest Mass, (2) the Bartlett stock, formerly called the Central Mass, (3) the Wallace stock, formerly called the Aplitic Porphyry Phase and Intra-mineral Porphyry dikes, and (4) the Traver stock, formerly called the Porphyritic Granite Phase and Late Rhyolite Porphyry dikes. The four phases of the Climax Stock have essentially the same composition, texture, and minerals. They are all composed of quartz-orthoclase-albite-biotite porphyry. Because of the strong and widespread hydrothermal alteration and similar composition, it is difficult to consistently distinguish the four phases.

**Alicante Stock**

The Alicante stock of the Climax Stock is an elliptical porphyry intrusion located mostly on the south side of the Climax Stock (figs. 12, 13, and 14). Subhedral phenocrysts of quartz and orthoclase average 2 to 3 mm across and are set in a fine-grained matrix of the same minerals. Albite content increases with depth. In places, the porphyry contains numerous ragged crystals of primary biotite, which along with its alteration product, sericite, defines a flow foliation near contacts.

**Bartlett Stock**

The Bartlett stock is a vertical plug that has an essentially circular plan form with a diameter of 1,200 ft on the Phillipson Level (elevation of 11,463 ft) of the Climax Mine (fig. 14). The Bartlett stock was named...
Figure 12. Generalized bedrock geology of the Climax area. (Adapted from Wallace and others, 1968).
Figure 13. Phillipson Level, Climax Mine, showing generalized geology and ore zones. (Adapted from Wallace and others, 1968).
Figure 14. 16 section, Climax Mine, showing generalized geology and ore zones. Line of 16 Section shown on Figure 13. (Adapted from Wallace and others, 1968).
the Central Mass because of its central location relative to the zones of alteration and mineralization of the Climax Stock by Wallace and others (1968). The porphyry of the Bartlett stock is coarser grained and considerably more altered than the Alicante stock porphyry. The orthoclase crystals are notably ragged, and the quartz crystals are circular to oval aggregates of irregular interlocking grains. Plagioclase and biotite are completely lacking above the Storke Level (elevation of 11,168 ft) (fig. 14). A weak flow foliation is developed throughout the Bartlett stock. In the eastern part of the Bartlett stock, a strong, steeply dipping tectonic foliation is expressed in the elongation of quartz crystals.

Wallace Stock and Intra-Mineral Porphyry Dikes
The Wallace stock of the Climax Stock was intruded into the Bartlett stock and generally is about the same size and shape as the Bartlett stock (fig. 13). The Intra-mineral Porphyry dikes were intruded into the radial tension fractures developed within the Bartlett stock and are so named because of their complex and overlapping relationships to the two main mineralization events in the Climax Stock.

The Wallace stock is similar to the other phases of the Climax Stock. It is a fine-grained rock with sparse phenocrysts of quartz in a fine-grained matrix of quartz and alkali feldspar. Coarse-grained pegmatic phases of the stock contain smaller amounts of biotite and fluorite.

The Intra-mineral Porphyry dikes are coarser grained than the Wallace stock and contain abundant and large phenocrysts of quartz and orthoclase. The quartz phenocrysts are generally broken and angular fragments, and shards are common. Albite crystals are rarely seen in the dikes. There are two other varieties of the Intra-mineral Porphyry dikes: fine-grained, pyritic rhyolite and biotite porphyry with few phenocrysts of quartz and feldspar. Albite has been observed in many of the dikes, particularly above the Phillipson Level. Many of the quartz phenocrysts are angular and "broken." The groundmass is very fine grained and contains abundant fragmental material.

The Chalk Mountain stock is interpreted to be part of the Climax Stock because of spatial association, age, and whole-rock chemical attributes (Bookstrom and others, 1988). The Chalk Mountain stock is a rhyolite porphyry with abundant, dark, smoky quartz phenocrysts and chatoyant sanidine phenocrysts in a fine-grained groundmass (Shannon and others, 2006).

Traver Stock and Late Rhyolite Porphyry Dikes
The Traver stock, located below the Wallace stock, is a medium- to coarse-grained, xenomorphic-granular assemblage of orthoclase, albite, and quartz, along with small flakes of biotite. Albite both replaces and is replaced by orthoclase.

Late Rhyolite Porphyry dikes are exposed on the Phillipson Level; there, they trend almost due west across the Climax Stock and are terminated by the Mosquito fault (figs. 12 and 13). Other Late Rhyolite Porphyry dikes show a radial pattern around the center of the stock. Some of these dikes intrude the same tension fractures intruded by the earlier Intra-mineral Porphyry dikes.

On the 929 Level the Late Rhyolite Porphyry dikes are cut off by the Traver stock (Wallace and Bookstrom, 1993, p. 38).

Volcanic Rocks of the Grizzly Peak Caldera
Volcanic and associated intrusive rocks related to the development of the Grizzly Peak caldera crop out in the southwest corner of Lake County, south of Independence Pass. Precaldera rhyolite flows are found in and around the Grizzly Peak caldera (Fridrich and others, 1991); however, none of these are in Lake County. Extraprecaldera rhyolite dikes that intrude cone-shaped fractures are found as far as 13 mi northeast of the caldera rim (Cruson, 1973). These dikes are commonly hydrothermally altered.

The Grizzly Peak Tuff is the product of a single eruptive episode that formed the Grizzly Peak caldera at about 34 Ma. Tuffs are zoned from high-silica rhyolite at the base to low-silica rhyolite at the top. Fridrich and others (1991) divided the Grizzly Peak Tuff into six units on the basis of their composition and the position of two especially thick and widespread breccia units. Mostly intracaldera facies are recognized in the Grizzly Peak Tuff. Fridrich and others (1998) also dated outflow-facies rocks at 33.3 Ma that crop out about 30 mi to the north at Mount Sopris in Pitkin County and about 10 mi east of the caldera in the Arkansas River Valley, just north of the Lake County line.

Late Tertiary to Quaternary Igneous Rocks

Little Union Quartz Latite
The Little Union quartz latite was originally described by Emmons (1886) and later redefined by Behre (1953). This unit is exposed across a small area in Big Union Creek and Little Union Gulch, west and south of Empire Hill (pl. 1). The Little Union quartz latite is a brownish gray that weathers to darker brownish gray with rust-colored spots. It is composed of a groundmass of brownish-gray glass enclosing microlites of quartz, feldspar, and mica; the groundmass constitutes about 60 percent of the rock. The remainder consists of phenocrysts of plagioclase feldspar (25 percent), quartz
biotite (5 percent), and lesser amounts of orthoclase feldspar, magnetite, green hornblende, apatite, zircon, and titanite. Behre (1953) offered the following evidence for the young age of the Little Union quartz latite. Locally, it contains argillically altered xenoliths of the surrounding older rocks including the Precambrian rocks and fragments of the Pando Porphyry and the Gray porphyry group. The quartz latite outcrops stretch along the trace of the Mike fault; the unit cuts the Pando Porphyry and the Gray porphyry group. The quartz latite is not altered.

Rhyolite and Fragmental Porphyry
Outcrops of rhyolite and Fragmental Porphyry have been mapped in the Leadville district near Breece Hill (pl. 1) and as small pipes in underground workings. In northern Lake County, Chalk Mountain is composed of rhyolite. Megascopically, the rock resembles a fault breccia. Under the microscope, flow bands are observed around the angular fragments. There are subangular phenocrysts of quartz and feldspar and minor magnetite and biotite. The matrix is strongly altered (Behre, 1953). Emmons and others (1927) postulated a late Tertiary age for the rhyolite. Earlier workers had recognized the breccias that are currently referred to as the Fragmental Porphyry. Loughlin (1926) referred to rhyolite agglomerate in four funnel-shaped pipes in underground workings. Emmons and others (1927) described four breccia pipes in the northern part of the district. Behre (1953) recognized these breccias as rhyolite agglomerate in Iowa Gulch in the southern part of the Leadville district. The name "Fragmental Porphyry" for these breccia bodies came into usage by mine geologists at the Black Cloud Mine in Leadville in the 1970s. Hazlitt and Thompson (1990) described the Fragmental Porphyry as a dense, matrix-supported, heterolithic to monolithic breccia with subangular to rounded "pebble" fragments contained in a rock-flour matrix. Clasts in the Fragmental Porphyry include all rock types in the district, from Proterozoic rocks to Late Rhyolite Porphyry dike fragments, and phenocrysts of quartz and feldspar. Geologic relationships indicate that the Fragmental Porphyry is slightly younger than the ore-forming event, which is thought to have occurred at 39.6±1.7 Ma (Hazlitt and Thompson, 1990).
Lake County is situated on the eastern flank of the broadly antiformal Sawatch uplift that encompasses the Sawatch Range on the west and the subsidiary Mosquito Range block uplift on the east. The Arkansas Valley graben, part of the Rio Grande rift zone, lies between these two positive structural elements (fig. 2, pl. 1). The western and southeastern parts of the County consist of the Proterozoic cores of the Sawatch uplift and Mosquito Range uplift, respectively; the central part of Lake County consists of east-dipping Paleozoic rocks, which are locally overlain and intruded by Tertiary volcanic rocks and Late Cretaceous to Tertiary porphyritic intrusions. The structure of the eastern part of the County is complicated by many north-trending regional and local faults. The Mosquito fault, the Weston fault, and the Mike fault (pl. 1) are all major north-trending faults in the Mosquito Range. Movement along most of these faults resulted in down-to-the-west offset, except along parts of the Weston fault. The normal faults of the Mosquito Range are nearly vertical. Even the reverse faults have steep dips. The exceptions are the shallowly dipping South Dyer fault and a few minor faults on Mount Sherman and Mount Sheridan. In the northeast part of the County, northeast-trending faults are also prominent. Most of the faults in the Sawatch Range of Lake County trend north.

Mosquito Fault
The Mosquito fault is one of the major fault systems of the Colorado Rocky Mountains. It extends at least from east of Mount Sherman through the Leadville mining district, northward to become the bounding structure for the Climax Stock in the northeastern part of the County, and then north-northeastward to form a bounding structure of the Tenmile Range in Summit County (Widmann and others, 2004).

Downdip displacement on the Mosquito fault is about 600 ft at Ball Mountain in the Leadville district. Just a few miles to the north in Evans Amphitheater, displacement is 5,100 ft (Behre, 1953, p. 66). Wallace and others (1968) estimated more than 9,000 ft of vertical displacement and 1,500 ft of lateral displacement on the Mosquito fault at Climax.

The age of the Mosquito fault system is somewhat controversial. Relationships at Climax and in most of the Leadville district indicate that the fault is postmineralization and therefore younger than 24 Ma. Conflicting evidence—mainly mineralized veins that are parallel to the Mosquito fault—from prospects on Ball Mountain and in the Best Friend Mine and other mines in the Evans Amphitheater indicate that the fault was present prior to mineralization (Behre, 1953, p. 66). It may be that this part of the Mosquito fault is coincident with an older fault, as is common in Colorado (Tveten, 1979, p. 35).

Weston Fault
The Weston fault is a major north-northwest-trending fault system in Lake County. South of Empire Gulch, it is the site of a total vertical displacement of 1,200 ft down dropped to the west. Recent geologic mapping in South Park (Wallace and others, 1999; Wallace and Keller, 2003) indicates that the Weston fault system may extend some 30 mi south of Weston Pass for a total length of more than 50 mi.

South Dyer Fault
The South Dyer fault is well exposed on the south side of East Ball Mountain, West Dyer Mountain, and the Dyer Amphitheater (pl. 1 and Figure 15). It is one of the few faults in Lake County with a relatively shallow dip, about 40° to 65° NE. It strikes west-northwest in a region of predominantly north-striking, steeply dipping faults. On East Ball Mountain, the upper plate of the fault consists of Proterozoic rocks overlain by Paleozoic sedimentary rocks. On West Dyer Mountain, the lower plate of the fault consists of Cambrian Sawatch Quartzite.

Homestake Shear Zone
The Homestake shear zone was defined by Tweto and Sims (1963) and mapped in the Holy Cross quadrangle (Tveten, 1974b). The Homestake shear zone cuts through a small part of northern Lake County, near Homestake Peak (pl. 1). In most of the Sawatch Range, the Proterozoic gneiss has a shallowly dipping foliation. In and close to the Homestake shear zone, the foliation trends northeast and is vertical. The rocks
within the Homestake shear zone range from gouge and breccia through mylonite to recrystallized and refoliated gneiss. The Homestake shear zone was active during the metamorphic event that formed the gneiss at about 1,800 to 1,700 Ma. Evidence from the west side of the Sawatch Range indicates that the Homestake shear zone was active during deposition of the lower to middle Paleozoic sedimentary rocks (Tweto and Sims, 1963). However, recent detailed stratigraphic work on the lower Paleozoic strata of this region by Myrow and others (2003) suggests that the Homestake shear zone was not a major factor controlling the sedimentation in this area.

Sawatch Uplift
The Sawatch uplift forms the Sawatch Range in Lake County; it is antiformal in shape and is composed mostly of Proterozoic metamorphic and igneous rocks. An early structure expressed in the schists and gneisses consists of tightly compressed isoclinal folds trending N. 60° E. with steeply dipping, axial planes overturned to the northwest (Stark and Barnes, 1935). Several north-trending faults have been mapped on the eastern side of the Sawatch Range. Most of these are steeply dipping normal faults along which down-to-the-east movement occurred.

The area around the Sugar Loaf and St. Kevin mining districts is broken by several faults, which have been recognized by their associated silicification. The faults in this area trend northeast and northwest. Veins associated with mineralization trend mostly north (Singewald, 1955).

Tweto (1979) suggested that the Sawatch Range was uplifted and tilted westward as evidenced by (1) the high peaks of the range facing into the Arkansas River Valley and standing in front of the Continental Divide to the west and (2) the greater depth of erosion in the molybdenum deposits on the eastern part of the range (Climax excluded).

Rio Grande Rift-Arkansas Valley Graben
The Rio Grande Rift is expressed in Lake County by a structural graben or series of grabens between the Sawatch and Mosquito Ranges. The west side of the graben is usually bounded by only one or two faults; in contrast, the eastern side is step-faulted almost to the crest of the Mosquito Range (Tweto, 1979). Late Quaternary movement on the bounding faults on the west side of the graben has been documented by Widmann and others (2002). Faults on the east side of the graben also have had major Neogene movement, as evidenced by displacements of volcanic rocks and the Dry Union Formation. Gravity measurements southwest of Leadville in the graben indicate 3,000 to 4,000 ft of fill (Tweto and Case, 1972).

Grizzly Peak Caldera-Ring Fracture Zone
Volcanic rocks and the northern part of the ring-fracture zone of the Grizzly Peak caldera have been mapped in the extreme southwestern part of Lake County. Collapse of the Grizzly Peak caldera occurred during the eruption of the Grizzly Peak Tuff along the ring-fracture zone about 34 Ma. The throw of the ring-fracture zone along the northern rim of the caldera is estimated to be 2,300 to 3,000 ft; the minimum subsidence within the ring-fracture zone is estimated to be 9,800 to 11,500 ft (Fridrich and others, 1991, fig. 11).
Lake County is the site of two of Colorado’s most famous mining districts, the Leadville district and the Climax district (fig. 4). These two districts have played an important part in the establishment of mineral wealth of Colorado. The history of mining in the Leadville district began with the discovery of placer gold in California Gulch, which led to the discovery of the base-metal massive sulfide deposits that made the district famous. The Climax district was discovered as prospectors fanned out prospecting for gold deposits. They found molybdenum instead. In the twentieth century, the Climax Mine grew to become the world’s most important producer of molybdenum.

Other mining districts in Lake County are of lesser importance economically but provide much of scientific value. They include the Twin Lakes district, the Sugar Loaf and St. Kevin districts, the Tennessee Pass district, the Granite district, and the Weston Pass district. Table 3 lists all the mining districts of Lake County and their estimated production values.

**CLIMAX DISTRICT**

**Discovery and Early History**

The Climax deposit is located in northeastern Lake County at Fremont Pass, near the headwaters of the Arkansas River. The altitude around the Climax deposits ranges from 11,000 ft to 13,600 ft. State Highway 24 and the Colorado and Southern rail line are within 1,000 ft of the deposit.

In 1879, a prospector named Charles Senter was searching for gold on Bartlett Mountain (pl. 1), part of the Mosquito Range in central Colorado. He found a yellow-stained outcrop, which is usually a good sign of the presence of sulfide minerals and gold. The outcrop yielded only a gray crystalline rock laced with thin veinlets of a dark bluish-gray greasy mineral and pyrite. Senter staked three claims over this outcrop because of the presence of the pyrite. He thought the gray mineral was some sort of lead or even graphite. It took Senter an additional 14 years to get his samples analyzed. The strange gray mineral was a sulfide of molybdenum, now recognized as molybdenite.

The small settlement of Climax was established at 11,318 ft near Fremont Pass just below Bartlett Mountain in 1884. Blessed with short but spectacular summers and long hard winters, Climax remained only a couple of bunkhouses at a railroad siding on the Denver-Leadville rail route.

In the 1890s, molybdenum was just starting to be used in industrial processes for hardening steel. However, the known deposits of molybdenum were small but very rich vein deposits. Other prospectors and businessmen had heard of the strange metal on Bartlett Mountain near Climax. They staked claims around Senter’s original discovery and in 1911 shipped some ore to a mill in Denver. Although metallurgical processes were improving, the low-grade ores from

<table>
<thead>
<tr>
<th>Mining District</th>
<th>Years of Operation</th>
<th>Estimated Value of Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twin Lakes</td>
<td>1884 – 1953</td>
<td>$66,053 (under reported)</td>
</tr>
<tr>
<td>Sugar Loaf - St. Kevin</td>
<td>1880s – 1948</td>
<td>$10 – 15 million</td>
</tr>
<tr>
<td>Tennessee Pass</td>
<td>1898 – 1936</td>
<td>$100,000</td>
</tr>
<tr>
<td>Weston Pass (also in Park County)</td>
<td>1902 – 1948</td>
<td>$125,000</td>
</tr>
<tr>
<td>Granite (also in Chaffee County)</td>
<td>1860 – 1878 – 1936</td>
<td>$1.3 million</td>
</tr>
<tr>
<td>Leadville</td>
<td>1860 – 1999</td>
<td>$1.8 billion</td>
</tr>
<tr>
<td>Gold</td>
<td></td>
<td>$105 million</td>
</tr>
<tr>
<td>Silver</td>
<td></td>
<td>$530 million</td>
</tr>
<tr>
<td>Lead</td>
<td></td>
<td>$470 million</td>
</tr>
<tr>
<td>Zinc</td>
<td></td>
<td>$696 million</td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td>$77 million</td>
</tr>
<tr>
<td>Climax, molybdenum</td>
<td>1917 – 1995</td>
<td>$4 billion</td>
</tr>
</tbody>
</table>
Climax could not compete with the small, but high-grade, vein deposits being mined in Norway.

In 1916, with World War I raging in Europe, a German company with American headquarters in New York became interested in the molybdenite deposits at Climax. Molybdenum’s steel hardening properties made molybdenum alloy steel excellent for armaments. The German company’s American subsidiary was called the American Metal Company. They conducted test mining and eventually gained control of the deposit. The company was nationalized in 1917 as America entered World War I against Germany, and Climax Molybdenum Company was formed. A schoolhouse, post office, and residences were established at Climax in 1918. The new Climax Mine produced about 250 tons of ore per day. The first rail cars of molybdenite concentrate were shipped from the Climax Mine in April 1918. Thus began the long history of mining and milling at Climax.

When World War I ended in November 1918, the demand for and the price of molybdenum crashed. The industry slowly recovered during the 1920s and 1930s as Climax Molybdenum Company developed new uses for molybdenum. In 1929, the Climax Mine instituted a new system of bulk underground mining—the block-caving method. The highly efficient block-caving method allowed production to climb to more than 6,000 tons of ore per day. As the depression of the 1930s ended, the Climax Mine was making its first significant profits and was supplying 90 percent of the world demand for molybdenum.

Post-World War II History

Increasing production at the Climax Mine required more miners and mill workers. However, the harsh conditions of long, hard winters and high altitude at Climax caused many miners to quit after only a short period. Nevertheless, a company town grew up at Climax, and families soon settled into the routine of life in the high Rockies (Figure 16).

World War II and the quickly ensuing Korean War fostered new uses for molybdenum in pigments, fertilizers, and high-temperature alloy steel for jet engines. Recovery circuits were installed in the mill to collect the small amounts of tin and tungsten associated with the molybdenite ore, as these metals were both important for the war effort. Production during those war years and the following Cold War years was deemed a high priority by the American government, and in 1957 production reached 35,000 tons per day, making Climax the world’s largest underground mine. In 1960, the company expanded the mine and mill workings onto the site of the village of Climax. Most of the miners and other workers moved to the nearby town of Leadville, creating a boom in that venerable old mining town.

In 1964, Climax engineers designed and set off in the Climax Mine the world’s largest nonnuclear explosion. They used 416,000 pounds of explosives to blast 1.5 million tons of ore, leaving behind a semicircular depression of broken rock called the Glory Hole (Figure 17). During the boom years of the 1970s, production increased to a spectacular 50,000 tons of ore per day. The price for molybdenum rose from $2
per pound to $9.50 per pound and up to $30 per pound on the spot market. An open-pit mine was constructed, and employment increased to 3,000 workers in the underground and open-pit mines and the mill. As profits increased, the company (now called American Metals Climax [AMAX] following the 1956 merger of the Climax Molybdenum Company with the American Metals Company) opened the new state-of-the-art Henderson Mine in Clear Creek County in 1976. However, the storm clouds for molybdenum were growing on the horizon (Voynick, 1996).

Because of the high price of molybdenum in the 1970s, many large porphyry copper mines in Arizona, Chile, and British Columbia installed recovery circuits in their mills to capture by-product molybdenum. With increasing molybdenum supplies and decreased demand owing to a national recession, which began in the early 1980s, the Climax Mine began a series of painful layoffs that eventually led to the suspension of mining. Despite these difficulties, mining at Climax continued on a sporadic basis through the early 1990s. The last ore shipments containing about 3 million pounds of molybdenum were completed in 1995. During 2004 and 2005, molybdenum prices rose to an all time high of $37 per pound, causing the mine owners, Phelps Dodge Corporation, to evaluate reopening the mine.

Through 1995, the Climax Mine had produced 500 million tons of ore that yielded about 1 million tons of elemental molybdenum with a "year-mined" value of $4 billion. These numbers equate to an average ore-body grade of 0.410 percent MoS$_2$ with a 0.2 percent cutoff (Wallace and Bookstrom, 1993). There is still ore remaining in the openpit mine: 137 million tons containing about 500,000 pounds of molybdenum. Climax is, without doubt, the largest and most productive molybdenum deposit yet to be discovered. Figure 18 shows a graph of both Colorado molybdenum production and prices. Of note is the tremendous price increase of the late 1970s and the resultant price and production crash in the early 1980s.

**Geologic Characteristics**

At the Climax Mine, the oldest rocks are Paleoproterozoic (1,775 to 1,650 Ma) schist and gneiss, which have been intruded by Mesoproterozoic (1,400 Ma) granite (fig. 12). Near the Climax deposit the schist is uniform in appearance and composition, except in areas near the contact with the younger granites. The schist is medium grained and composed mainly of biotite, quartz, and plagioclase. Near the granite contact, the schist commonly contains sillimanite (Butler and Vanderwilt, 1931, p. 325).

The granite is chiefly gray to pinkish gray, medium to coarse grained, and massive. Coarse-grained granite near Bartlett Mountain displays a conspicuous alignment of tabular feldspars. Study with a petrographic microscope reveals microcline, quartz, orthoclase, oligoclase, biotite, muscovite, apatite, magnetite, titanite, and garnet, in order of decreasing abundance. Microcline forms tabular crystals and is very abundant. Quartz is present as interstitial grains and inclusions in
feldspar. All the oligoclase shows some alteration to sericite. The mica minerals may be separate from each other or intergrown and generally constitute less than 15 percent of the rock. The biotite is commonly altered to an aggregate of magnetite and chlorite (Butler and Vanderwilt, 1931, p. 326).

The Cambrian Sawatch Quartzite overlies Proterozoic granite on the east side of the Mosquito fault. The Pennsylvanian Minturn Formation is on the west side of the Mosquito fault in contact with the ore body on the east side. Abundant quartz monzonite porphyry dikes and sills intrude the Minturn Formation (fig. 12).

Two groups of Tertiary igneous rocks have intruded the Climax area. The first group consists of “pre-ore” diorite porphyry and the just-mentioned quartz monzonite porphyry. The quartz monzonite porphyry is similar to the Lincoln Porphyry of the Leadville and Alma mining districts. The second group consists of the composite intrusive complex of the Climax Stock, which is the host rock for the Climax molybdenum deposit. The following description of igneous units and associated alteration and ore bodies is summarized from Wallace and others (1968).

**Climax Stock**

The Climax Stock consists of four main intrusive bodies. The intrusive bodies are similar in composition, essentially high-silica rhyolite porphyry, but each contains a particular suite of hydrothermal alteration products. In general, a zone of silicification—High-Silica Rock—lies on the upper part of each productive igneous phase. Zones of molybdenite ore cap and flank the High-Silica Rock. Zones of pyrite-tungsten mineralization lie along the upper and outer surfaces of the molybdenite ore bodies. Table 4 lists each of the igneous and hydrothermal events of the Climax Stock and their approximate ages. Intrusion of the rhyolite porphyry stocks began about 33 Ma and may have lasted as long as 15 m.y., according to the fission-track and K-Ar dates listed in Table 4. However, dating of igneous and hydrothermal activity at the Urad-Henderson molybdenum porphyry deposit in Clear Creek County by the 40Ar-39Ar method reduced the time span indicated by fission-track and K-Ar methods from 10.6 m.y. to 2.95 or possibly 3.43 m.y. (Geissman and others, 1992, in Shannon and others, 2006). Therefore, Shannon and others (2006) suggested that application of high-resolution 40Ar-39Ar dating at Climax would probably likewise reduce the interpreted 15 m.y. span of igneous and hydrothermal activity.

**Ceresco Ore Body—Alicante Stock**

The Alicante stock is an elliptical body of porphyry on the southwest side of the Climax Stock (fig. 13). On the Phillipson Level, the Alicante stock is 1,800 ft by 1,100 ft. Below the Phillipson Level, it plunges northward in contact with the Bartlett stock (fig. 14). The Ceresco Ore Body lies well outside the Alicante stock, and the porphyry is not affected by the mineralization. Dikes that extend from the Alicante stock into the ore body are well mineralized.
Upper Ore Body—Bartlett Stock
The Upper Ore Body lies above and outside the Bartlett stock. However, mineralization extends into the porphyry in some places (fig. 14).

Lower Ore Body—Wallace Stock and Intra-Mineral Porphyry Dikes
The Lower Ore Body lies just above the upper contact with the Wallace stock, but some molybdenite mineralization is also present in the upper and outer parts of that phase. The Intra-mineral Porphyry dikes cut cleanly across the Upper Ore Body; the dikes commonly contain fragments of the Upper Ore Body. In the Lower Ore Body, the Intra-mineral Porphyry dikes commonly contain significant molybdenite mineralization (fig. 14).

"Barren" Stage—Traver Stock and Late Rhyolite Porphyry Dikes
Most Late Rhyolite Porphyry dikes have pegmatitic borders with coarse quartz, potassium feldspar, fluorite, and rhodochrosite. Pyrite, chalcopyrite, sphalerite, and molybdenite are common constituents of the pegmatitic phase.

Structure
There are three main faults that cut the Climax Stock: the East fault, the South fault, and the Mosquito fault. The East fault is a normal fault that dips about 45°–50° E. (fig. 13). It branches into a splayed fault system in its southern segment. Along it, both the Upper Ore Body and the Lower Ore Body are displaced by approximately 330 ft. The fault contains crushed rock, fine-grained quartz, and lesser amounts of coarse fluo- rite, rhodochrosite, pyrite, and fine-grained sphalerite, chalcopyrite, and galena. These minerals are typical of Late "Barren" Stage mineralization; therefore, the fault predates that stage. The fault is probably related to the intrusion of the Porphyritic Granite Phase.

Ore Deposits
Three main ore bodies were formed by the multiple intrusions of the Climax Stock: the Upper Ore Body, the Lower Ore Body, and the Ceresco Ore Body. The Ceresco Ore Body is related to the emplacement of the Alicante stock, the earliest porphyry intrusion. Figure 14 shows the remains of the Ceresco Ore Body and its projected position prior to erosion removing most of the ore body. The Upper and Lower Ore Bodies are related to the intrusion of the Bartlett stock and Wallace stock, respectively. The Upper Ore Body has produced most of the ore from the Climax Mine.

Upper Ore Body
The Upper Ore Body occupies a position directly above the Bartlett stock of the Climax Stock. Its shape

<table>
<thead>
<tr>
<th>Stage</th>
<th>Hydrothermal Event (Ore Body or Alteration Zone)</th>
<th>Igneous Event (Phase of Climax Stock)</th>
<th>Age(Ma), Method</th>
<th>Age Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ceresco Ore Body</td>
<td>Alicante stock and irregular and anastomosing dike swarm</td>
<td>33.2±2.1, FT</td>
<td>White and others (1981)</td>
</tr>
<tr>
<td>2</td>
<td>Upper Ore Body</td>
<td>Bartlett stock and related arcuate dikes and sheets</td>
<td>30.6±0.4, K-Ar 29.8±0.4, K-Ar</td>
<td>Bookstrom and others (1988) White and others (1981)</td>
</tr>
<tr>
<td>3</td>
<td>Lower Ore Body</td>
<td>Wallace stock and Intra-mineral Porphyry Dikes Chalk Mountain rhyolite porphyry</td>
<td>26.1±1.2, FT 27.7±1.9</td>
<td>Bookstrom and others (1988) Bookstrom and others (1988)</td>
</tr>
<tr>
<td>4a</td>
<td>Late Barren Stage of mineralization</td>
<td>Late rhyolite porphyry dikes</td>
<td>25.1, FT 25.5±1.2</td>
<td>Smith (1979) White and others (1981)</td>
</tr>
<tr>
<td>4b</td>
<td>Late Barren Stage of mineralization</td>
<td>Traver stock</td>
<td>18.2±0.9, FT 25.3±0.3, K-Ar</td>
<td>White and others (1981) White and others (1981)</td>
</tr>
</tbody>
</table>

Table 4. Climax Stock igneous and hydrothermal events and approximate ages of the events (adapted from Wallace and others, 1968; Wallace, 1995) Abbreviations: FT = fission track, zircon; K-Ar = potassium-argon.

The South fault is located in the southern part of the stock and is a normal fault with about 200 to 300 ft of slip. The fault dips about 30° NE.; however, at places the dip steepens to 50°–60° NE. The fault commonly is filled with light- to dark-gray chalcedony and fluorite. The South fault probably formed late in the sequence of intrusive and hydrothermal events at Climax.

The Mosquito fault is a major structure in the Climax area and throughout the entire Mosquito Range of Lake County. At Climax, the fault strikes about N. 10° E. and dips 70° W. The fault has more than 9,000 ft of normal separation. The hanging wall has apparently moved about 1,500 ft in a left-lateral sense. In the Climax Mine, the Mosquito fault is a zone of fractured and broken rock that is several hundred feet wide. Crushed-rock zones are as wide as 25 to 50 ft. Deep drill holes have intercepted molybdenite deposits along the Mosquito fault, probably related to the Ceresco Ore Body. Most of the observed movement along the fault is post-ore deposition.

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is that of a tilted, inverted bowl. The tilt to the west (fig. 14) is a result of tilting of the Climax Stock caused by the intrusion of the Wallace stock and the Traver stock into the Bartlett stock. The Upper Ore Body has random and oriented fractures. The oriented fractures are moderately to steeply dipping and are arranged in a radial fashion about the Bartlett stock. Flat or gently dipping fractures are mostly random and less common. Potassic alteration is common in the Upper Ore Body. In some places, the parent texture of the Proterozoic schist is preserved. At other areas, the original texture and minerals of the schist have been converted to an aggregate of pinkish orthoclase and minor quartz. Quartz-molybdenite veinlets cut across the potassic alteration and indicate that alteration preceded mineralization. In addition, some of the quartz-molybdenite veinlets contain potassium feldspar, which suggests that mineralization and alteration occurred simultaneously. Orthoclase and adularia are also constituents of the quartz-pyrite-tungsten veinlets.

Almost all of the ore in the Upper Ore Body is contained in quartz-molybdenite veinlets. Quartz is the most abundant mineral, and orthoclase and fluorite are present in lesser amounts. The molybdenite forms tiny hexagonal plates embedded in quartz, commonly along the veinlet walls. High-Silica Rock associated with the Upper Ore Body is finely crystalline, white to light-gray, hydrothermal quartz. It underlies the Upper Ore Body and forms a zone 1,500 ft in diameter and 300 to 600 ft thick (fig. 19). The silicification of the parent rock and the potassic altered rock in this zone is almost complete. The Upper Ore Body has been altered in places by the High-Silica Rock related to later intrusive bodies of the Climax Stock. In these areas, the molybdenite in the veinlets has been dispersed in the High-Silica Rock.

Pyrite and tungsten minerals were deposited in a distinct zone above and peripheral to the molybdenum ore zones (Figure 19). Pyrite-quartz-sericite veinlets contain tungsten in the oxide form as huebnerite and wolframite. Other minerals in the Upper Ore Body include cassiterite, brannerite, and ilmenorutile.

Pyrite and tungsten minerals occur in a distinct zone above and peripheral to the molybdenum ore zones (fig. 19). Tungsten occurs in the oxide form as huebnerite and wolframite in pyrite-quartz-sericite veinlets. Other minerals that occur in the Upper Ore Body include cassiterite, brannerite, and ilmenorutile.

CERESCO ORE BODY
The Ceresco Ore Body was largely stripped away by erosion. The remaining part of the ore body is exposed in a small area on the northeast side of the Climax Stock and on the southwest side of the stock on the Phillipson Level of the Climax Mine (fig. 14). Most of the mineralization in the Ceresco Ore Body is similar to that in the Upper Ore Body. What remains of the Ceresco Ore Body is much less fractured than the Upper Ore Body; therefore, mineralization is generally more erratic and lower grade.

LOWER ORE BODY
The Lower Ore Body, which lies about 100 to 200 ft above the Wallace stock, is smaller and lower grade than the Upper Ore Body (fig. 14). The Upper and Lower Ore Bodies merge in the eastern part of the Phillipson Level. The Lower Ore Body is not as tilted to the west as the Upper Ore Body. The general pattern of mineralized fractures is similar to that observed in the Upper Ore Body. Potassic alteration is widespread in the Lower Ore Body. In some places, the alteration has overprinted High-Silica Rock of the Upper Ore Body. Mineralization styles of the Upper and Lower Ore Bodies are very similar. The main difference between the Upper and Lower Ore Bodies is the thickness of the zone of tungsten minerals. Like the Upper Ore Body, tungsten minerals were deposited above and outward from the molybdenum ore zone; however, in the Lower Ore Body, tungsten minerals also are found well within the main zone and into the footwall of the Lower Ore Body. The tungsten zone is about 700 ft thick and consists of quartz-pyrite-tungsten veinlets as in the Upper Ore Body. Most of the tungsten produced at the Climax Mine came from this ore body.

LATE "BARREN" STAGE
The Late "Barren" Stage of mineralization is thought to have been associated with the final intrusive stage of the Climax Stock-the Traver stock and Late Rhyolite Porphyry dikes. The ore minerals form stockwork veinlets, stringers, disseminations in pegmatitic pods, segregations in silicified zones, and irregular veins that fill the South and East faults. Quartz-molybdenite veinlets of the Late Barren Stage cut across the High-Silica Rock of the Lower Ore Body.

Even though the Climax Mine has not operated since 1995, it still holds the title as the world's greatest single producer of molybdenum. The recognition of the cyclic nature of the intrusions and ore-body development at Climax was one of the great advances in the study of economic geology and igneous rocks during the last half of the twentieth century.

LEADVILLE DISTRICT
Discovery and Early History
Mining in the district began with the discovery of placer gold in California Gulch in early 1860. A gold rush soon followed. News reports such as the following capture the excitement of those days:
Figure 19: Generalized geology and ore zones, showing dual nature of the Climax Upper Ore Body. (adapted from Wallace and others, 1968).
"On Wednesday eve of last week two rough looking individuals, sunburned and shaggy, entered the office of Pikes Peak Express Co., bearing sacks upon their shoulders which they deposited upon the counter like bags of corn.... Then causing door to be closed, they opened their pouches and emptied them of $27,000 in gulch gold [worth approximately $425,000 at 2002 prices].... The shining dust, whose luster had never been dimmed by any retorting process, glittered with peculiar brilliancy and abounded in nuggets, largest of which were twice the size of silver dollars.... Owners of the treasure are two miners just in from California Gulch.... Their names were J.M. Rafferty from Ohio and George Stevens from Philadelphia" (The Mountaineer, September 26, 1860, quoted in Shannon and Shannon, 1985).

A tent city, originally called "Boughtown" and then later officially named "Oro City," was soon established. Other nearby gulches were intensely prospected for placer gold, but these had been scoured by Pleistocene glaciation that removed the gold placers; only California Gulch had significant quantities of alluvial gold (Thompson and Arehart, 1990). Peak placer activity lasted from 1860 to 1863; by then the richest ground had been worked, and majority of miners had drifted away to other camps. Placer mining continued on an ever-decreasing basis until about 1875, yielding about 344,000 oz (Thompson and Arehart, 1990). The discovery of veins with large masses of free gold at the Printer Boy Mine in 1868 helped extend the life of the camp, but did not reverse the trend of declining production.

From the early days of the development of the district, large amounts of heavy blue-black sands interfered with the placer operations; these were recognized by at least some of the miners as lead carbonate. However, economics of the day precluded processing of lead minerals unless they were excessively rich in silver, owing to the great distances to then-existing smelters. In 1874, the first outcropping lode of silver-bearing lead carbonate was located at the Rock Mine. Although rich in lead, this ore proved to be low in silver. Even so, shipments still made some profit despite the high transport charges to a St. Louis smelter. In 1876, several other lode claims were discovered, and some extremely rich assays (600 to 800 oz per ton silver) were obtained (Emmons and others, 1927). By this time, there was a lead-silver smelter at Georgetown, and several new smelters were being constructed in the vicinity. In 1877, the fabulous ore bodies at Fryer Hill were discovered, and the rush—considered the largest in the State of Colorado—was on (Henderson, 1926). Leadville, located 7 mi to the north of the site of Oro City, had an estimated population of 200 people in the spring of 1877. Within two years, Leadville was the second largest city in the State and had a population of more than 15,000. By 1880, there were 12 smelters in operation, and annual production had risen to more than 10 million ounces of silver and 66 million pounds of lead (Tweto, 1968) (Figure 20).

This was a bonanza period of phenomenal wealth, at least for some individuals. One of the best known is H.A.W. Tabor. Tabor was a frontier grocer who grub-staked two prospectors who sunk a shaft on Fryer Hill into what turned out to be the Little Pittsburgh Mine, a property whose production exceeded $10 million (in the dollar value at the time of production). Tabor was a man of immense luck, both good and bad. Emmons and others (1927) described how Tabor, acting as a buyer for a syndicate of wholesalers, purchased a claim for $40,000 from a disreputable character named Chicken Bill. It seems Chicken Bill did not complete his shaft on the claim to bedrock, but rather had salted the bottom with ore from a nearby mine. After the transaction with Tabor, Chicken Bill could not resist relaying to his cronies his role in the affair, word of which reached the ears of the syndicate Tabor was representing. They declined to complete the transaction, and Tabor was stuck with the property. Tabor then completed the shaft, which encountered the Chrysolite ore body. All told, the Chrysolite yielded $1.5 million in profits to Tabor, who later sold it for a similar amount. Tabor acquired phenomenal wealth from Leadville, became a U.S. Senator, divorced his wife, married (with President Chester Arthur attending) a much younger woman nicknamed Baby Doe, and then proceeded to lose his entire fortune in the Silver Crash of 1893. Tabor and Baby Doe both died penniless; Baby Doe froze to death in the shack built on one of Tabor’s last holdings, the Matchless Mine (Figure 21).

A happier story deals with Meyer Guggenheim, a Philadelphia lace merchant. In 1881, he purchased for $5,000 a half interest in two lackluster claims in California Gulch, the A.Y. and Minnie. He then proceeded to spend $70,000 in dewatering, shaft sinking, and underground development before he hit a major strike at the A.Y. By 1888, the two mines were yielding him $750,000 a year and totaled more than $15 million prior to their exhaustion in 1902. The proceeds from these two properties allowed the Guggenheims to build a mining empire. Three major twentieth-century mining corporations arose from the humble beginnings in California Gulch: The American Smelting and Refinery Company (later known as Asarco Inc.), Guggenheim Brothers (discovers of Chuquicamata, El Salvador, and other important deposits), and the Kennecott Copper Corporation (Smith, 1988).
Mining in the bonanza period was of carbonate ore, which was the oxidized residue of massive sulfides that had replaced dolomite. Mining typically was restricted to depths of less than 500 ft. By the late 1880s, many of the mines had reached sulfide minerals. The decreased silver-lead grades coupled with then-undesirable zinc caused a significant decline in production. In 1893, gold-rich lodes were discovered in the Breece Hill area; these sustained the district following the Silver Crash of that year. Lode gold ore, together with growing recovery of zinc sulfide from 1899 onward, maintained the district until the depression of 1907 when metal prices decreased and output fell significantly. In 1909, zinc carbonate was found peripheral to and beneath many of the old stopes. A zinc carbonate boom then followed and lasted until about 1925. The district then entered a period of continuing, but declining sulfide ore production from carbonate replacement bodies. In 1938, the Resurrection Mining Company (formed from a merger of Newmont Mining Corporation and Hecla Mining Company properties within the district) discovered gold-rich vein ores beneath some of the carbonate replacement stopes and for the next 19 years produced a substantial output (Smith, 1988).

**Post–World War II History**

Following World War II, there were discoveries of ore in the deeply down faulted “Down Dropped Block;” this area entered into production in the early 1950s. A fire in 1956 destroyed most of the surface facilities of the Resurrection property, and this, combined with increasing underground costs and low metal prices, led to the cessation of their operations in 1957. The district was now dormant for the first time in 97 years.

However, exploration continued. The reopening of the Irene shaft and 2,300 ft of exploration drifting in 1965 by a joint venture of Resurrection and Asarco led to the discovery of sulfide manto deposits within the "Down-Dropped Block." [Manto deposits are defined as flat, bedded, and sheetlike mineral deposits. The term is from the Spanish word for mantle or cloak (Guilbert and Park, 1986).] These were put into production in 1971. The mine, known as the Black Cloud, started life with 10 years’ worth of reserves (2.1 million tons). The Black Cloud operation lasted until 1999, more than doubling the then-known reserves and shutting down with resources remaining. During the Black Cloud’s 28 years of production, the mine yielded
a total of 5,637,000 tons averaging 0.063 oz per ton gold, 2.09 oz per ton silver, 3.53 percent lead, 8.18 percent zinc, and 0.13 percent copper (Asarco, unpublished data).

Remaining resources at the Black Cloud Mine are listed as 308,000 tons averaging 0.03 oz per ton gold, 1.6 oz per ton silver, 2.4 percent lead, 8.5 percent zinc, and 0.1 percent copper (S. McGeorge, 2000, personal communication); these were uneconomic at 1999 metal prices. In addition to low metal prices, operating costs were high (and increasing) owing to multiple handling of ore and increased distances from the production shaft. Ultimately, a new production shaft would have to be sunk if production in the district were to continue; then-current resources could not justify the expense of a new shaft. Therefore, the pumps were turned off and the workings allowed to flood. The district is now dormant save for some ongoing exploration (in 2001) by Leadville Mining and Milling Company in the ground directly north of the Black Cloud workings.

**The Yak Tunnel and Its Remediation**

Water was a particular problem at Leadville and greatly hindered operations. In 1889, work was started on a tunnel, now known as the Yak tunnel, which would serve to drain the main part of the district (Shannon and Shannon, 1985). The mouth of the tunnel was located in the lower part of California Gulch, about half way between Leadville and the site of Oro City. The tunnel then proceeded in an east-northeast fashion toward Breece Hill, turning to the northeast just past the Ibex Mine, and eventually reaching the Resurrection shafts at the far northeastern end of the district (Tweto, 1968, fig. 1). The 4-mi tunnel was completed in 1912. Local mines were charged for dewatering and for hauling of ore through the tunnel. Development activity in the Yak tunnel decreased significantly following World War I, but continued at a low rate through the Depression. In 1940, the Resurrection Mining Company purchased the Yak tunnel for $50,000; it then proceeded to build a mill at the portal where it processed ore from its White Cap and Fortune mines (Smith, 1988). The Resurrection properties closed in 1957. Track to the portal of the Yak was pulled in 1963, following closure of the Asarco smelter in 1961 (Shannon and Shannon, 1985). In 1955, Resurrection had formed a joint venture with Asarco to explore and develop the area that became the Black Cloud Mine; ownership of the Yak tunnel fell to the Resurrection-Asarco joint venture.

Unfortunately, the Yak tunnel did more than just drain water from the district’s mines. Undesirable quantities of metals were concentrated in the acidic environment, particularly lead, zinc, and copper. The acidic drainage from the tunnel was a significant environmental issue that had to be addressed to protect downstream waterways. The area around the tunnel was eventually remediated to mitigate the environmental impacts.
drainage water as well so that the Yak tunnel acted as a point-source discharge. In 1983, the Yak tunnel and surrounding area was declared a Superfund site. The Resurrection-Asarco joint venture was obliged to build and operate in perpetuity a water treatment plant, which it does to this day, with annual operating costs on the order of $1.2 million (R. Litle, 2000, personal communication). More than $20 million has been spent by the joint venture on reclamation and treatment associated with the Yak tunnel—an amount that has far exceeded the total profits generated by the tunnel.

Potential liability associated with Superfund has served to preclude outsider interest in the district. Further, district-scale exploration by the Resurrection-Asarco joint venture, for all intents and purposes, ceased in the mid-1980s. This world-class mining district, with abundant perceived exploration potential, has essentially lain fallow since 1985 because of potential legal liabilities.

Production Totals
Leadville is one of the great metal producing districts of the world. Through 1999, Leadville has yielded approximately 28.9 mil tons of ore with 3.3 mil oz of gold, 265 mil oz of silver, 2,354 mil pounds of lead, 1,936 mil lbs of zinc, and 110 mil pounds of copper (Thompson and Arehart, 1990, ASARCO unpublished data). In addition, there has also been significant (nearly 6 mil tons) production of manganese ores with grades up to 45 percent manganese, as well as limited bismuth production (from ore grading 5–16 percent bismuth), and sulfuric acid from pyrite ores (Tweto, 1968).

Regional Geology
The Leadville district has been a focus of detailed geologic study since Emmons’s (1886) extensive monograph, which was one of the first detailed scientific studies of an existing mining district. The summary that follows is based on this work (Emmons, 1886) as well as that of Emmons and Irving (1907), Emmons and others (1927), Behre (1953), Tweto (1968), and Thompson and Arehart (1990). Readers are advised to refer to these works for additional information. However, despite the intensive study by Emmons and others (1927), much of the details of the geology of the district remain unknown. This is because of extensive surficial deposits and vast dumps that preclude surface observations. As well, the weak ground at Leadville has led to caving and virtual obliteration of the workings.

The Leadville district is located in the center of the Colorado Mineral Belt, which is a northeast-trending string of Tertiary intrusive rocks with a high concentration of economic mineral deposits (fig. 3). In particular, the Colorado Mineral Belt is noted for carbonate replacement deposits such as those at Leadville, Aspen, and Gilman; porphyry molybdenum deposits such as Climax and Henderson; gold-silver-base-metal vein deposits such as those at Breckenridge, Central City, Creede, and in the La Plata district; and the gold-silver telluride and tungsten deposits of Boulder County.

The Leadville district lies on the western flank of the Mosquito Range (fig. 4). A 2,660-ft-thick section of Paleozoic marine sedimentary rocks overlies Mesoproterozoic St. Kevin Granite and hosts, along with the Tertiary rocks, the district’s ore deposits. At Leadville, the northeast trend of the Colorado Mineral Belt is intersected by the postmineralization, north-trending Rio Grande Rift. In general, sedimentary rocks in the district have an eastward dip off the Sawatch uplift, but are normally faulted, step-wise, into the graben valley to the west of the district. A critical exception to this pattern is a north-trending graben in the eastern part of the district, known informally as the Down-Dropped Block. The formation of the Down-Dropped Block lowered the ore-hosting sedimentary section in this part of the district and is the locale for recent mining at the Black Cloud Mine.

Stratigraphy
Sedimentary rocks in the Leadville district consist of about 500 ft of Cambrian through Mississippian quartzites and dolomites and more than 2,000 ft of Pennsylvanian black shale, quartzite, and arkose. Virtually all of these units host ore in the district. The principal ore hosts are the three carbonate units: the Leadville Dolostone, the Dyer Formation, and the Manitou Formation. The Mississippian Leadville Dolostone is by far the predominant host for carbonate replacement ore, containing approximately 80 percent of the total. A karst surface and associated karst-fill deposits (Molas Formation) mark the top of the Leadville Dolostone and have served to localize ore in some places.

The stratigraphic section is rarely found intact within the district. Rather it is extensively intruded by a series of igneous dikes, sills, and plugs that can inflate the Paleozoic stratigraphy to two or three times its normal thickness or segment it into islands or isolated blocks within a sea of porphyry.
Igneous Rocks

Excluding the Proterozoic granite basement, there are six different igneous intrusive rocks ranging in age from Late Cretaceous (72 Ma) to early Tertiary (38.5 Ma) that crop out in the district. Leadville was clearly a long-lived center of igneous activity. Mineralization occurred toward the end of the igneous cycle at 39.6±1.7 Ma (Thompson and Arehart, 1990, p.153). The early pre-ore intrusions range in composition from quartz latite to quartz monzonite. All but one were porphyritic. The most important of these-the Johnson Gulch Porphyry (43.1 Ma)-formed the Breece Hill “stock” on which mineralization appears centered, on the basis of metal ratios and zoning (Figure 22). This is not a true stock in the conventional sense, but rather a composite of different igneous sills fused together into a Christmas-tree-like laccolith. Although clearly pre-ore, the Breece Hill igneous center acted as a focal point for later ore-forming fluids.

The only significant post-ore igneous rock is the “Late Rhyolite Porphyry,” dated at 38.5 Ma. This rock and its accompanying hydrothermal breccia, known locally as “Fragmental Porphyry” (Figure 23) (Hazlitt and Thompson, 1990), crop out around the margins of the Breece Hill complex. Intrusion of the Fragmental Porphyry postdated main-stage mineralization, as sulfide clasts (in cases as much as a hundred tons) are found contained within the Fragmental Porphyry. In turn, pyrite-base-metal veinlets and/or late golden barite locally cut the Fragmental Porphyry. It appears that the Late Rhyolite Porphyry and the Fragmental Porphyry are late extensions of the same magmatic and hydrothermal system that formed the ore deposits at Leadville.

In terms of composition and age, the rhyolite porphyry is earlier and less chemically evolved than the high-silica rhyolite porphyries responsible for molybdenum mineralization at Climax (33 to 25 Ma) and Henderson (27.8 to 23.1 Ma) (White and others, 1981). The Leadville mining district is characterized by polymetallic base- and precious-metal sulfide and oxide mantos hosted by Mississippian, Devonian, and Ordovician carbonate rocks. Exploration is complicated by a series of steeply dipping, north-striking faults with recurrent movement. The faults provided a conduit for the intrusions and hydrothermal solutions. Intrusions both displaced and obliterated the stratigraphic sequence. Alteration halos associated with mineral emplacement are typically small.

The primary method of exploration in later years of the district was by underground core and percussion drilling. Targets were selected on the basis of stratigraphy, structure, and proximity of intrusive rocks (especially the Fragmental Porphyry). These techniques were sufficient to nearly triple the effective life of the last mine, the Black Cloud. The Black Cloud Mine area, the Down-Dropped Block (Figure 24), and the district as a whole contain a number of identified targets that have not been tested; exploration potential is perceived as excellent. District-scale exploration by Asarco (operator of the Resurrection-Asarco joint venture) has been virtually nonexistent since 1982 and minimal for five years preceding that. What exploration was done was focused exclusively on the vicinity of the mine area. Certainly there appears room for additional discoveries using modern exploration techniques.

Structure

Structures in the Leadville mining district are extremely complex. Repeated faulting evidently followed the intrusion of each igneous rock. There was significant postore faulting as well that chopped the district into a series of blocks. Generally these faults strike north to northeast and dip steeply (more than 70°). Recurrent slip on faults produced fault zones as wide as 35 ft. Faults within the Down-Dropped Block stair-step down from west to east to the center of the graben and stair-step up to the eastern edge. Outcrops of Fragmental Porphyry found along the periphery of the Down-Dropped Block suggest the possibility that this graben formed as the result of magmatic devolatilization, possibly in a subvolcanic setting. Although structures served as conduits for the hydrothermal solutions, not every structure carried every mineralizing solution, and many faults are not mineralized.

Ore Deposits

The Leadville mining district is noted for six types of mineral deposits (Table 5). By far, base- and precious-metal mantos form the dominant type of deposit. Orebody sizes ranged from 39,000 to 1.2 million tons (or larger-early records about ore-body size are unclear). A typical ore body at the Black Cloud Mine was 500,000 to 800,000 tons.

Descriptions of the ore minerals and the mines of the greater Leadville district from Emmons and others (1927) and Behre (1953) are included in Appendix 1.
Figure 22. Map of Leadville district showing replacement ore bodies.
Figure 23. Location of Fragmental Porphyry pipes, Late Rhyolite Porphyry and projected ore bodies in the Leadville district.

Table 5. Types of mineral deposits of the Leadville mining district.

<table>
<thead>
<tr>
<th>Type of deposit</th>
<th>Gold (oz/ton)</th>
<th>Silver (oz/ton)</th>
<th>Lead (%)</th>
<th>Zinc (%)</th>
<th>Copper (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc-lead-silver-gold mantos (and their oxidized equivalents)</td>
<td>0.05–0.2*</td>
<td>2–6*</td>
<td>3–8*</td>
<td>6–30*</td>
<td>0.1–0.3*</td>
</tr>
<tr>
<td>Quartz-base-metal veins</td>
<td>0.1–0.5</td>
<td>2–13</td>
<td>5–15</td>
<td>4–10</td>
<td>–</td>
</tr>
<tr>
<td>Magnetite-serpentine-gold replacement bodies</td>
<td>0.06–0.17</td>
<td>2–4</td>
<td>–</td>
<td>–</td>
<td>Some</td>
</tr>
<tr>
<td>Quartz-pyrite-gold veins</td>
<td>0.5</td>
<td>30–40</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Disseminated pyrite-gold in porphyry</td>
<td>0.15–0.9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

1Typical grades. The grades marked with an asterisk (*) are for hypogene deposits; the grades marked with a dagger (†) are for supergene deposits. 2Typical grades. 3Average grades. 4Historic grades.
Figure 24. Generalized location map of ore bodies around the Black Cloud Mine in the Leadville district.
Supergene Deposits

Supergene deposits formed the backbone of the bonanza production days. Supergene ore was primarily oxide ore, though locally significant quantities of enriched sulfide ore were mined. Lead was originally deposited in the hypogene environment as galena, which later was typically oxidized to anglesite and cerussite without much apparent migration. The cerussite was accompanied by considerable quantities of silver chloride minerals, particularly close to the surface. Native silver and argentite, if present, tended to form deeper (in the enriched sulfide zone) and directly precipitated on the sulfides (Loughlin and Behre, 1947). Zinc was originally deposited in the mineral sphalerite in the hypogene environment; the sphalerite was completely dissolved, and the zinc was carried downward and reprecipitated as smithsonite, hemimorphite, or calamine. The zinc phases tended to replace manganosiderite or dolomite at favorable locations beneath or lateral to the original ore bodies. Loughlin and Behre (1947) stated that large bodies of high-grade zinc oxide formed where manganosiderite had been the only original gangue mineral around the primary ore bodies, which in turn graded out into the dolomite country rock. If jasperoid, quartzite, or porphyry underlay the original ore body, then the descending zinc solutions became scattered in passing through these rocks, and only small bodies of low-grade ore resulted.

Copper was leached from the oxide zone and redeposited as chalcocite coatings on chalcopyrite and pyrite and as covellite coatings on sphalerite. Sphalerite, particularly if coated with covellite, is said by Loughlin and Behre (1947) to have been particularly effective in precipitating gold; some of the richest gold shoots were of this type.

Oxidation of manganosiderite, which tends to form an outer halo about zinc-lead ore bodies in the western part of the district (Emmons and others, 1927), yielded black manganese-iron ore and locally high-grade manganese oxide. Manganese oxide was used for furnace flux or steel manufacture. The value of this material as flux was significantly increased by its associated lead and silver content.

Ore Controls

In the Leadville mining district, mantos are commonly found at the upper Leadville Dolostone contact beneath porphyry sills, which may have acted as aquitards. The uppermost contact of the Leadville Dolostone is usually the most productive. This contact was known to old miners as the “first contact” (if a porphyry sill was present). The second contact was commonly between the Redcliff and Castle Butte Members of the Leadville Dolostone (again if the contact was occupied by a porphyry sill), and the third contact was typically the basal contact between the Leadville Dolostone and the dolomitic Dyer Formation. In most cases, the first contact had the best manto ore bodies.

Structural controls are common. Ore bodies are adjacent to or strongly associated with major faults in the district; mineralizing fluids used the faults, both reverse and normal, as conduits. Many ore bodies are located at the intersection of dikes and sills, particularly on the downdip side of dikes, and have vein roots or branches away from a central vein. In many cases, these veins did not continue upward to the surface.

The presence of karst appears to have controlled some of the mineralization, although the significance of karst features has been debated in the Black Cloud Mine. The upper contact of the Leadville Dolostone is a karst surface, and cave channels have been reported from the western part of the Leadville district. Increased permeability due to the formation of karst may well be the reason that the upper contact of the Leadville Dolostone is such a favorable ore host. Not all karst features were mineralized, but mineralization included and preserved some bedding features.

Ore bodies in the Black Cloud Mine have a strong spatial association with the Fragmental Porphyry (fig. 23). The fact that the emplacement of the Fragmental Porphyry was approximately contemporaneous with the timing of mineralization suggests that a genetic relationship exists as well.

Exploration at the Black Cloud Mine for carbonate replacement ore bodies, however, dominantly focused on veins. Where veins were intercepted in workings, drifts were then driven along them to their intersection with favorable carbonate stratigraphy. Other factors (paleokarst, Fragmental Porphyry) were of secondary importance; the primary criterion was a favorable (mineralized) structure that intersected dolomite.

Ore Genesis

The genesis and chemical parameters of ore deposition are summarized in Thompson and Beatty (1990). Hydrothermal solutions were generally hot (350° to 420°C), acidic, and ascending. Metals and sulfur were deposited in the carbonates as a result of pH changes, cooling, and decreases in pressure. Alteration halos (weak argillic to sericitic) extend a few meters into intrusive rocks adjacent to ore bodies. (There is also widespread sericitic to argillic plus or minus pyrite alteration of intrusive rocks unrelated to specific ore bodies, particularly in the Breece Hill area.) Within carbonate in the Black Cloud Mine, a knife-sharp
contact was typical between massive sulfide mineralization and apparently unaltered dolomite. Ore bodies in the western part of the district, however, typically had a manganosiderite halo. The most peripheral ore bodies in the western side of the district commonly were bordered by jasperoid (Emmons and others, 1927; Thompson and Arehart, 1990, fig. 16).

Five to seven episodes of mineralization occurred, and not every ore body was affected by every episode. The first stage of mineralization was the formation of magnetite-serpentine skarn brought about by the intrusion of the Breeze Hill stock at about 43 Ma (Thompson and Beaty, 1990). The first sulfide mineralization deposited pyrite, which in some sites replaced magnetite. The main base-metal mineralization deposited varying amounts of lead, zinc, cadmium, copper, iron, and minor amounts of silver. This process may have been caused by the intrusion of a large stock under the Breeze Hill stock at 39.6 Ma (Thompson and Beaty, 1990). The precious-metal mineralization overprinted gold and silver on the existing base metals or magnetite. Later episodes of mineralization include late-stage vein quartz, late-stage vug dolomite, and finally vug-filling golden barite. Zoning within a hypogene ore body consists of a base-metal core (as much as 40 percent combined lead and zinc, but deficient in precious metals) surrounded by a pyritic precious-metal halo. Both were mined at the Black Cloud Mine.

**Minerals and Ore Textures**

Primary sulfide minerals of the Leadville mining district are marmatitic sphalerite, galena (some of which was argentiferous), pyrite, and chalcopyrite. Precious-metal minerals varied by ore body, but typically consisted of tetrahedrite-tennantite, electrum, and gold-silver-bismuth tellurides (Gray and Titley, 1990). More than 100 minerals have been reported from the district (Emmons and others, 1927). A variety of ore textures, such as sulfide banding, rod texture, bird’s eye texture, and zebra rock have been described within the district (Emmons and others, 1927; Behre, 1953; Thompson and Arehart, 1990).

**Metal Ratios, Fluid Inclusions, Isotopes**

Metal ratios based on production statistics show a pronounced bulls-eye centered on the Breeze Hill igneous complex (fig. 22). This bulls-eye is elongated to the northeast and captures the Resurrection ore bodies within the Ag/Au > 20 contour. A small local area of low Ag/Au ratios also appears centered on the Black Cloud ore bodies. Contouring of district fluid-inclusion values (Thompson and Beaty, 1990, fig. 2) confirms the metal-ratio pattern. The overall hottest part of the district—having average ore-formation temperatures greater than 350°C—centered on the Breeze Hill intrusive complex and decreased away to cooler temperatures of less than 250°C at the district margins. An oxygen isotope distribution diagram (Thompson and Beaty, 1990, fig. 14) shows a similar pattern. Thompson and Beaty (1990) interpreted the available metal ratio, isotopic, and fluid-inclusion data to indicate magmatic derivation of water, sulfur, and lead from an igneous source centered on the Breeze Hill magmatic center. Other workers, such as DeVoto (1983) and Smith (1996) postulated that basinal brines may have had a significant role in the formation of these ore bodies. However, the isotopic evidence presented by Thompson and Beaty (1990, p. 174) offers convincing evidence of the magmatic origin of these ore deposits. The exploration ramifications of these models have not been fully addressed in the Leadville district and await future discoveries by future workers.

**Weston Pass District**

**Introduction**

The Weston Pass district is located in southern Lake County along the Weston Pass Road at 11,900 ft near Weston Pass; it is partly in Lake County and in Park County (Figure 25). The Weston Pass district was discovered around 1890, but little work took place until the Ruby Mine was developed in 1902. The Ruby Mine was the most important mine in the district (Behre, 1932). The district is small; only nine mines are shown on Behre’s (1932) map.

**Stratigraphy**

The full Proterozoic-Paleozoic stratigraphic sequence exists at Weston Pass. The main ore bodies are located along a well-defined stratigraphic zone in the Leadville Dolostone. In this area, the Leadville Dolostone is about 370 ft thick, much thicker than the approximately 140 ft in the Leadville district to the north. Two small sills of Pando Porphyry, which in this district has the composition of muscovite granite with a porphyritic texture, intrude the Leadville Dolostone.

**Structure**

The structure of the district is simple; Paleozoic sedimentary rocks strike northwest and dip about 25° NE. Near the west side of the Weston fault, the strata flatten and change strike to east and northeast. Closer to the Weston fault the strata are slightly overturned (not shown on simplified map in fig. 25). The change in attitude indicates that the block on the east side of the fault moved upward and to the north. On the north side of the district, the west-trending Weston fault juxtaposes Proterozoic rocks against the Pennsylvanian Minturn Formation. The minimum throw on this fault is about 1,200 ft (Behre, 1932).
The most striking structural feature is a silicified breccia zone in the Leadville Dolostone, which extends laterally for about 7,200 ft. The breccia zone maintains a constant stratigraphic position about 90 ft above the base of the formation throughout its length. The breccia zone is about 20 ft thick and consists of light-gray, highly silicified, dense jasperoid. The jasperoid is broken into angular fragments and recemented by iron-stained silica. Behre (1932, p. 64) suggested that the silicified zone is a thrust fault, which could account for the thickening of the Leadville Dolostone in this district.

**Ore Deposits**

The most common ore mineral is galena. Rarely sphalerite and pyrite are present. Oxide minerals are cerusite, anglesite, calamine, smithsonite, iron oxide (limonite?), and chalcedony. Dolomite is the most abundant gangue mineral often forming “zebra rock”; a characteristic banded black-white texture in dolomite of the Leadville district.

Ore bodies are associated with an “ore bed” in the Leadville Dolomite; this zone is stratigraphically 75 ft higher than the silicified jasperoid breccia previously described. Ore minerals are disseminated in vuggy cavity zones, which generally have a thickness of less than 10 ft.

The ore grades are the Ruby Mine were reported to be higher than other mines of the district. Lead grades varied from 15 to 46 percent, zinc from 4 to 28 percent, silver 4.8 oz per ton, and gold from the Colin Campbell Claim at 0.10 oz per ton (Behre, 1932, p. 68).
GRANITE AND TWO BITS DISTRICTS

Introduction
The Granite and Two Bits districts (and the Lost Canyon Placer district) are in southernmost Lake County and northern Chaffee County along and to the east of the Arkansas River (Figures 26 and 27). The average elevation of these two districts is 9,000 to 9,500 ft. Placer gold was discovered in 1859 near the present town of Granite in Chaffee County. Prospecting in the early 1860s lead to the discovery of gold-bearing quartz veins of Yankee Blade Hill (Figure 26). The two largest mines of the district were the Belle of Granite and the Yankee Blade Mines, which together produced about 47,000 oz of gold. Most of the district production came the period 1862–1878. In 1908, the Granite Tunnel was driven to test the deep vein potential of the Yankee Blade district. By 1936 some 6,000 ft of tunnel and drift had been completed (Gese and Scott, 1993). Vanderwilt (1947, p. 47) reports production of 3,628 oz of gold from 1932 to 1945 from the Granite and Lost Canyon Placer districts (mostly in Chaffee County).

American Gold Resources carried out a mineral exploration program on Yankee Blade Hill of the Granite district from 1985 to 1989. In 1988 four drill holes were completed to depths of 581 to 684 ft. Selected parts of the core were analyzed; the highest concentration of gold was 0.097 oz per ton (Gese and Scott, 1993, p. 60).

Figure 26. Geologic map of the Granite district. (Adapted from Gese and Scott, 1993).
Stratigraphy and Lithology
The host rock for the district is Proterozoic biotite gneiss and migmatitic gneiss, which has been intruded by a synkinematic adamellite and two-feldspar granite. The biotite gneiss is highly foliated and locally migmatized; it contains as much as 50 percent quartz, 25 to 30 percent biotite, and 5 to 10 percent fibrous sillimanite. Stretched quartz pebbles are present locally and indicate the sedimentary origin of the gneiss (Anonymous, 1982). There are a few east-northeast-striking rhyolite-andesite dikes of Laramide age in the district. Some of the dikes are associated with the gold-bearing fissure veins of the district. R.F. Marvin, in Hedlund and others (1983), reported a potassium-argon age of 65.3±2.4 Ma for a rhyolite dike in the district.

Structure
The metamorphic gneisses have been deformed into a dismembered syncline about 2.8 mi across with an axial plane that strikes northeast. The granitic rocks intrude the keel of the fold. The fissure veins are steeply dipping and are hosted by the gneiss except for the two veins in the Two Bit district. The veins there preferentially follow the north-northeast foliation of the gneiss (Anonymous, 1982).

Ore Deposits
The ore deposits of the Granite and Two Bit districts are quartz-pyrite-gold fissure veins (figs. 26 and 27). The veins form swarms on Yankee Blade Hill; as many as 19 veins have been observed in a 2,054-ft interval. The veins are as long as 3,000 ft, as wide as 1 to 3 ft, and discontinuous along strike. The veins have a relatively simple mineral inventory-chiefly early pyrite and gold as well as minor amounts of chalcopyrite, galena, and sphalerite. The veins are oxidized to depths of about 200 ft, and in the oxidized zone the gold is coarser grained than in the sulfide ore. Alteration of wall rock around the veins is primarily silicification near the vein and chlorite and sericite farther from the vein.
Grades range from 0.005 to 10 oz per ton gold. Some veins in the Yankee Blade Hill area have grades of approximately 0.7 oz per ton gold. Silver grades are low, 0.7 to 0.64 oz per ton. Boron geochemical anomalies are associated with most of the veins. The boron is probably related to the presence of tourmaline; however, tourmaline is not described as a gangue mineral in any available literature (Hedlund and others, 1983). Table 6 shows the estimated production of each of the mines from the Granite and Two Bit districts.

### Table 6. Estimated gold production from the Granite and Two Bit districts. (From Hedlund and others, 1983)

<table>
<thead>
<tr>
<th>Mine</th>
<th>Gold produced (troy oz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Belle of Granite</td>
<td>24,000</td>
</tr>
<tr>
<td>Yankee Blade</td>
<td>23,000</td>
</tr>
<tr>
<td>Magenta</td>
<td>9,600</td>
</tr>
<tr>
<td>Robert George</td>
<td>4,800</td>
</tr>
<tr>
<td>New Year</td>
<td>3,800</td>
</tr>
<tr>
<td>Bunker Hill</td>
<td>3,300</td>
</tr>
<tr>
<td>Washington</td>
<td>2,800</td>
</tr>
<tr>
<td>D.C.C.</td>
<td>1,200</td>
</tr>
<tr>
<td>Gopher</td>
<td>960</td>
</tr>
<tr>
<td>B and B</td>
<td>400</td>
</tr>
<tr>
<td>California</td>
<td>380</td>
</tr>
<tr>
<td>Yosemite-Keystone</td>
<td>350</td>
</tr>
<tr>
<td>Hattie Jane</td>
<td>46</td>
</tr>
<tr>
<td>Two Bits and Two Bits Extension</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Yankee Blade Hill

Ten of the veins (fig. 26) on Yankee Blade Hill have been productive; however, most gold production came from two veins. One of these was developed by the Yankee Blade, Gopher, and Bunker Hill mines; the other was developed by the Robert George and Magenta mines.

The Granite tunnel was dug at the 9,330 ft level to intercept the lower levels of the veins on Yankee Blade Hill. Only 3 of the 19 intercepted quartz-pyrite-gold fissure veins contained economic gold concentrations. Over 4,000 ft of drifting was accomplished on these veins. Gold concentrations were correlated with high concentrations of galena and chalcopyrite. A total of 429 oz of gold was produced from the tunnel from 1930 to 1936 (Gese and Scott, 1993).

Belle of Granite Mine

The Belle of Granite Mine (fig. 26) was developed on a 1 to 5 ft wide quartz-pyrite-gold fissure vein that follows the footwall of a Laramide age andesite porphyry dike in sheared and altered schist. The mine included a 450 ft deep shaft with six levels and more than 3,000 ft of workings. Higher-grade ore was located along northwest-trending fractures (Gese and Scott, 1993).

Two Bits and Two Bits Extension Mines

The Two Bit and Two Bits Extension (fig. 27) are located north of the main Granite district. These mines were mainly silver producers; however, the amount of production is unknown. Veins bearing silver, chalcopyrite, galena, and sphalerite strike north-northeast. The granite wall rock is chloritized. The presence of 300 parts per million antimony in dump samples may indicate the presence of silver sulfosalts (Hedlund and others, 1983, p. 11).

Twin Lakes (Gordon) District

Introduction

The Twin Lakes mining district is located 16 mi southwest of the city of Leadville and approximately 2 mi northwest of the village of Twin Lakes on the steep eastern slopes of Parry Peak at elevations above 11,800 ft. The early history of the district is poorly known. The principal mine, the Gordon, was worked starting in 1884 and by 1919 had development on four levels (Howell, 1919). There are at least eight veins in the area (Figure 28), all of which shipped gold- (silver) ore to a mill in Twin Lakes by way of a gravity tram. Early production records are not available. Incomplete records from the American Smelting and Refinery Company smelter at Leadville from 1937 to 1942 indicate that 163 tons of crude ore averaging 1.6 oz per ton gold, 4.8 oz per ton silver, 9.7 percent lead, 2.1 percent zinc, and 0.7 percent copper were shipped from the Gordon Mine. Production at the Gordon Mine was apparently stopped by Federal order during World War II; there is no evidence that it reopened after the war.

In general, the district consists of a series of northwest-trending, shallow-dipping, fault veins cutting the Tertiary Twin Lakes Granite and Paleoproterozoic schist. Mineral deposits are spatially associated with a set of northwest-trending quartz monzonite porphyry dikes. The surface geology of the district is poorly exposed. In 1991, there was access to more than 2,100 ft of underground workings district-wide; these provided exposures revealing the nature of the geology and mineral deposits. The workings were mapped and sampled in detail by one of the authors, Paul J. Bartos, and Cindy L. Williams as part of an exploration project for Asarco. Parts of the following were summarized from Ms. Williams’ report.
Lithology
The oldest rock in the area is a dark-gray to black, fine-grained, quartz, biotite-sillimanite schist of Paleoproterozoic age. This rock constitutes the wall rock for the eastern, less productive, part of the district. The Twin Lakes Granite, host rock for most of the district’s mines, is one of the phases of the Twin Lakes batholith, a large composite intrusion whose outcrop covers more than 45 sq mi (Wilshire, 1969; Cruson, 1973). In the district, the Twin Lakes Granite is typically light gray to pink, and relatively coarse-grained; it has phenocrysts 0.5 to 1.5 cm in length and a distinct porphyritic texture. The local miner’s term for this rock was “corn granite” (Howell, 1919). Potassium feldspar phenocrysts as long as 6 cm are visible at some places. Quartz and potassium feldspar are the dominant phenocrysts, and approximately 5 percent biotite phenocrysts are also present. Chemically, the composition of the Twin Lakes batholith ranges from granodiorite to quartz monzonite (Wilshire, 1969); the granite appears to be a slightly more silicic local phase. Cunningham and others (1977) reported an age of 64 Ma for the Twin Lakes batholith.

The quartz monzonite porphyry dikes are typically gray to green; the porphyry contains minor phenocrysts of potassium feldspar, embayed quartz, and biotite in a fine-grained matrix. Howell (1919) termed these dikes “quartz porphyry” and considered them of rhyolitic composition; the presence of minor but persistent small plagioclase phenocryst laths suggest that a quartz monzonite to quartz latite composition is more likely. Several small monzonite porphyry dikes of similar appearance, but with distinctly fewer quartz phenocrysts, have been mapped in the eastern part of the district. Most likely, these dikes are cogenetic with the quartz monzonite porphyry dikes; younger veins cut both types of dikes, although sericitic and local silicic alteration and metal ratios are clearly centered on the quartz monzonite porphyry dikes. These dikes have been included by Fridrich and others (1991, fig. 1B) as part of the extracaldera dike swarm that marked the onset of Grizzly Peak caldera volcanism. If so, then these dikes are at least older than 34 Ma (age of eruption of the Grizzly Peak Tuff). Cunningham and others (1977) reported an alteration age of 46 to 43 Ma for the Twin Lakes batholith, which may reflect the age of quartz monzonite porphyry dike emplacement.

Figure 28. Generalized geologic map of the Gordon Mine area, Twin Lakes district.
Structure
Structurally, the Twin Lakes district is dominated by a series of subparallel stacked reverse faults that generally strike N. 60°–80° E. and dip 35°–70° NW. (Figure 29). Estimated offsets on these faults are on the order of several hundred feet, and slickensides suggest a large component of strike-slip. A second group of faults strikes N. 20° W. to N. 20° E.; these faults are particularly prominent in the Gordon Mine where their intersection with the main Gordon reverse fault yielded zones of intensely fractured and mineralized rock more than 60 ft in width. The north-trending faults both cut and are offset by the northeast-trending reverse faults and appear to have limited offsets, on the order of 1 ft to tens of feet.

Ore Deposits
Veins at Twin Lakes are dominated by quartz and disseminated fine-grained pyrite, galena, sphalerite, and chalcopyrite. Principal economic values were gold, which was commonly free and coarse, typically filling small cracks in the quartz or interstices in the sulfides. Vein widths range from inches to 8 ft, and gouge is strongly developed on both walls. Typically, veins are observed in the shear zones associated with the northeast-trending reverse faults; wider pods of mineral deposits were typical at the intersections of the reverse faults with the north-trending fractures. Argillically altered rock surrounds mineralized veins and forms zones as much as 125 ft wide, which typically contain significantly anomalous concentrations of gold.

Alteration is more intense and pervasive around the Gordon vein and adjacent veins than elsewhere in the district. Mineralogic and metal ratio zoning is also centered directly on the Gordon Mine. The Gordon and adjacent veins are characterized by sheared rock with only minor quartz, pyrite, and cerussite (after galena), whereas peripheral veins to the north and south contain significantly more quartz (increasing outward), galena, sphalerite, and pyrite. Beyond these base-metal veins, the dominant vein filling is barite with minor amounts of quartz and pyrite. Silver concentrations in the far-peripheral veins can be considerably higher (up to 14 oz per ton silver) than in veins near the Gordon Mine. Contours of Ag/Au ratios are centered on the Gordon Mine with a 350- by 150-ft core zone of Ag/Au ratios less than or equal to 2, surrounded by a 900- by 2,000-ft area of Ag/Au ratios approximately equal to 10, and then peripheral areas with Ag/Au ratios of 75 to 100 and higher (Figure 30).

Excluding the mapping and sampling just described, no modern exploration or any drilling appears to have occurred in the district.

SUGAR LOAF–ST. KEVIN DISTRICT

Introduction
The Sugar Loaf district is located approximately 6 mi west of Leadville, directly south of Turquoise Lake. The St. Kevin district, on the north shore of Turquoise

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**Figure 29. Geologic cross section of the Gordon Mine area (section line A–A’ on Figure 28).**
Lake, is essentially contiguous to Sugar Loaf. The history of both districts is similar. Nearly all the veins were discovered in the 1880s, supposedly by one man, Tom Welsh (Singewald, 1955). Peak production was from the 1880s until the Silver Crash in 1893. Some mines continued production until World War I, and one mine, the Dinero, continued producing into the 1920s. Reliable production records from this area are not available from before 1914; Singewald (1955) estimated the total value of production from both districts as $10 to $15 million. Metals from the district were dominantly silver and subordinate gold.

There are four main vein zones in the Sugar Loaf district: Dinero, Tiger, Venture, and Bartlett; smaller veins were emplaced on the periphery of the district (Figure 31). The Dinero Mine is estimated to have yielded $1 to $2 million; the Venture, Tiger and Silvers mines each yielded between $500,000 and $1.5 million; and the T.L. Welsh, Red Hook, and Nellie C. Mines each yielded $100,000 to $500,000. Production records from the Dinero Mine from 1914 to 1928 indicated an output of 9,259 tons, of which 939 tons were manganese ore and the rest silver ore. The manganese ore averaged 12 percent manganese; the silver ore averaged 62.7 oz per ton silver, 0.155 oz per ton gold, 0.12 percent copper, 1.88 percent lead, and unknown zinc (Singewald, 1955). An anonymous compilation of records from the Dinero and adjacent mines from 1891 to 1923 reported by Singewald (1955) suggested that shipment grades were 11 to 140 oz per ton silver, 0.04 to 0.5 oz per ton gold, 0 to 14 percent zinc, and less than 1 percent lead. Average grades from the more than 25,000 tons shipped (worth approximately $800,000 at the time) were 63 oz per ton silver, 0.17 oz per ton gold, and 4.3 percent zinc. Zinc grades increased with depth of the workings; average shipment grades started at 0.3 percent and finished at 5.2 percent. This change in the zinc concentration reflected near-surface leaching of sphalerite. In contrast, silver grades were relatively constant over the depth of the workings.

**Lithology**

The area is characterized by poor exposures in dense forest with a glacial drift cover 10 to 15 ft thick. Dumps constitute the principal exposure. The bedrock

![Diagram](image-url)

**Figure 30.** Gold-silver zoning map of the Twin Lakes district.
Figure 31. Vein pattern in Sugar Loaf and St. Kevin districts.
is dominantly Mesoproterozoic granite with islands of Paleoproterozoic gneiss and schist (Figure 32). These rocks are cut by Tertiary porphyry dikes and mineralized veins. The granite was originally correlated to the Silver Plume Granite by Stark and Barnes (1935); Tweto (1987) considered it a separate Proterozoic intrusion, termed the St. Kevin Granite. The granite is typically medium grained and gray; it has small flakes of biotite and subordinate muscovite scattered among larger grains of feldspar and quartz. The granite is locally foliated. Chemically, it appears more akin to quartz monzonite than to true granite (Singewald, 1955); for historical purposes, the granite nomenclature is retained. The biotite schist, quartz-mica gneiss, and migmatite are all medium grained; mica grains are commonly larger than the quartz or feldspar grains. Dikes and pods of granite and pegmatite cut the schist and gneiss; outcrops are insufficient to resolve completely these field relationships.

A series of east-trending Tertiary porphyry dikes cut the Proterozoic rocks. These are typically gray-white and have rare phenocrysts of quartz, muscovite, and potassium feldspar in a fine-grained groundmass. The overall composition appears to be that of a quartz latite. These dikes have been tentatively correlated to the Pando Porphyry (Early White Porphyry) by Singewald (1955), which has been dated in the Leadville mining district at 72 Ma (Pearson and others, 1962).

**Structure**

Veins at Sugar Loaf strike due north (±25°), whereas the porphyry dikes tend to be oriented east-west. Other dikes trend northeast and northwest. In contrast, the dominant vein orientation at St. Kevin is N. 70° E. Most, but not all, veins at Sugar Loaf are contained within granite, and a preferred rock type with respect to vein width, vein concentration, or alteration style, was not observed. Veins appear to cut the porphyry dikes, although field relationships are insufficient to state whether offset occurred or not.
Ore Deposits
The veins are not true veins in the sense of having well-defined walls; rather they are broad, steeply dipping (57° to 78°) shear zones containing broken rock, gouge, and sulfide minerals. Multiple high-grade fissures and fractures within a given shear zone are common. Compared to the country rock, these shear zones are low in silica so they typically do not crop out, but form topographic depressions. The country rock is typically intensely altered to aggregates of sericite, pyrite, and clay and contains stringers and lenses of sulfides with or without fine-grained chert-like quartz. Alteration halos are broad, with measured widths of 200 to 800 ft. Total amount of sulfate in the alteration zones is on the order of several percent. Pyrite is the dominant sulfide, followed by sphalerite, and to a much lesser degree, galena. Minor amounts of chalcopyrite, tetrahedrite, and argentite are also found in the alteration zones (Sandberg, 1935). In addition to fine-grained silica (chert), rhodochrosite and manganocalcite gangue are present in some deposits (Singewald, 1955). Native silver appears to have been the principal ore mineral during early production; tetrahedrite and argentite have also been reported (Sandberg, 1935). Ore shoots typically bottomed within 100 to 200 ft of the surface (Singewald, 1955). Both Sandberg (1935) and Singewald (1955) thought that this limited vertical distribution of the ore bodies in part represented the hypogene distribution of silver. Some ore minerals are laterally zoned: sphalerite and galena seem restricted to the northern part of the Sugar Loaf district, and the concentration of pyrite in the Tiger-Shields vein set distinctly diminishes away from the main Tiger shear (K. Friehauf in unpublished Asarco report, 1990).

In addition to the sericitic alteration associated with the vein zones, Singewald (1955) described “chert zones” (fine-grained silicification) associated with the porphyry dikes. One of these chert zones forms Sugarloaf Mountain, where the chert zone is as wide as 100 ft thick and nearly 1 mi long. (The "Sugarloaf" in Sugarloaf Mountain is spelled as one word, whereas the "Sugar Loaf" district as named by Singewald (1955) is spelled as two words.) Overwhelmingly, the chert zones are associated-spatially and probably genetically-with the porphyry dikes and not with the mineralized shear zones. The granite in the chert zones is so thoroughly silicified by local silica veinlets and high-density chert stockworks that only remnant original texture can be seen. Typically, this silicification is not associated with sulfides, and the chert zones have a dominant east-west orientation, whereas sulfide "veins" tend to be oriented north-south. The chert-like quartz is present in an early, light-colored variety and a later dark-gray variety, which has associated sulfides. The indicated paragenetic sequence of mineralization is (1) emplacement of porphyry dikes; (2) silicification by fine-grained, light-colored chert followed by a change in the orientation of fracture filling; (3) silicification by dark chert; and (4) sulfide deposition (typically early pyrite followed by sphalerite, galena, and silver). Samples of sericitic granite cut by light-colored chert veinlets suggest that sericitic alteration preceded (or at least was broadly contemporaneous with) silica deposition (Singewald, 1955).

Sulfides formed zones of high-grade mineralization within much larger sericitic alteration halos. Extensive sampling (avoiding obvious high-grade material) of the Diner and Tiger-Shields area dumps averaged 0.025 oz per ton gold, 4.7 oz per ton silver (98 samples) and 0.014 oz per ton gold, 2.4 oz per ton silver (66 samples), respectively (K. Friehauf in unpublished Asarco report, 1990). These dumps, which included crosscut material, were thought to represent the entire shear zone and not just the high-grade "fracture-veins" within them.

Asarco completed an induced polarization (IP) and resistivity survey to delineate the veins of the Sugar Loaf district and conducted a reverse-circulation drilling program in 1990. This exploration effort produced 15 drill holes having inclinations of 45° and 61° and depths ranging from 125 to 505 ft (5,540 ft total) (Figure 33; drill-hole locations are proprietary). These drill holes typically encountered intervals of 10 to 40 ft (not true thicknesses as the drill holes cut the steeply dipping shear zones at angles less than perpendicular); assays of the drill samples ranged from 0.01 to 0.025 oz per ton gold, 0.5 to 3 oz per ton silver. The sericitic alteration halos were broad; widths measured 200 to 800 ft. The drilling served to confirm the dump sampling (and thus the overall grades of the shear zones), but did not establish sufficient bulk tonnage material to justify additional exploration. As far as is known, the district has been dormant since Asarco’s drilling.

TENNESSEE PASS DISTRICT

Introduction
The Tennessee Pass mining district straddles the Lake County-Eagle County line at Tennessee Pass (Figure 34). The district is at an elevation of about 10,500 ft. Little is written on the early history of the district. The most prominent mine, the Jennie June, is reported to have produced about $100,000 of gold ore within a few years of its discovery in about 1898. The mine was last worked in 1936. It consisted of a shaft with two levels at 80 and 150 ft (Tweto, 1956). There are two other significant mines in the Lake County part of the district, the Lucy L. and the Golden Gate; however, there are no production records from these mines, and their locations are not given on commonly available maps of the district.
Figure 33. Vein and mine map of the Sugar Loaf district.
Figure 34. Geologic map of the Tennessee Pass district.
Noranda Exploration Inc. and Tenneco Minerals conducted exploration in the district in the 1980s. Exploration drilling was completed about 1.5 mi southeast of Cooper Hill in an area known as “Buckeye Gulch alteration zone” (Pohl and Beaty, 1990). Zones of Leadville Dolomite, which were replaced by a pyrite-rich mixture of sulfide, sulfosalt, and telluride minerals were intercepted by at least two of the drill holes. Gold concentrations in the sulfide replacement zone varied from 1.7 ppm (parts per million) over 5 ft, to 2.3 ppm over 5 ft, to 96 ppm over 2 ft (Pohl and Beaty, 1990, Table 1).

**Stratigraphy**

The Tennessee Pass area consists of Proterozoic gneiss and schist overlain by approximately 400 ft of lower Paleozoic sedimentary rocks. These strata are overlain by the Lower Pennsylvanian Molas Formation, an unconformity-related red clay deposit. The Molas Formation is overlain by 125 ft of Middle Pennsylvanian Belden Shale and an undetermined thickness of the Minturn Formation. The Pando Porphyry intrudes the Belden Shale near Cooper Hill. The Lincoln Porphyry and the Sacramento Porphyry form large quartz monzonite sills in the Minturn Formation.

**Structure**

The strata of the Tennessee Pass mining district have been deformed into an east-dipping homoclinal sequence. Measured dips are on the order of 7° to 10° (Tweto, 1956). Several east-northeast-trending normal faults have been mapped in the area (fig. 34).

**Ore Deposits**

The ore host rock in the major mines of the Tennessee Pass district is the Mississippian Leadville Dolostone. Gold and sulfide minerals were produced from three stratigraphic levels in the Leadville Dolostone (Figure 35) (Beaty and others, 1987). Mineral deposits also have been found in some of the strata underlying the Leadville Dolostone. There are two types of gold deposits found in the district, jasperoid and dolomite breccia. The jasperoid consists of light-gray, very fine grained quartz with calcite pseudomorphs after pyrite. The dolomite breccia found at the Jennie June Mine consists of fine-grained dolostone and chert clasts in a dolomite sand matrix. The breccias are locally iron stained and contain abundant pyrite (Beaty and others, 1987). The grade of gold mineralization is about 0.3 to 0.4 oz per ton (Gese and Scott, 1993).

### OTHER METAL DEPOSITS

**Homestake Mine**

The Homestake Mine is located in northwest Lake County about 2 mi south of Homestake Peak (pl. 1). The host rock for the Homestake Mine is Proterozoic gneiss and schist. Gold and silver mineralization in quartz veinlets 2 to 4 in. wide is associated with east-to northeast-trending quartz veins.

The main vein is a pyritic, silicified, limonitic shear zone that extends for 3,900 ft and attains a width of 20 ft. Precious metals along with galena, chalcopyrite, sphalerite, bornite, siderite, calcite, and barite were produced. Workings at the Homestake Mine consist of five shafts and eight adits. Selected rock samples collected by the U.S. Bureau of Mines (Lundby and Brown, 1987) show concentrations from nil to 0.42 oz per ton gold and from 5.1 to 87.3 oz per ton silver. However, most of the samples collected contained no economic metal concentrations.

**Champion Mine and Iron Mike Mines**

There are a number of small mines and vein prospects in the general vicinity of Lackawanna Gulch (pl. 1), located approximately 14 mi southwest of Leadville. By far the largest of these was the Mount Champion Mine, situated on the south side of Mount Champion, close to the summit. The property was discovered in 1881, but was not developed until 1907 when the Mount Champion Mining Company purchased the property and started construction of a 50-ton/day mill and a 6,100-ft-long tramline. Significant production started in 1912 and continued until 1918. U.S. Bureau of Mines records indicate that 4,759 tons of direct shipping ore were produced at a grade of 3.23 oz per ton gold and 2.6 oz per ton silver. In addition, 40,259 tons of milling ore assaying 0.374 oz per ton gold and 0.28 oz per ton silver were mined. This ore also had minor amounts of lead (1 percent) and, locally, copper (0.3 to 1 percent). During this period, the Mount Champion Mine generated 26,500 oz of gold and a total estimated metal value of $550,000 to $600,000. The Mount Champion Mine was dormant from 1919 to 1936. From 1937 to 1940, the property was leased, and there was small-scale mining; incomplete records suggest that 17.5 tons averaging 2 oz per ton gold and 2 oz per ton silver were mined (G.L. Fairchild, unpublished report, 1974). There is no record of mining activity past 1941. In the late 1970s through the early 1980s, the property was further explored with five drill holes, totaling 400 ft.
During this period, a small firm (Minerals, Inc.) claimed a resource at Mount Champion of 93,000 tons averaging 0.4 oz per ton gold; the basis for this resource estimate is unknown, and no record exists of any subsequent mining.

The Mt. Champion Mine is developed on a single quartz vein-fault striking N55E, with dips ranging between 20 and 60° to the southeast, averaging 45°. Total known vein length is 1,400 ft. Post-mineral faults truncate the vein and create a complicated structure. This vein was developed on four levels for 1,000 ft along strike and 320 ft down dip. Mineral-ization consists of quartz, pyrite, galena, and gold in pods and dilation zones in the fault, which is interpreted as a reverse fault (G.L. Fairchild, private report, 1974). Typical pod dimensions are 20 to 160 ft along strike and 30 to 120 ft along dip. Widths are on the order of 1 to 10 ft. These mineralized pods, in an otherwise continuous, but narrow vein tend to occur in the flatter portion of the vein and near horizontal breaks in the hanging wall or footwall. The mineralization consisted of white quartz with occasional (up to 5 percent) pyrite, galena, chalcopyrite, sphalerite, and gold. Approximately half of the gold was free, and typically not visible. The rest of the gold was commonly associated with pyrite (Howell, 1919). There was no apparent lateral or vertical zonation. Alteration consisted of silicification and argillization next to the vein and continuing up to two ft away, with more distal propylitization.

The rock in the area is typically black biotite or hornblende schist. This schist contains local injections of gneiss and granitoids. The wall rock for the Mt Champion Mine is the Proterozoic Mt. Champion quartz monzonite, which forms a sill-like body. This is a light-gray, medium-grained rock, with quartz evenly distributed throughout and feldspar grains up to 5 mm. The quartz monzonite contains some coarse biotite, and minor amounts of apatite and magnetite. The best portion of the vein is in the quartz monzonite; where
the vein crosses into schist, it becomes thinner, and quickly turns into a series of thin stringers, with more lower metal grades, such that it couldn’t be mined (Howell, 1919). In addition to the schist and quartz monzonite, thin dikes of fine-grained, gray, alaskite porphyry occur in the area.

Within the general Lackawanna Gulch area, Howell (1919) reported an additional five veins. These are respectively; the Eureka, Independence, Mauser No. 1 and No. 2, and D.M. Elder veins. Typically, these are quartz, pyrite, gold, plus or minus galena veins of limited strike length and thickness (typical vein widths of 0.5 to 1.5 ft). The Eureka vein, located near the mouth of Mountain Boy Gulch, is the exception, with a strike length of 500 ft and widths up to 10 ft (averaging 3 to 5 ft). It had some limited production (estimated at perhaps as much as 5,000 tons). Production from other veins in the area is believed trivial.

The Iron Mike Mine is located up South Half Moon Creek about two miles west of Mount Elbert. The host rock is Proterozoic granite. There is no published literature that discusses the geology, mineralogy, and production amounts of the Iron Mike Mine.

**Placer Deposits**

The junction of the Arkansas River and California Gulch, about 2 mi west-southwest of present-day Leadville, was the site of the first gold discovery in Lake County in late 1859. Prospectors returned to this site in early spring of 1860 and by following the California Gulch upstream discovered rich gold placers in the alluvium and terrace deposits of the gulch. A gold rush ensued, which led to the establishment of Oro City, the first settlement with a post office in the upper Arkansas River Valley. The gold rush was over within a few years; however, placer operations continued through the 1930s (Parker, 1974, p. 17–19). Henderson (1926, p. 176) estimated the value of gold placer production from 1859 to 1867, mostly from California Gulch, as $5.272 million (approximately $164,000 oz of gold at an average price of $32 per ounce during the Civil War years).

Placer gold was mined in California Gulch from modern alluvium and high-level terrace gravels. The irregular gold flakes and nuggets came mostly from the prolific lode deposits of Printer Boy Hill, as the gulch gravels do not contain placer gold upstream of Printer Boy Hill. Cerussite (PbCO$_3$) occurred in the placer deposits of upper California Gulch, and it interfered with gold recovery from the sluice boxes. When it was finally identified, it guided prospectors to the rich lead-zinc-silver lode deposits of the Leadville district (Parker, 1974).

The placers of the **Twin Lakes district** are in Lake and Chaffee Counties and were worked continuously from 1860 to 1918. They produced gold worth about $3 million. The Derry Ranch placer is located on Box, Herrington, and Corske Creeks about 1.5 mi north of Twin Lakes. Mining on these placer deposits commenced in 1915 with the construction of a 6-cu-ft dredge for the Empire Dredging Company. The Empire Dredging Company stated that the gravels were 35 ft thick and had a value of $0.20 per cu yd (at a gold price of $20.67 per ounce) (Parker, 1974). The dredge worked these gravels until 1932 when it was dismantled. Other companies worked these **Derry Ranch placers** until 1951. The estimated total production was more than $1.3 million. The placer deposits are primarily in modern stream alluvium except for those parts of Corske Creek that are in glacial moraine. The produced gold had a fineness of 765 and was fine grained, about the size of a pinhead, but a few 0.5-in. nuggets were found as well (Parker, 1974, p. 50–61). Some minor placer deposits were worked at the confluence of Lake Creek and the Arkansas River. Between 1860 and 1867, these produced gold with a value of about $55,000 (Parker, 1974).

Placer workings are located in Buckeye Gulch, a tributary of the East Fork of the Arkansas River in secs. 29 and 32, T. 8 S., R. 79 W. Buckeye Gulch is a narrow valley with glacial drift deposits in the upper part and alluvial-fan deposits in the lower part near its confluence with the East Fork of the Arkansas River. The placer workings are in boulder gravel composed of porphyry and Minturn Formation clasts. Gold was derived from pyrite-quartz veins at the head of the gulch (Parker, 1974, p. 34).

Small placer deposits were mined in East Tennessee Creek and Thayer Gulch in T. 8 S., R. 80 W. Source rocks in these two streams are mostly lower Paleozoic strata and Paleoproterozoic metamorphic rocks of the Tennessee Pass district. In 1938, the placers on East Tennessee Creek produced 471 oz of gold at a fineness of 888.5 (Parker, 1974, p. 38).

Other small placer deposits were found in Colorado and Frying Pan Gulches in the Sugar Loaf district. Source rocks of the gold in this area are quartz veins in weathered and saprolitized Mesoproterozoic granite. No reliable information on gold production from these placers exists (Parker, 1974, p. 38–42).

Several other small placer deposits in Lake County produced minor amounts of gold. These are located in Flume Gulch south of Twin Lakes, Two Bit Gulch about 2 mi north of Twin Lakes, and along the Arkansas River (Parker, 1974).
An abundance of high-quality Quaternary gravel (Qg on pl. 1) deposits line the Arkansas River Valley of Lake County. These deposits have been and are currently being exploited for construction material. The Colorado Division of Minerals and Geology lists four active sand and gravel operations in Lake County for 2006. One of these is used by the Climax Mine for the purposes of their mine and tailings pond reclamation and one is operated by Lake County. The remaining two operations are commercial sand and gravel quarries.

Older gravel deposits and older glacial drift deposits (Qgo and Qdo on pl. 1) are composed of angular to subangular boulder clasts, some of which are many feet in diameter, that are coated with mineral matter and more weathered than the Arkansas River Valley gravels. Hence the gravels of these older deposits will be less durable in any commercial use. The matrix is pebble to gravel size material and clay (Capps, 1909). Glacial drift deposits (both Qd and Qdo on pl. 1) tend to include finer-grained material along with sand and gravel and may be less suitable for easily processed construction material.


