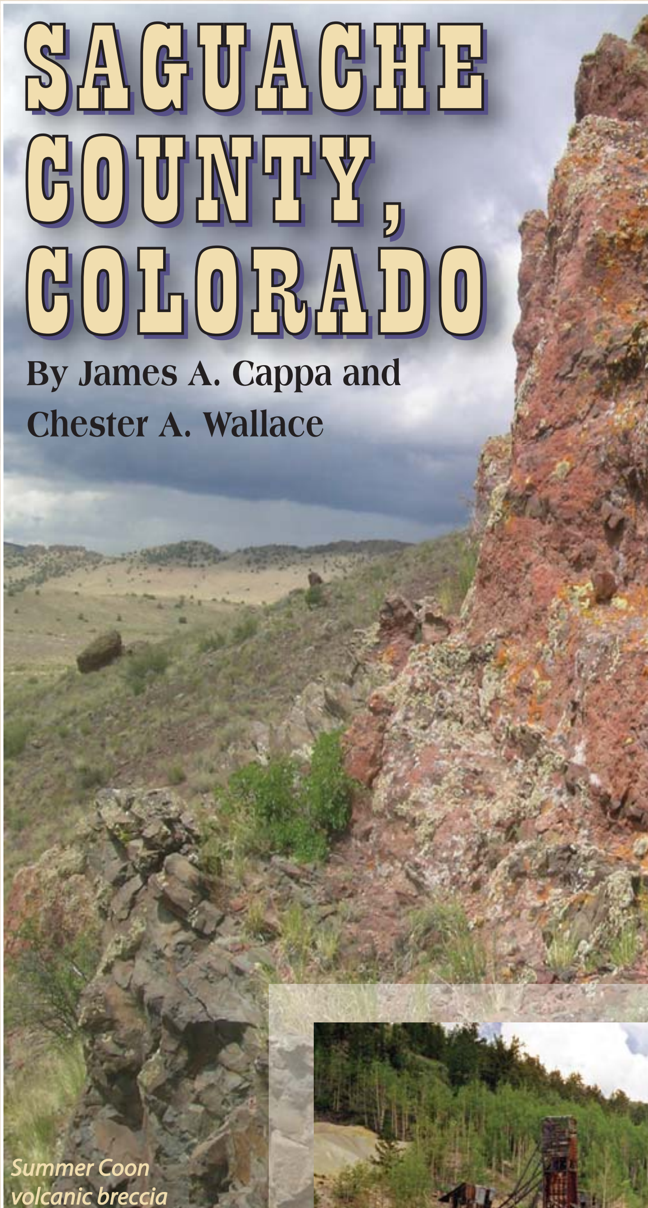
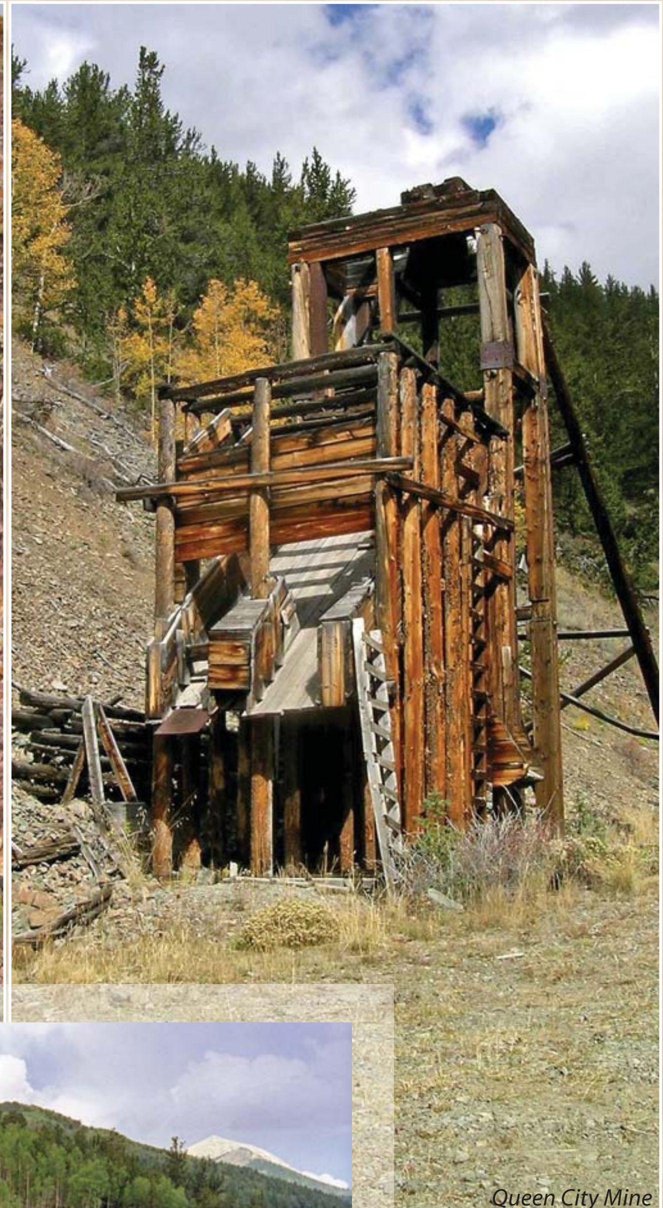
RESOURCE SERIES 44

Geology and Mineral Resources of SAGUACHE COUNTY, COLORADO

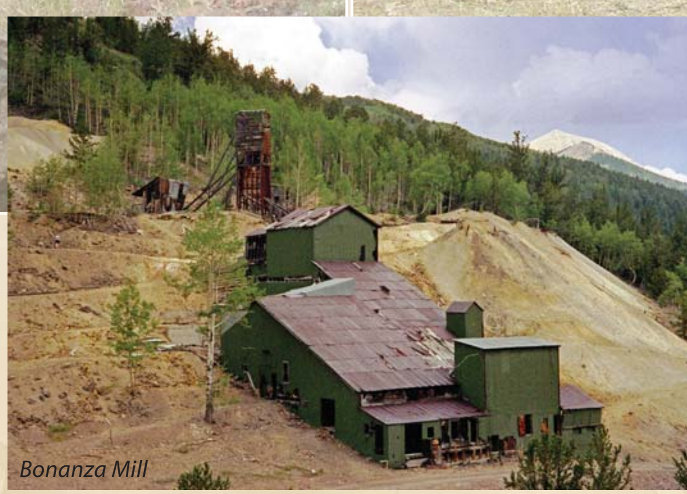
By James A. Cappa and
Chester A. Wallace



Summer Coon volcanic breccia



Queen City Mine



Bonanza Mill

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
2007

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DOI: https://doi.org/10.58783/cgs.rs44.kqie1264

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Denver, Colorado
2007

Cover design, illustration, layout and production by Larry Scott, CGS.

FOREWORD

Colorado Geological Survey Resource Series 44, *Geology and Mineral Resources of Saguache County, Colorado,* describes the geologic setting and the various mineral deposits of Saguache County. This report presents descriptions of the county's known precious and base metal deposits, industrial minerals and construction materials, geothermal resources, and oil and gas resources. In addition, this report contains a single 1:50,000-scale geologic map of the county. James A. Cappa and Chester A. Wallace wrote this report in 2002 and 2003. Mary Eberle of Boulder, Colorado did an outstanding job of editing the report.The objective of this publication is to provide geologic information to resource developers, government planners, and interested citizens.

Funding for this project came from the Department of Natural Resources Severance Tax Operational Fund. Severance taxes are derived from the production of gas, oil, coal, and minerals in Colorado.

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Chief, Mineral and Energy Resource Section

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Introduction

This report describes the geology and mineral resources of Saguache County, Colorado. A geologic map at a scale of 1:100,000 was compiled from source materials at different scales and is included here as **plate 1**. Reconnaissance field investigations were conducted to sharpen rock-unit descriptions and to better understand the geologic setting of the main mining districts. The geologic section of this report presents an account of the geologic setting, stratigraphy, and structure of Saguache County. The section on mineral deposits includes descriptions of the deposits and mining districts in the county.

The two main metal-mining districts in Saguache County are the Bonanza (Kerber Creek) district, located northwest of Saguache, Colorado, and the Crestone district, located along the western front of the Sangre de Cristo Range. These two districts had mineral production between 1879 and 1969, but neither district is currently active. Smaller mining districts are scattered through the county, as well as areas that have potential for industrial minerals and deposits of construction materials. Uranium mining in Saguache County continued until 1976.

Oil and gas exploration in Saguache County resulted in 17 deep drill holes. No oil or gas is produced in the county. Low-temperature geothermal resources have been identified along the west side of the Sangre de Cristo Range and in the eastern San Juan volcanic field.

Included with this report is **Appendix 1**, which contains transcriptions of mineral deposits and mine descriptions of the Bonanza district from U.S. Geological Survey Professional Paper 169 (Burbank, 1932). These descriptions are preserved as originally written.

Geographic Setting

Saguache County is located in the south-central part of Colorado and includes within its borders, the northern part of the San Luis Valley, the western part of the Sangre de Cristo Range, the eastern La Garita Mountains (part of the San Juan Mountains), and the Cochetopa Hills. **(fig. 1)**. The county is 3,169 sq mi in area. Saguache County was created in 1866 from parts of Lake and Costilla Counties, and in 1895, a small piece of the southwestern part of Saguache County was added to Mineral County. The largest town in Saguache County is Center, which had a population of 2,392 in 2000. Other concentrations of population are the towns of Saguache, Crestone, and Moffat. The town of Saguache is the county seat. The population of Saguache County was 4,619 in 1990 and 5,917 in 2000.

The eastern boundary of Saguache County is formed by the sharp divide of the Sangre de Cristo Range, which includes Simmons Peak at 12,050 ft, Bushnell Peak at 13,105 ft, Cottonwood Peak at 13,588 ft, and Crestone Peak at 14,294 ft. The Sangre de Cristo Range rises from the flat valley floor, at an elevation of about 8,000 ft, to between 12,000 and 14,000 ft along the range crest over a distance of 4 mi. The rugged, west-facing slope of the Sangre de Cristo Range

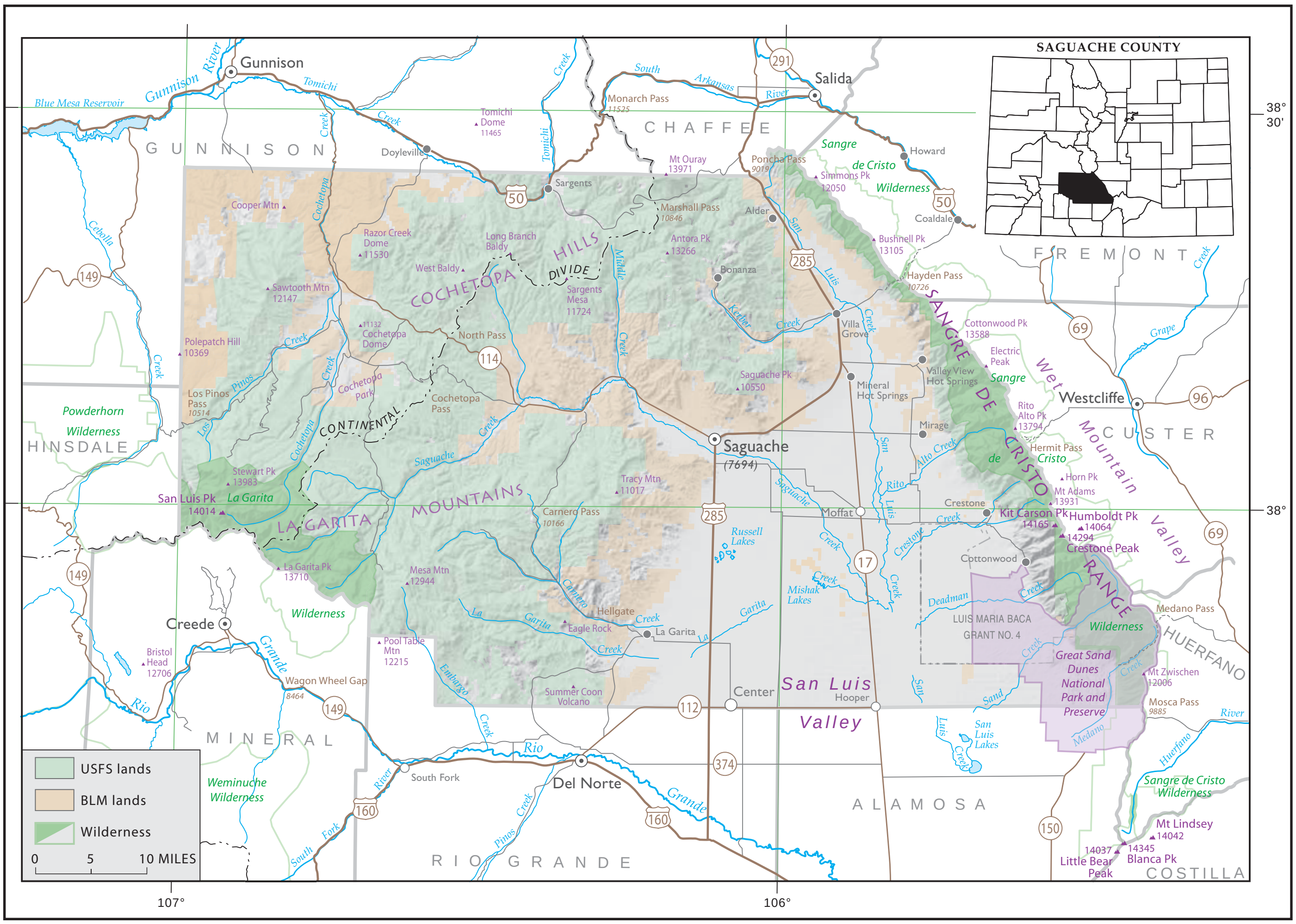


Figure 1. Location map of Saguache County. USFS, U.S. Forest Service; BLM, U.S. Bureau of Land Management.

provides spectacular views from the San Luis Valley. The Great Sand Dunes National Park and Preserve is named for the scenic dunes that cover the east edge of the San Luis Valley in the southeastern part of Saguache County. The Baca Ranch, an original Spanish land grant, is located north of Great Sand Dunes National Park. The ranch was acquired in 2000 by the National Park Service.

The east-central part of the county is a broad, alluvium-filled valley that forms the northern limit of the San Luis Valley; the valley broadens toward the south and at the southern border of the county, the valley is about 45 mi wide. San Luis Creek flows toward the south across the central part of the valley, but like most creeks in the valley, it disappears into the alluvium of the valley floor. Common drainage features in the northern part of the San Luis Valley include artesian springs and spring-fed lakes and ponds that form along discontinuous drainages. These lakes and ponds are an integral part of the Central Flyway along which the few remaining Whooping Cranes and the more numerous Sandhill Cranes migrate twice yearly. The lakes and ponds form a refuge and resting ground for cranes, ducks, geese, and shorebirds.

Mountainous terrain in the western part of the county is named the Cochetopa Hills in the north and the La Garita Mountains in the south. No clear dividing line separates the two geographic entities. The highest peaks in the western part of Saguache County are along the southwestern border where San Luis Peak is 14,014 ft and neighboring Stewart Peak is 13,983 ft in elevation. Most of the summits in the western part of the county are 10,000 ft to 11,000 ft in elevation.

Saguache County depends mainly on farming and ranching to sustain its economy. The town of Center is the regional hub of commerce, which is dominated by agricultural businesses. The abundance of artesian water to supply irrigation systems is crucial to farming in the northern part of the San Luis Valley. The main crops are alfalfa, potatoes, barley, wheat, carrots, and lettuce.

The active mines in Saguache County are aggregate quarries. No metal mines are active in the county, although the Bonanza mining district, which is northwest of Villa Grove, is a mining camp that dates from 1879 and is currently a tourist attraction.

The principal geographic elements of Saguache County consist of the western flank of the Sangre de Cristo Range, the San Luis Valley, the Cochetopa Hills and La Garita Mountains (fig. 1). Each geographic element is a distinct tectonostratigraphic terrane (**fig. 2**):

- The **Sangre de Cristo Range** is underlain by folded and thrust-faulted Proterozoic meta-morphic and igneous rocks and Paleozoic sedi mentary rocks.
- The **San Luis Valley** is a structural depression that is filled with sedimentary materials of late Tertiary and Quaternary age.
- The **Cochetopa Hills and La Garita Mountains** consist of a block-faulted terrane of Proterozoic metamorphic and igneous rocks and Paleozoic and Mesozoic sedimentary rocks, overlain by intermediate-composition and silicic volcanic rocks of the San Juan volcanic field.

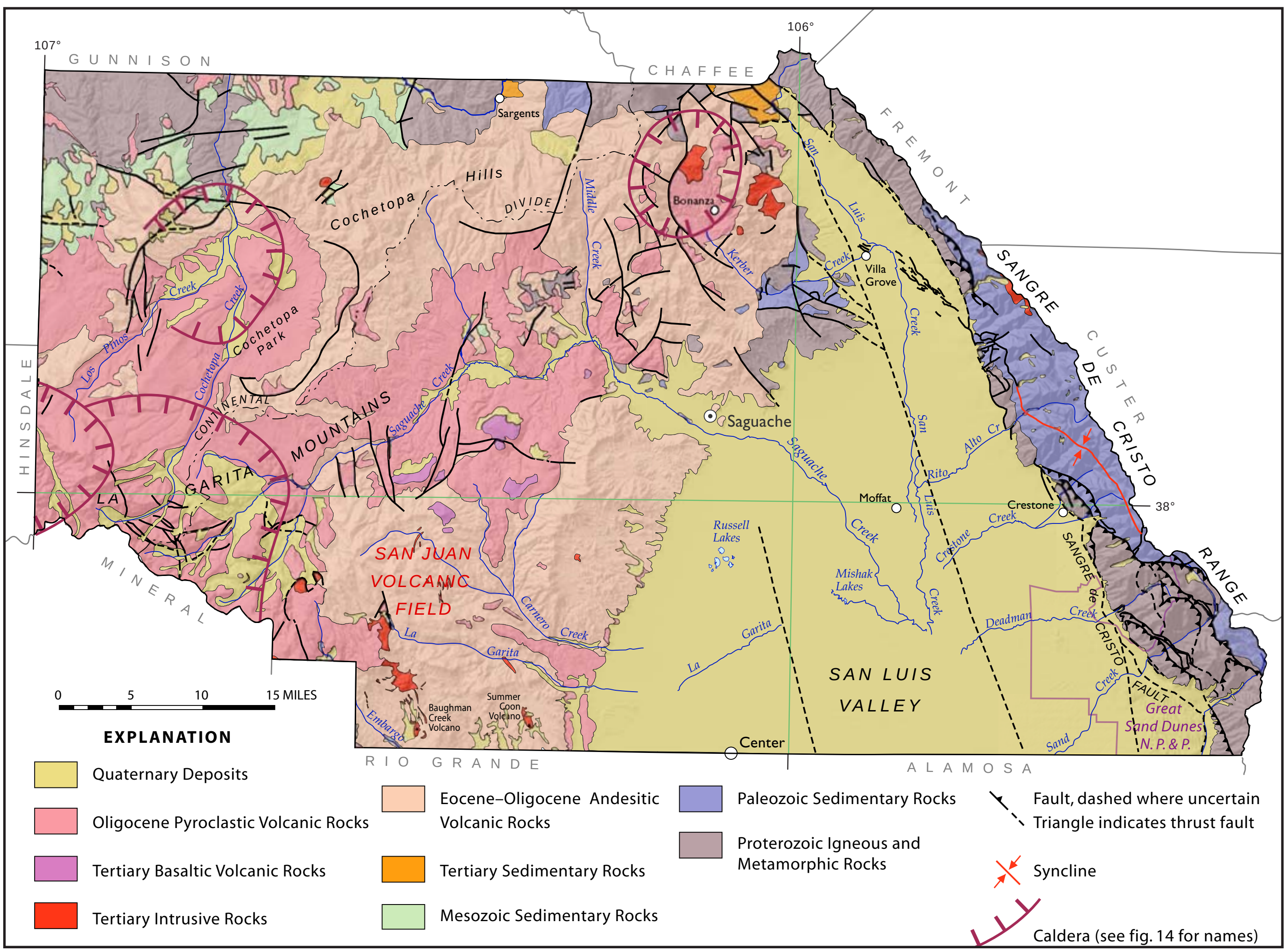


Figure 2. Geological features of Saguache County.

The Sangre de Cristo Range contains Paleoproterozoic (about 1,800 Ma) metasedimentary and metavolcanic rocks along the lower part of the west flank, and at some places, these old rocks are thrust over younger (Pennsylvanian and Permian) strata. These Paleoproterozoic rocks are mainly interlayered hornblende schist and quartzofeldspathic gneiss, leucocratic gneiss, and amphibolite. Plutonic rocks (about 1,700 Ma) are scattered through the northern part of the range, and these consist of gabbro, metagabbro, and quartz monzonite. Mesoproterozoic rocks (about 1,400 Ma) are exposed on the west-facing escarpment where quartz monzonite intrudes the older Paleoproterozoic rocks. Overlying the Proterozoic rocks along the east-facing escarpment are lower Paleozoic dolostone, sandstone, and limestone that were deposited in shallow-marine conditions between Cambrian and Mississippian time. Disconformities separate most of these formations. A thick sequence of sandstone, siltstone, shale, conglomerate and minor interbeds of limestone of Pennsylvanian and Permian age was deposited on Mississippian limestone. These clastic rocks are dominantly coarse grained, and they were deposited in deltas and nearshore-marine conditions. Quaternary units in the Sangre de Cristo Range are mainly glacial deposits of till, rock glaciers, outwash gravel, and lacustrine beds.

Sedimentary rocks in the Sangre de Cristo Range were thrust-faulted and folded, possibly along existing structures, into tight, commonly isoclinal synclines and anticlines during Late Cretaceous and early Cenozoic time. Hoy and Ridgway (2002) documented stratigraphic and structural features in the Pennsylvanian and Permian age rocks that strongly suggest syndepositional deformation. The Sangre de Cristo Range is bounded on the west by the Sangre de Cristo fault, which is a normal fault. The west block is downthrown to form the San Luis Valley. Uplift and cooling of the Sangre de Cristo block started in early Miocene time, and slip has continued through Quaternary time.

The San Luis Valley is situated in a complex rift basin that is hinged on the west side. The resulting basin is filled with Tertiary sedimentary and volcanic rocks and unconsolidated Quaternary deposits that overlie probable Paleoproterozoic metamorphic, igneous, and sedimentary rocks. The San Luis Valley is a northern extension of the Rio Grande rift. Ash-flow tuffs, erupted from calderas of the San Juan volcanic field, form the earliest deposits in the Rio Grande rift, which began to subside during Eocene and Oligocene time. Between Miocene and Quaternary time, conglomerate, sandstone, siltstone, and some shale filled the deepening sedimentary basin in the graben as slip on the Sangre de Cristo fault increased. Quaternary units in the San Luis Valley consist of till, outwash, lacustrine deposits, alluvial fans, and extensive eolian deposits of the Great Sand Dunes National Park and Preserve. Cenozoic and Quaternary faults bound small grabens in the sedimentary basin.

The Cochetopa Hills are a block-faulted terrane of Paleoproterozoic metamorphic and igneous rocks overlain unconformably by Phanerozoic sedimentary strata and Oligocene ash-flow tuffs; the La Garita Mountains are composed of early volcanic rocks of intermediate composition and overlying ash-flow tuffs erupted from nearby calderas. In the Cochetopa Hills, the block-faulted terrane composed of Paleoproterozoic metamorphic and igneous rocks and faulted sequences of Paleozoic and Mesozoic strata is exposed in windows through ash-flow tuffs that were erupted from nearby calderas of the San Juan volcanic field. Early volcanic activity in the San Juan volcanic field produced andesite and rhyodacite flows, breccia, and air-fall tuffs in the La Garita Mountains and Cochetopa Hills areas. Two prominent volcanic edifices, the Summer Coon and Baughman Creek volcanoes, are preserved in the southwestern part of the county. Overlying the early intermediate-composition volcanic rocks are ash-flow tuffs that were erupted from the La Garita, San Luis, Cochetopa Park, and Bonanza calderas. Extensive sheets of ash-flow and air-fall tuffs composed mainly of silicic latite (quartz latite), rhyodacite, and rhyolite blanket older volcanic, sedimentary, metamorphic, and igneous rocks in the La Garita Mountains and Cochetopa Hills. Quaternary deposits in the La Garita Mountains consist mainly of glacial deposits in the highest elevations, landslide masses where extensive areas of volcanic rocks are exposed, and alluvium in modern drainages. In the Cochetopa Hills, Quaternary deposits are mainly landslide debris in volcanic rocks and alluvium in modern drainages.

Stratigraphy

The oldest rocks in Saguache County are Proterozoic metamorphic and igneous rocks **(fig. 3)**, which are nonconformably overlain by a lower Paleozoic sequence of quartzite, dolostone, limestone, and rare shale, which is overlain by an upper Paleozoic sequence of shale and feldspathic siltstone, sandstone, and conglomerate. In the western part of the county, Jurassic and Cretaceous shale, siltstone, and sandstone overlie Paleozoic strata. Volcanic rocks dominate the western part of the county where the San Juan volcanic field is composed of an early series of andesite flows, ash-flow tuffs, and air-fall tuffs. A later series of felsic to intermediate ash-flow tuffs were erupted during caldera-collapse events. Tertiary and Quaternary conglomerate, sandstone, and shale filled the San Luis Valley during an extensional tectonic event that formed the Rio Grande rift. Glacial deposits were laid down during at least two alpine glaciations in the Sangre de Cristo Range and La Garita Mountains. During the Pleistocene, winds eroded sand from the San Luis Valley and formed the extensive dune fields, many of which are now located in the Great Sand Dunes National Park and Preserve.

PROTEROZOIC ROCKS

In Saguache County, Proterozoic rocks are composed of igneous and metamorphic rocks that range from Paleoproterozoic (2,500 to 1,600 Ma) to Mesoproterozoic (1,600 to 1,000 ± 50 Ma) in age. These rocks are exposed throughout the Sangre de Cristo Range. In the central part of the Sangre de Cristo Range in Saguache County, Paleozoic sedimentary rocks nonconformably overly the Proterozoic rocks. The area west of Villa Grove and north of Saguache also contains a sequence of Proterozoic rocks. Other exposures are mainly in the northwestern part of the county in the Cochetopa Hills (fig. 2).

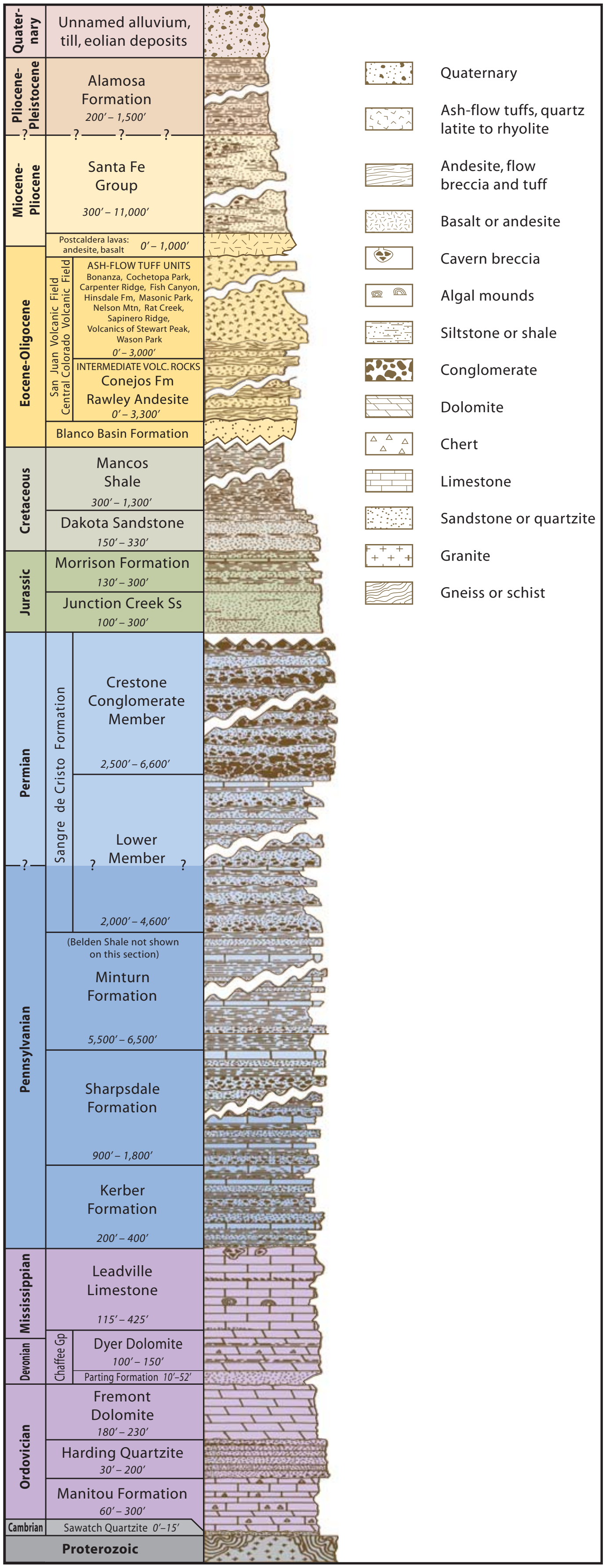
The Proterozoic Eon is represented in the county by metavolcanic and metasedimentary rocks about 1,700 to 1,800 Ma in age (Paleoproterozoic), intermediate-composition plutonic rocks about 1,700 Ma in age (Paleoproterozoic), and plutonic granitic rocks about 1,400 Ma in age (Mesoproterozoic).

Paleoproterozoic Rocks

METAMORPHIC ROCKS

Metasedimentary and Metavolcanic Rocks

Metamorphic rocks in Saguache County are poorly dated by radiometric methods; the Paleoproterozoic age is determined by lithological and textural similarities with other well dated metamorphic rocks in Colorado (Tweto, 1980). Felsic and hornblendic gneiss is a common unit in the northwestern part of Saguache County (Tweto and others, 1976), and this unit consists of interlayered hornblende schist and quartzofeldspathic gneiss (labeled as Xgn in plate1) **(fig. 4)**. All lithological descriptions in this section are from Hedlund and Olson, 1974, 1975; Olson and others, 1975; Olson, 1976a, 1976b; Olson and Steven, 1976a, 1976b. The hornblende schist is a dark-greenish-black, fine-grained, moderately foliated rock that contains mostly hornblende and andesine, plus accessory biotite, calcite, chlorite, and iron oxides. Hornblende is commonly altered to chlorite. Preserved amygdules, breccia, and local pillow structures denote the volcanic origin of this unit. Quartzofeldspathic gneiss is commonly light- to medium-gray, fine-grained gneiss composed of large crystals of albite-oligoclase in a finer-grained granoblastic or microcrystalline groundmass of quartz, microcline, and oligoclase. Accessory minerals are muscovite, epidote, biotite, and iron oxides. Felsite and felsite porphyry were mapped by Olson (1976a, 1976b) as less metamorphosed equivalents of the quartzofeldspathic gneiss. Olson (1976a, 1976b) described these felsites are light-gray to yellowish-gray, fine-grained, metamorphosed rhyolite, quartz latite, and tuffaceous sedimentary rocks composed of phenocrysts of albite-oligoclase and quartz in a microcrystalline groundmass of quartz, feldspar, biotite, muscovite, chlorite, epidote, and iron oxide minerals. Eutaxitic textures, phenocrysts, broken feldspar grains, and devitrified and recrystallized lapilli indicate a volcanic origin as welded or unwelded tuffs, although some rocks may be intrusive. Amphibolite bodies probably represent metamorphosed sills and dikes that were intruded later and metamorphosed with the original volcanic rocks.



Detailed and reconnaissance geologic mapping in the 1980s by the U.S. Geological Survey refined the structure and stratigraphy of the Sangre de Cristo Range (Taylor and others, 1975; Van Alstine, 1974, 1975; Lindsey and others, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989). In the Sangre de Cristo Range and in the Poncha Pass area, the names used for Proterozoic rocks differed from the names used by Tweto and others (1976) in the Montrose quadrangle to designate Proterozoic units. These Early Proterozoic rock units are well exposed along the prominent west-facing escarpment of the Sangre de Cristo Range.

The oldest of these Paleoproterozoic rock units was mapped as gneiss and leucocratic gneiss by Taylor and others (1975), Lindsey and others (1986b), Lindsey and Soulliere (1987), and Johnson and others (1989). The gneiss on our map (pl. 1) was described by Lindsey and others (1986b) as interlayered, well-foliated, mafic and felsic gneiss in pink, gray, and black colors. Locally the gneiss is migmatitic and intruded by pegmatite and mafic dikes. Mafic gneiss consists of quartz, plagioclase, orthoclase, biotite, and accessory magnetite and sphene. Felsic interlayers in the gneiss are rich in quartz and feldspar. The protolith may have been sedimentary and volcanic rocks. The leucocratic gneiss described by Lindsey and others (1986b) is white to medium-gray, locally migmatitic gneiss of granitic and granodioritic composition. Leucocratic layers are composed of 35 percent plagioclase, 30 percent quartz, 30 percent microcline, and 4 percent biotite plus a trace of muscovite and hornblende. Cataclastic textures are pervasive. Mafic layers account for about 20 percent of the rock and consist of 40 percent plagioclase, 25 percent quartz, 20 percent microcline, and 15 percent biotite and hornblende. The protolith for leucocratic layers may have been volcanic rocks of rhyolite to dacite composition, and for mafic layers, the protolith may have been metavolcanic rocks of basalt or andesite composition (Lindsey and others, 1986b).

In the northern part of Saguache County, metasedimentary and metavolcanic rocks consist mainly of metamorphosed shale, siltstone, sandstone, and interbedded volcanic rocks (labeled as Xfh on plate 1). The metamorphic grade varies between greenschist facies and amphibolite facies, and the dominant rock types are slate, phyllite, schist, and gneiss consisting of quartz, biotite, microcline, and albite-oligoclase. Accessory minerals are muscovite, epidote, apatite, chlorite, iron oxides, and rare amphibole (Hedlund and Olson, 1974, 1975; Olson and others, 1975; Olson,

Figure 3. Composite stratigraphic column of Saguache County.

Figure 4. Outcrop of Paleoproterozoic gneiss showing recumbent folding. Clayton Cone (pl. 1) 2 mi west of Villa Grove.

1976a, 1976b; Olson and Steven, 1976a, 1976b). Rocks are thinly laminated to massive. Layers of metabasalt and meta-andesite **(fig. 5)** are composed of dark-greenish-black, fine-grained, amphibole schist composed of actinolite or hornblende, albite or oligoclase, and accessory biotite, chlorite, calcite, and magnetite. Metabasalt and meta-andesite preserve amygdules, clastic textures, and pillow structures that indicate an origin as volcanic flows, tuffs, and breccia. Original clastic textures, such as graded bedding, still exist where the rocks are less metamorphosed. Thin conglomerate beds are exposed locally. More intensely metamorphosed rocks are quartz-biotite schist and gneiss **(fig. 6)**. Amphibolite bodies probably represent sills and dikes that were intruded later and metamorphosed with the original sedimentary and interlayered volcanic rocks.

In the eastern part of Saguache County, in the Sangre de Cristo Range and in the Poncha Pass areas, metasedimentary and metavolcanic rock units are mapped as Xvs on plate 1. (Taylor and others, 1975; Van Alstine, 1974, 1975). Regionally, the metamorphic grade of these rocks varies from amphibolite to greenschist facies. As reported by Taylor and others (1975), this unit is mainly muscovite-feldspar gneiss, biotite-plagioclase metarhyolite tuff, metabasalt, phyllite, slate, siltite, argillite, muscovite schist, spotted schist, and metamorphosed sedimentary breccia and tuff. Most rocks are muscovite rich. Sillimanite is present

Figure 5. Boulder of Paleoproterozoic meta-andesite. Upper Dorsey Creek (pl. 1) Sangre de Cristo Range. Hammer is 16 in. long.

rarely. These rocks are little deformed at some places, and original rock textures, such as graded bedding and cross-laminae, are preserved despite the high metamorphic grade. Regionally, these rocks are more metamorphosed toward the south and west and less metamorphosed toward the north. These rocks grade into gneiss, as shown on the accompanying plate 1. North of Saguache County near Salida, Colorado, Bickford and others (1989) reported a uranium-lead age of 1,728 ± 6 Ma for zircons from a similar metasedimentary and metavolcanic unit.

Plutonic Rocks

Metagabbro and gabbro form stocks, sills, and dikes scattered through the northern part of Saguache County. Lithological descriptions are taken from Taylor and others, 1975; Olson, 1974, 1976a, 1976b; Hedlund and Olson, 1974; Lindsey and others, 1986b; Lindsey and Soulliere, 1987). Generally, these dark-greenish-gray and greenish-black rocks are foliated or massive and are composed of hornblende, plagioclase, and olivine or augite. Hornblende is commonly altered to chlorite. Accessory minerals are epidote, clinozoisite, biotite, sphene, apatite, calcite, and magnetite.

Granitic stocks crop out as isolated intrusions in the northern part of Saguache County (Taylor and others, 1975; Olson, 1974, 1976a, 1976b; Hedlund and Olson, 1974; Lindsey and others, 1986b; Lindsey and Soulliere, 1987). Included in this general class of igneous rocks are quartz monzonite and granite. In the northwestern part of Saguache County, the quartz monzonite of Cochetopa Creek is composed of pink and reddish-gray, medium-grained, nonfoliated rocks consisting of 35 to 40 percent microcline, 25 percent oligoclase, 20 to 30 percent quartz, and 3 to 10 percent biotite (Olson and Steven, 1976a, 1976b). The quartz monzonite of Gold Basin is light pinkish gray, medium grained, and composed of 65 percent oligoclase, 2 to 5 percent microcline, 27 percent quartz, and 7 percent biotite (Hedlund and Olson, 1974). In the eastern part of Saguache County, quartz monzonite plutons are rare, but in the Sangre de Cristo Range, the quartz monzonite of Music Pass (Johnson and others, 1987) is a gray to pink, coarse-grained, foliated porphyry composed of 25 to 45 percent microcline phenocrysts in a groundmass consisting of 60 percent plagioclase, 20 percent quartz, and 20 percent biotite. Granite forms isolated stocks in the northwestern part of Saguache County where Hedlund and Olson (1974) and Olson (1976b) described several granite intrusions that typically are light pinkish gray, light gray, and grayish pink, fine to medium grained, and composed of 30 to 65 percent oligoclase, 20 to 35 percent quartz, 2 to 47 percent microcline, and 2 to 11 percent biotite. Hornblende, epidote, sphene, garnet, and apatite are common accessory minerals.

Figure 6. Outcrop of Paleoproterozoic quartz-biotite gneiss. Upper Dorsey Creek (pl.1), Sangre de Cristo Range.

Mesoproterozoic Rocks

Plutonic Rocks

Mesoproterozoic igneous rocks are represented by a granitic stock and rare dikes in the northwestern part of Saguache County and by quartz monzonite stocks in the Sangre de Cristo Range in the southeastern part of the county. Olson and others (1975) described leucogranite and quartz monzonite from the northwestern corner of the county as light-pinkish-gray, medium- to fine-grained, or aplitic, leucogranite and quartz monzonite. This unit is composed of perthitic microcline, albite-oligoclase, quartz, and rare biotite, muscovite, apatite, iron oxides, and chlorite. Locally, this granitic unit is sheared and sericitic. In the Sangre de Cristo Range, quartz monzonite is exposed in the east face of the escarpment; Johnson and others (1987) described this unit as a gray to pink, medium-grained, nonfoliated quartz monzonite composed of 35 percent plagioclase, 30 percent microcline, 30 percent quartz, and 2 to 5 percent biotite. The minerals of this rock are extensively altered to chlorite, epidote, and muscovite. This unit is correlated with the 1,400 Ma Silver Plume Granite by Taylor and others (1975).

PHANEROZOIC SEDIMENTARY ROCKS

Paleozoic Rocks

Paleozoic sedimentary rocks in Saguache County are mainly interbedded clastic rocks and carbonate rocks that were deposited in shallow-water and nearshore conditions. These rocks overlie Proterozoic metamorphic and igneous rocks on a regional unconformity and range in age from Cambrian to Early Permian. The Sawatch Quartzite (Late Cambrian) (Ross and Tweto, 1980), which is the oldest Paleozoic unit in this region, forms thin and discontinuous beds in Saguache County; where a thin layer of Sawatch Quartzite is present, most geologists have included it with the overlying Manitou Formation. In most of the county where the Sawatch Quartzite is absent or too thin to be mapped separately, the Paleozoic sequence consists of the Manitou Formation, Harding Quartzite, Fremont Dolomite, Chaffee Group, Leadville Limestone, Kerber Formation, Sharpsdale Formation, Minturn Formation, and Sangre de Cristo Formation, in ascending order. Most of these sedimentary rock units are separated by disconformities and angular unconformities that represent long periods of nondeposition or deposition and later erosion (Ross and Tweto, 1980). The thickness of Paleozoic rocks is about 24,000 ft in the county.

Cambrian Rocks

Sawatch Quartzite

The Sawatch Quartzite of Late Cambrian age overlies Proterozoic metamorphic and igneous rocks in isolated patches in parts of Saguache County. The Sawatch Quartzite was named by Eldridge (1894) for exposures in the area of Crested Butte and parts of the Sawatch Range. North of Sawatch County, along the Arkansas River, the Sawatch Quartzite is 4 to 6 in. thick, but it is 15 ft thick in Brier Creek, 2 mi north of the county boundary. In the area of the Marshall Pass mining district, however, the Sawatch Quartzite is less than 3 ft thick at most places (Olson, 1983). Reports on rocks of the Sangre de Cristo Range (Taylor and others, 1975; Lindsey and others, 1985c, 1986b; Johnson and others, 1989) do not indicate whether a thin representative of the Sawatch Quartzite is present. Burbank (1932) described small patches of feldspathic quartzite that could represent the Sawatch Quartzite in the Kerber Creek area northwest of the town of Villa Grove.

The Sawatch Quartzite is a grayish-white, light-gray, and white, quartz-cemented, medium- to coarse-grained, conglomeratic orthoquartzite and feldspathic quartzite. Pebbles and sand grains are rounded to well rounded, and conglomeratic beds generally are found at the base of the unit. Crossbedding and shallow channels are the main primary-bedding structures. The depositional environment of the Sawatch Quartzite was probably shallow-marine water on a stable shelf (Campbell, 1972).

The Peerless Formation and the overlying Dotsero Formation as redefined by Myrow and others (2003) are not found in Saguache County.

Ordovician Rocks

Manitou Formation

With the exception of the northwest part of the county, the Manitou Formation of Early Ordovician age is the Paleozoic unit that commonly nonconformably overlies Proterozoic rocks and consists of moderate-gray, light-gray, and dark-gray cherty dolostone. The Manitou Formation was named “Manitou limestone” from a type locality north of Manitou Springs by Brainerd and others (1933). The Manitou Formation was named by Berg and Ross (1959); however, other authors named these rocks the Manitou Dolomite (Ross and Tweto, 1980; Olson, 1983). The Manitou Formation is exposed mainly in the eastern part of Saguache County in the Sangre de Cristo Range (Scott and others, 1978; Johnson, 1969). This unit is also exposed west and southwest of Villa Grove **(fig. 7)** and east of the town of Sargents (Tweto and others, 1976).

In the Sangre de Cristo Range, the Manitou Formation is a moderate-gray, light-gray, and dark-gray cherty dolomitic limestone (fig. 7) that is thinly bedded and laminated. Characteristic of the Manitou Formation is the presence of black and light-grayish-white chert nodules and interbeds **(fig. 8)** in the dolomitic limestone. Chert is internally laminated parallel to bedding.

The thickness of the Manitou Formation varies in Saguache County. In the Sangre de Cristo Range, the Manitou thins from 187 ft in the north (Taylor and others, 1975) to 30 to 65 ft near Crestone (Lindsey and others, 1985d). South of Crestone, the Manitou Formation is absent (Lindsey and others, 1986b), but farther south near Great Sand Dunes National Park and Preserve, the Manitou Formation is 195 ft thick (Johnson and others, 1989). West of Villa Grove, Burbank (1932) described the “lower member of the Tomichi limestone” as a 90- to 200-ft-thick, gray, dolomitic limestone; this unit is correlative with the Manitou Formation. Olson (1983) reported 254- to 300-ft thicknesses of Manitou Formation in the Marshall Pass area about 5 mi east of Sargents; these are the westernmost exposures of the Manitou in Saguache County.

Figure 7. Outcrop of pinkish-gray dolomite of Manitou Formation. Clayton Cone (pl. 1) 2 mi west of Villa Grove. Hammer is 16 in. long.

Figure 8. Outcrop of white, bedded chert in pinkish-gray dolomite of the Manitou Formation. Clayton Cone (pl. 1), 2 mi west of Villa Grove.

The depositional environment of the Manitou Formation was a low-energy, shallow-marine shelf that ranged to intertidal depths (Campbell, 1972). The thin laminae may represent algal mats that grew in the photic zone.

Harding Quartzite

The Harding Quartzite of Middle Ordovician age overlies the Manitou Formation on a disconformable contact at many places in Saguache County (Lindsey and others, 1985d; Johnson and others, 1989; Olson, 1983); however, the Harding directly overlies Mesoproterozoic rocks in the Crestone area of the Sangre de Cristo Range (Lindsey and others, 1986b). The "Harding sandstone" was first described and named by Walcott (1892) for exposures near Cañon City, Colorado. The Harding Quartzite has been termed the "Harding Sandstone" (Lindsey and others, 1985d, 1986b) and "Harding Formation" (Gerhart, 1974). The Harding Quartzite is a dark-reddish-gray, dark-grayish-orange, dark-grayish-red, light-gray, and rusty-orange, silica-cemented, mottled, orthoquartzite **(fig. 9)**. The quartzite is completely cemented by silica, and it has the conchoidal fracture of a quartzite. A pebble conglomerate is found at some places in the lower 3 ft of the unit. Quartzite beds range from 1 in. thick to about 8 in. thick and contain planar lamination and planar crossbeds. Phosphatic bony plates of primitive fish are present in the formation locally (Lindsey and others, 1985d; Johnson and others, 1989; Olson, 1983). In westernmost exposures of the Harding Quartzite, Olson (1983) described a sulfide-rich black shale zone, 2 to 6 in. thick, in the upper part of this unit.

In the northern part of the Sangre de Cristo Range, Taylor and others (1975) reported 65 ft of the Harding Quartzite, and Lindsey and Soulliere (1987) indicated that the quartzite was about 100 ft thick. In the Crestone area, the Harding Quartzite increases from about 100 ft thick to about 200 ft thick (Lindsey and others, 1985d). South of Crestone, the Harding Quartzite overlies Paleoproterozoic gneiss and is 65 to 100 ft thick; farther to the south, in the area of the Great Sand Dunes National Park and Preserve, Johnson and others (1989) indicated that the Harding is 100 ft thick. Burbank (1932) described the 60- to 90-ft-thick "Quartzite member of the Tomichi limestone" in the Kerber Creek area as correlative to the "Harding sandstone." The Harding Quartzite appears to thin westward; Olson (1983) reported a 30- to 40-ft thickness of the unit in the Marshall Pass area about 5 mi east of Sargents.

The Harding Quartzite was deposited in a shallow-marine and strandline environment in which tides and currents created sand bars and deposited sheet sands. The phosphatic bony plates of primitive fish may record brackish-water conditions.

Fremont Dolomite

The Fremont Dolomite was originally named the Fremont Formation by C. D. Walcott in 1989 for exposures of this unit on the east–facing slope of Fremont Peak west of Cañon City (Sweet, 1954).

The Fremont Dolomite of Middle and Late Ordovician age overlies the Harding Quartzite on a disconformable contact. The Fremont Dolomite is a light-gray, moderate-gray, and dark-gray, massive-weathering, crystalline, fetid dolostone that contains echinoid debris in a fine-grained dolostone matrix; trilobite and brachiopod fragments are found on some bedding planes. Dolostone is mottled light gray and moderate gray, and rare black chert nodules are irregu-

Figure 9. Outcrop of Harding Quartzite. Clayton Cone (pl. 1), 2 mi west of Villa Grove. Hammer is 16 in. long.

larly distributed through it. Beds are generally 2 in. to 40 in. thick, and bedding is poorly developed. This resistant-weathering dolostone has a rough and uneven weathering surface that has sharp ridges along some bedding planes (Sweet, 1954).

The Fremont Dolomite is thicker in the Sangre de Cristo Range than in the area northwest of the town of Saguache. In the northern part of the Sangre de Cristo Range, the Fremont Dolomite is about 230 ft thick (Taylor and others, 1975). South of Valley View Hot Springs, the Fremont Dolomite is about 328 ft thick, and near Great Sand Dunes National Park and Preserve, the formation is 230 ft thick. In the Kerber Creek area, Burbank (1932) reported that the “Upper limestone member of the Tomichi limestone” was about 300 ft thick. This “dolomitic limestone” is correlative to the Fremont Dolomite. Olson (1983) determined a thickness of about 180 ft for the Fremont Dolomite in the Cochetopa Hills east of Sargents in the Marshall Creek drainage.

The Fremont Dolomite was deposited in a shallow-marine, tropical, carbonate-bank environment. The carbonate bank supported a varied sessile fauna. The restricted water circulation allowed accumulation of organic material in a poorly oxygenated water column.

Mississippian? and Devonian Rocks

Chaffee Group

The Chaffee Group of Late Devonian to Early Mississippian age rests disconformably on the Fremont Dolomite. The Chaffee Group is divided into the Parting Formation at the base and the Dyer Dolomite at the top (Wrucke and Dings, 1979). Campbell (1972) applied group rank to the Chaffee and formation rank to the Parting Formation and Dyer Dolomite, and he subdivided the Parting and Dyer into several members on the basis of measured sections. Olson (1983) also applied group rank to the Chaffee Group rocks he mapped 5 mi east of Sargents. The U.S. Geological Survey series of maps in the Sangre de Cristo Range applied formation rank to the Chaffee (Taylor and others, 1975; Lindsey and others, 1985d; Lindsey and Soulliere, 1987), but Johnson and others (1989) used group rank for the Chaffee and applied formation designations to the Dyer Dolomite and the Parting Formation. We retain the nomenclature hierarchy of Campbell (1972).

Parting Formation

The Parting Formation of Late Devonian age is a light-gray, pale-brownish-gray, and grayish-pink, fine-grained, silica-cemented orthoquartzite. Rare interbeds of dolostone and shale are 2 to 8 in. thick, and some pebbly and granular sandstone interbeds are included. Quartzite beds are generally 2 to 10 in. thick, and planar lamination and rare planar crossbeds are the principal sedimentary structures. At some places, the Parting Formation is not densely cemented, and the quartzite is friable. In the Sangre de Cristo Range, however, the Parting Formation is so well cemented that it forms a resistant-weathering mass.

In the Sangre de Cristo Range, the thickness of the Parting Formation ranges between 10 and 52 ft, but no trend of thickness variation is evident from the maps (Taylor and others, 1975; Lindsey and others, 1985d, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989). Near the Bonanza mining district, Burbank (1932) assigned a thickness of about 10 to 50 ft for the “sandstone member of the Chaffee formation,” and Olson (1983) gave a thickness of 10 to 20 ft for his Parting Formation in the Cochetopa Hills east of Sargents. The Parting Formation was deposited in a shallow-marine and strandline environment. Crossbeds may record subaqueous dunes.

Dyer Dolomite

The Dyer Dolomite of Late Devonian to Early Mississippian age is a yellowish-gray, light gray, and pale-yellowish-gray, laminated and microlaminated, finely crystalline dolostone that contains some interbeds of light-grayish-green and light-greenish-gray shale **(fig. 10)**. Rare chert layers are interbedded with the dolostone, and they range from 0.5 to 2 in. thick (Taylor and others, 1975; Lindsey and others, 1985d, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989).

In the Sangre de Cristo Range, the Dyer Dolomite is about 100 ft thick where complete sections are found (Taylor and others, 1975; Lindsey and others, 1985d, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989). In the Bonanza mining district, the "Middle limestone member of the Chaffee formation" is correlative with the Dyer Dolomite and is about 100 ft thick (Burbank, 1932), but 5 mi east of Sargents, Olson (1983) gave a thickness of 130 to 150 ft for the Dyer Dolomite.

The Dyer Dolomite was deposited in a shallow-marine, tropical, intertidal environment in which lime mud accumulated. Microlaminated lime mud could represent algal mats that grew in the photic zone.

Mississippian Rocks

Leadville Limestone

The Leadville Limestone of Early Mississippian age overlies the Dyer Dolomite of the Chaffee Group on a disconformable contact and is composed of moderate- to dark-gray, crystalline, fossiliferous, cherty limestone. The Leadville Limestone, 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). Tweto and Lovering (1977) redescribed this unit as the Leadville Dolomite, and Armstrong and others (1992) redescribed this unit as the Leadville Dolostone. The Leadville Limestone of Saguache County is exposed mainly in the Sangre de Cristo Range and in the Cochetopa Hills area northwest of the town of Saguache.

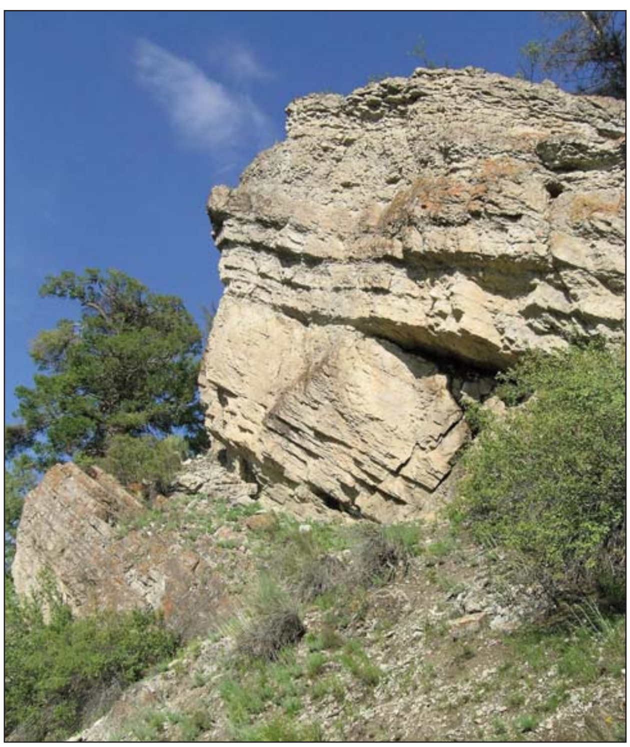


Figure 10. Outcrop of tan-weathering Dyer Dolomite. South side of Kerber Creek about 6 mi west of Villa Grove. Piñon pine on left of photograph is about 6 ft tall.

In the Sangre de Cristo Range, the Leadville Limestone is composed of interbedded zones of dark-gray and moderate-gray, finely crystalline, thin- to thick-bedded limestone and dolomitic limestone. The limestone contains lenticular interbeds of biomicrite, oolitic limestone, and stromatolitic limestone and beds of conglomeratic limestone that are interspersed sporadically through the sequence. Some limestone and dolomitic limestone are mottled light gray and moderate gray, and nodules of black chert are common at some levels in this unit. The base of the Leadville Limestone is marked by lenticular beds of sandy limestone and limestone conglomerate; sandy limestone is composed of medium-grained orthoquartzite and calcite cement.

In the Cochetopa Hills area, Olson (1983) described the Leadville Limestone as the Leadville "Dolomite" that is composed of massive, blue-gray and brownish-gray dolostone and subordinate limestone (**figs. 11 and 12**). A thinly bedded, blue-gray, sandy limestone is at the base. The Leadville Dolomite of Olson (1983) is 330 to 425 ft thick. Burbank (1932) described a 350- to 400-ft section of blue-gray limestone in the Kerber Creek area as "Leadville limestone." The basal 10 to 15 ft of the Kerber Creek section consists of shale or shaley limestone (Burbank, 1932).

The Leadville Limestone ranges from 115 to 330 ft thick in the Sangre de Cristo Range (Taylor and others, 1975; Lindsey and others, 1985d, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989). Much of the thickness variation results from postlithification dissolution and volume reduction that resulted from silicification of limestone. A dissolution event after Early Mississippian time, but before the Early Pennsylvanian, formed prominent caves and dissolution breccias in the upper part of this unit.

The depositional environment of the Leadville Limestone was a shallow-marine, tropical, intertidal environment in which wave activity scoured the carbonate bank to produce oolites and limestone conglomerate. Clastic material from nearby land areas was transported across the carbonate mud flat. The substrate of carbonate mud supported a varied sessile fauna of bryozoa, corals, brachiopods, and crinoids (Nadeau, 1972), and the presence of stromatolites indicates water depths in the photic zone.

Pennsylvanian Rocks

The Pennsylvanian Period in Colorado was a time of active block faulting and basin subsidence that resulted in accumulation of thick sequences of clastic rocks and rapid lateral changes in lithofacies. These events are partly responsible for the different rock-unit

Figure 11. Outcrop of Leadville Limestone showing cavernous weathering. South side of Kerber Creek about 6 mi west of Villa Grove. Orange fence post in foreground of photograph is about 4 ft tall.

nomenclature applied to local areas. The Pennsylvanian stratigraphic succession in Saguache County was deposited in the rapidly subsiding Central Colorado trough (De Voto, 1972) between the Uncompahgre uplift on the west and the Sangre de Cristo and Ancestral Front Range uplifts on the east. Pennsylvanian rocks are mainly clastic units that contain minor limestone; they accumulated in terrestrial and marine environments.

The Pennsylvanian stratigraphic sequence in Saguache County is, in ascending order, the Kerber, Sharpsdale, Minturn, and Sangre de Cristo Formations, the last of which appears to be Pennsylvanian in the lower part and Permian in the upper part (De Voto and Peel, 1972). On the geologic map, the Kerber and Sharpsdale Formations are included with the Minturn Formation as shown on the Pueblo 1° × 2° quadrangle (Scott and others, 1978). Pennsylvanian strata are found only in the Sangre de Cristo Range and in the Cochetopa Hills northwest of the town of Saguache.

The composition of Pennsylvanian coarse- to fine-grained clastic rocks and siltstone is generally arkose, subarkose, and minor orthoquartzite, according to the classification of Pettijohn (1957). Conglomerates are polymict and range from pebble conglomerate to boulder conglomerate. Conglomerate may be matrix supported or framework supported. Limestone beds commonly contain silt- and sand-sized quartz, feldspar, and lithic fragments, and some limestone beds are argillaceous.

Kerber Formation

The Kerber Formation of Early or Middle Pennsylvanian age overlies the Leadville Limestone along Kerber Creek near the Bonanza mining district (Burbank, 1932) and consists of a sequence of red, gray, or yellow siltstone, sandstone, conglomerate, and limestone. Burbank (1932) named the Kerber Formation for Kerber Creek, but he did not designate a type locality; the stratigraphic sequence that he described totaled about 200 ft thick. Brill (1952) extended the Kerber Formation north to the Arkansas River near Wellsville, Colorado, and Litsey (1958) described the Kerber Formation from Lime Canyon in the Sangre de Cristo Range, which is 8 mi northeast of Mineral Hot Springs in Saguache County. Pierce (1969) extended the Kerber Formation north from Wellsville, and Peel (1971) mapped the Kerber Formation along the west flank of the Sangre de Cristo Range to near Crestone. Furthermore, Peel (1971) indicated that Kerber Formation lithologies are found as far south as Deer Creek, which is south of the southern limit of Saguache County. A later geologic map of the northern Sangre de Cristo Range by Taylor and others (1975) grouped the Belden Shale and Minturn Formation and incorporated rocks previously assigned to the Kerber Formation by Brill (1952) and Pierce (1969) into the Belden and Minturn unit. A series of geologic maps by the U.S. Geological Survey in the Sangre de Cristo Range (Lindsey and others, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989) included rocks of the Kerber Formation in their Minturn Formation undivided, although Lindsey and others (1985d) separated a unit that combined the Kerber and Sharpsdale Formations north of Crestone, Colorado.

The Kerber Formation is composed of grayish-green, olive-drab, greenish-brown, and olive-brown, coarse-grained arkose and conglomeratic arkose, medium- and fine-grained arkose, siltstone, and shale. Black shale, black siltstone, moderate-gray limestone, discontinuous coal beds, and rare dolostone appear as interbeds in the olive-drab and grayish-green rocks.

Figure 12. Exposure of dark gray to black Leadville Limestone in a quarry. Limekiln Creek about 6 mi west of Villa Grove. Hammer is 16 in. long.

Coarse-grained zones are separated by zones of medium- and fine-grained arkose, siltstone, or shale that are 10 to 33 ft thick. Coarse-grained rocks are most abundant near the base of the Kerber Formation, and finer-grained rocks, mostly olive-drab shale and siltstone and black shale, become more common upward in the sequence. Moderate-gray limestone interbeds are common near the top of the Kerber; they range between 3 and 15 ft thick and contain brachiopods. Primary sedimentary structures in coarse-grained rocks are dominated by large-scale and medium-scale planar and trough crossbeds, channels, ripple cross-lamination, cuspate and linguoid ripple marks, climbing ripples, and planar lamination that forms parting lineation. Primary sedimentary structures in fine-grained rocks are ripple cross-lamination, rib-and-furrow structures, planar lamination, microlamination, and water-expulsion structures. Conglomeratic and sandy units contain coarse-grained rocks at the base and become finer grained upward. The upper contact of the Kerber Formation appears to be gradational with the overlying Sharpsdale Formation (De Voto and Peel, 1972).

The thickness of the Kerber Formation is about 200 ft along Kerber Creek (Burbank, 1932). In the northern part of the Sangre de Cristo Range, the Kerber Formation is between about 290 and 400 ft thick (Peel, 1971).

The Kerber Formation was deposited along the edge of a narrow, subsiding trough between the Front Range uplift on the east and the Uncompahgre uplift to the west (Peel, 1971). Carbonaceous shale, thin coal beds, and limestones record a marine and coastal lowland environment, whereas conglomerate, sandstone, and siltstone were deposited in alluvial channels that traversed the coastal lowland, in marine and brackish deltas, and as shallow-marine sheet sands. Marine conditions were more common during deposition of the upper part of the Kerber, as indicated by the increase in limestone beds near the top of the unit (Peel, 1971).

Sharpsdale Formation

The Sharpsdale Formation of Middle Pennsylvanian age overlies the Kerber Formation on an apparently gradational contact and is composed mainly of grayish-red, coarse-grained arkose and pebbly and granular arkose, with lesser amounts of grayish-red and purplish-red siltstone and shale. The Sharpsdale Formation was defined first by Chronic (1958), who established a type section in Huerfano County in the southern part of the Sangre de Cristo Range. Bolyard (1959) originally named this unit the Deer Creek Formation in an unpublished thesis (Bolyard, 1956), but the name was preoccupied, and Chronic (1958) applied the name of the nearest settlement of Sharpsdale to this sequence. A series of theses by students at the Colorado School of Mines mapped the Sharpsdale Formation in the Sangre de Cristo Range northward from the vicinity of Crestone to the Arkansas River area southeast of Salida, Colorado (Koch, 1963; Karig, 1964; Peel, 1971). Peel (1971) determined that the Sharpsdale Formation was present along Kerber Creek where Burbank (1932) first defined the Kerber Formation. Burbank (1932) ascribed beds now recognized as Sharpsdale to the lower part of the Maroon Formation. In the northern part of the Sangre de Cristo Range, later work by Taylor and colleagues of the U.S. Geological Survey included rocks of the Sharpsdale Formation in their combined Belden and Minturn Formation (Taylor and others, 1975). Geologic maps by Lindsey and others (1986b), Lindsey and Soulliere (1987), and Johnson and others (1989) of the Sangre de Cristo Range included rocks previously mapped as the Sharpsdale Formation in their Minturn Formation undivided.

The Sharpsdale Formation consists of grayish-red, purplish-red, and bright-grayish-red, coarse-grained arkose, pebbly arkose, boulder conglomerate, and medium- to fine-grained arkose layers interbedded with grayish-red, purplish-red, and bright-grayish-red siltstone and shale. Composite bedding units generally range from 24 in. to 50 ft thick. Channeled bases of these composite bedding units commonly overlie the fine-grained upper parts of fining-upward sequences. Moderate-gray limestone beds are found throughout the Sharpsdale Formation, and these fossiliferous carbonate beds are as thick as 33 ft at some places. Primary sedimentary structures in coarse-grained rocks are large- and medium-scale trough and planar crossbeds that form multiple cosets, channels, shale-chip conglomerate, and dispersed-pebble conglomerate. In medium- and fine-grained arkose and subarkose, primary structures are dominated by small-scale trough and planar crossbeds, shallow channels, ripple cross-lamination, climbing ripples, cuspate and linguoid ripples, rib-and-furrow structures, and planar lamination. Siltstone and silty shale beds at the tops of fining-upward sequences are dominated by ripple cross-lamination, planar lamination, flasers, and microlamination. Rare secondary sedimentary structures in sandstone beds are deformed and overturned crossbeds and load casts; secondary sedimentary structures in siltstone and shale are convolute lamination and small-scale load casts. Some fine-grained intervals in the Sharpsdale Formation are olive-drab, grayish-green, dark-gray, and moderate-gray, fine-grained sandstone, siltstone, and shale, and these fine-grained intervals are generally less than 3 ft thick. Fine-grained sulfide minerals are found in olive-drab, grayish-green, and dark-gray sandstone and siltstone beds, and pyrite, chalcopyrite, and possibly bornite appear to be interstitial diagenetic minerals.

The range of thickness of the Sharpsdale Formation is between 900 and 1,800 ft. In most of the Sangre de Cristo Range, about 1,100 ft is a common thickness.

The Sharpsdale Formation was deposited on alluvial fans and alluvial plains adjacent to uplifted blocks of crystalline and metamorphic Proterozoic rocks (De Voto and Peel, 1972).

Belden Shale

The Belden Shale of Early Pennsylvanian age was extended into Saguache County by Taylor and others (1975). This unit was mapped in the Cochetopa Hills east of Sargents by Olson (1983), but later reports on this region do not show the Belden Shale as a separately mapped unit in Saguache County. The Belden was named for the Belden Station on the Denver & Rio Grande Western Railroad by Brill (1942), who considered the Belden as the basal member of the “Battle Mountain formation.” Brill (1942) described the type section (measured on the north side of Rock Creek valley along U.S. Highway 24, 0.2 mi north of Gilman) as consisting of black and dark-gray carbonaceous shale, dark-gray argillaceous limestone, and some sandstone. Brill (1952) placed all beds above the Kerber Formation in the Minturn Formation in the Arkansas River Valley southeast of Salida, Colorado, which is north of Saguache County. About 15 mi north of Salida, Colorado, Wallace and Lawson (1998) showed that the Belden Shale pinches out to the south between the overlying Minturn Formation and the underlying Sharpsdale and Kerber Formations. Pierce (1969) and Peel (1971) did not map the Belden Shale in the area of the Arkansas River or in the northern part of the Sangre de Cristo Range. In addition, Lindsey and others (1985c, 1985d, 1986b), Lindsey and Soulliere (1987), and Johnson and others (1989) did not show the Belden Shale as a separate unit on geologic maps in the northern part of the Sangre de Cristo Range. Lindsey (written communication, 2003) indicated that he observed a carbonaceous shale unit as far south as Hayden Pass in the Sangre de Cristo Range that could be part of the Belden Formation; however, he included this carbonaceous shale in his Minturn Formation for mapping purposes.

Taylor and others (1975) described their “Belden Formation” as a dark-gray carbonaceous shale, shaly siltstone, and coarse- to fine-grained sandstone in thin beds, and this unit is about 500 ft thick. Olson (1983) described three members in his “Belden Formation”: (1) The lower member is composed of red or brown, fine-grained sandstone and shale interbedded with 3- to 10-ft-thick layers of carbonaceous black shale or mudstone and local red or yellow shale. No thickness is given for this lower unit. (2) The middle member is composed of layers of blue-gray limestone, partly fossiliferous, interbedded with gray to purplish-red shale, siltstone, and fine sandstone. Limestone beds range between a few inches thick and 100 ft thick. The middle member is 100 to 400 ft thick. (3) Buff or olive-drab, medium- to coarse-grained sandstone, interbedded siltstone, gray shale, and minor conglomeratic sandstone make up the upper member, which has a minimum thickness of about 660 ft.

Regional mapping brings into question whether the "Belden Formation" of Taylor and others (1975) and Olson (1983) is properly assigned to the Belden Formation. Taylor and others' (1975) brief description of the Belden Formation could fit the Kerber Formation, as mapped by Pierce (1969) and Peel (1971), and part of the latter's Minturn Formation could be Sharpsdale Formation. Olson's (1983) description could accommodate the Kerber and Sharpsdale Formations and perhaps the Minturn Formation at the top. Reexamination of these units is beyond the scope of this report, but the similarity of Olson's "Belden Formation" to rocks mapped in the Sangre de Cristo Range suggests that his designation could be changed to Minturn Formation. A further possibility is that the Kerber and Sharpsdale Formations can be subdivided from the lower part of his Belden Formation, just as the Kerber and Sharpsdale can probably be separated from the Minturn Formation in the Sangre de Cristo Range as mapped by Lindsey and others (1985c, 1985d, 1986b), Lindsey and Soulliere (1987), and Johnson and others (1989).

Minturn Formation

The Minturn Formation of Middle Pennsylvanian age overlies either the Sharpsdale Formation on a gradational and conformable contact (Peel, 1971) or the Leadville Limestone on a disconformable contact (Lindsey and others, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989). The Minturn Formation is composed mainly of interbedded sandstone, conglomerate, siltstone, shale, and limestone; some beds are fossiliferous. The Minturn Formation was named by Tweto (1949) from exposures in cliffs along the east side of the Eagle Valley near Minturn, Colorado, but no type locality was designated. Bolyard (1959) extended the term "Madera Formation" into the Sangre de Cristo Range from New Mexico, but in later reports, these rocks are shown as Minturn Formation in Saguache County (Lindsey and others, 1985c, 1985d, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989).

Lindsey and others (1985a) described a reference section for the Minturn Formation in the Sangre de Cristo Range in which the basal contact of the formation is the Spread Eagle Peak thrust fault. The following description is from Lindsey and others (1985a), and although not stated in that report, siltstone, sandstone, and conglomerate contain feldspar and lithic fragments, and shale and silty shale contain abundant mica on bedding planes. Sandstone beds are coarse to fine grained and gray to pink, and some beds are conglomeratic. Sandstone beds are commonly lenticular and contain planar and trough crossbeds, ripple cross-lamination, planar lamination, flute casts, normal and reverse grading, and plant remains. Shale and siltstone are interbedded with coarse-grained strata, and fine-grained beds are composed mainly of gray, black, gray-black, brown-black, gray-green, and rarely dark-red, laminated, thinly bedded shale and siltstone. Shale may be fissile, and these fine-grained beds contain ripple cross-lamination, load casts, trough crossbeds, and mud chips. Limestone beds are more common in the upper part of the Minturn than in the lower part, and they are composed of gray and brown, silty and shaly carbonate. Limestone beds contain wavy laminae and ripple cross-lamination. Crinoid columnals, brachiopods, stromatolites, sponge spicules, bryozoans, fusulinids, and conodonts are found in some limestone beds (Lindsey and others, 1985a, 1986b; Lindsey and Soulliere, 1987). Marker beds and informal members distinguished in the reference section in the Sangre de Cristo Range are lenticular and grade laterally into other lithofacies, but a main turbidite member and a conglomeratic sandstone member have been traced for more than 8 mi along strike (Soulliere and others, 1984). Marker beds could not be correlated across thrust faults.

The reference section of the Minturn Formation in the Sangre de Cristo Range is about 6,500 ft thick (Lindsey and others, 1985a). De Voto and Peel (1972) estimated a thickness of 5,500 ft near Valley View Hot Springs, and Brill (1952) gave 4,200 ft as the thickness of the Minturn Formation in the Arkansas River Valley, but that number includes an unknown thickness of the Kerber and Sharpsdale Formations.

The Minturn Formation was deposited in deltaic and prodeltaic marine environments and in a low-lying coastal plain of mainly marine influence (De Voto and Peel, 1972; Lindsey, 2001). The turbidites that are interbedded with the coarser-grained prodelta lithofacies are delta-front turbidites, and interbedded limestones are shallow-marine carbonates (Lindsey, 2001).

Pennsylvanian and Permian Rocks

Sangre de Cristo Formation

The Sangre de Cristo Formation of Middle or Late Pennsylvanian and Early Permian age overlies the Minturn Formation on a gradational contact in Saguache County and is composed mainly of grayish-pink, reddish-gray, and dark-red conglomerate, sandstone, siltstone, and shale. The name "Sangre de Cristo conglomerate" was first used by Hills (1899) for coarse clastic rocks exposed west of the Elmoro quadrangle (scale 1:125,000), which is located east of Trinidad, Colorado. Melton (1925) established two members in the Sangre de Cristo Formation: (1) a "Lower Sangre de Cristo conglomerate" at the base and (2) the

"Crestone Conglomerate" at the top. Bolyard (1959) retained the two members of Melton (1925) and designated a type area east of the town of Crestone. In the Arkansas River Valley southeast of Salida, Colorado, Pierce (1969) subdivided the Sangre de Cristo Formation into four informal units that were grouped into "lower" and "upper" members. Peel (1971) distinguished a lower member, which was overlain by the Crestone Conglomerate Member of the Sangre de Cristo Formation. Lindsey and Schaefer (1984) established a principal reference section for the Sangre de Cristo Formation in the northern Sangre de Cristo Range that subdivided the formation into a lower member of red conglomerate, sandstone, siltstone, and shale and an overlying Crestone Conglomerate Member, which is a prominent boulder conglomerate. The following description of the Sangre de Cristo Formation is mainly from Lindsey and Schaefer (1984), and although not stated in that report, siltstone, sandstone, and conglomerate contain feldspar and lithic fragments. Most of these rocks are classed as subarkose, arkose, and minor orthoquartzite (Pettijohn, 1957).

The lower member of the Sangre de Cristo Formation is composed mainly of fining-upward cycles of conglomerate, sandstone, siltstone, and shale. Conglomerate and conglomeratic sandstone fill channels at the base of the cycle and grade upward into sandstone, siltstone, and shale in decreasing bed thickness. These fining-upward cycles are prominently stratified. The rocks are dominated by red, grayish-red, and maroon colors. Sandstone beds contain planar and trough crossbeds, and the upper parts of sandstone beds generally contain planar lamination, ripple cross-lamination, and ripple marks. The uppermost shaly interval commonly contains calcareous nodules that were interpreted by Lindsey and Schaefer (1984) as "paleocaliche." Where limestone beds are present, they are at the top of the cycle, and locally, they contain marine invertebrate fossils. Fragments of plant fossils are rare. In the upper 610 ft of the lower member, coarse, poorly stratified conglomerate beds are interspersed with the upward-fining cycles. These coarse beds are clast- and matrix-supported, pebble to cobble conglomerate; the clasts are composed of rounded to angular igneous and metamorphic rocks.

The Crestone Conglomerate Member of the Sangre de Cristo Formation is composed mostly of coarse conglomerate, conglomerate, conglomeratic sandstone, sandstone, and minor siltstone and shale (Lindsey and Schaefer, 1984). The conglomerate units are unsorted, unstratified, and chaotically packed and are composed of angular to subrounded clasts that range up to boulder size. According to Lindsey and Schaefer (1984), the clasts are composed of red syenite, pink to red porphyritic felsite, granite, gneiss of different types, gray quartzite, and minor amounts of other igneous and metamorphic rocks. The conglomerate beds have sharp and, locally, erosional basal contacts. These chaotic conglomerate beds become better stratified, better sorted, and fine grained near the top. The tops of these chaotically packed conglomerate beds commonly have a thin sandstone bed at the upper boundary. Sequences of fining-upward stratified conglomerate and sandstone alternate with the chaotically packed conglomerate, and these bedded units contain planar lamination and crossbeds. Near the top of the Crestone Conglomerate Member is a sequence of 770 ft of fining-upward conglomerate, sandstone, and shale; this sequence resembles the fining-upward cycles of the lower member.

The thickness of the Sangre de Cristo Formation varies in Saguache County; this unit is always eroded at the top, and the numerous thrust faults mapped in the Sangre de Cristo Range make thickness determinations uncertain at best. In the northern Sangre de Cristo Range, Peel (1971) and De Voto and Peel (1972) estimated that the thickness of the Sangre de Cristo Formation totaled about 15,000 ft. Lindsey and Soulliere (1987) and Lindsey and others (1985d) estimated that the lower member of the Sangre de Cristo Formation was about 4,600 ft thick and that the Crestone Member was approximately 6,600 ft thick. Karig (1964) showed more than 2,000 ft in his lower member and about 2,500 ft in his upper member near Crestone. In the Kerber Creek area, Burbank (1932) showed more than 3,400 ft of Maroon Formation, which is generally regarded as correlative with the Sangre de Cristo Formation (Brill, 1952; De Voto, 1972), but Brill (1952) regarded the sequence along Kerber Creek as the Kerber and Minturn Formations.

The depositional environments of the Sangre de Cristo Formation are mainly terrestrial environments. According to Lindsey and Schaefer (1984), upward-fining units resemble the vertical profiles of braided-stream deposits of Maill (1978). The coarse-grained conglomerate interbeds in the upper part of the lower member probably represent debris-flow or mudflow deposits (Lindsey and Schaefer, 1984). The braided streams flowed over alluvial fans, and the fining-upward sequences of the lower member were deposited on the lower part of the fan. Marine limestone interbeds indicate that the braided streams drained to the sea (Lindsey and Schaefer, 1984). Chaotically packed conglomerate beds of the Crestone Conglomerate Member represent debris-flow deposits on the upper part of alluvial fans, and the upper part of the alluvial fans prograded over the braided-stream deposits of the lower member (Lindsey and Schaefer, 1984).

Mesozoic Rocks

Mesozoic rocks in Saguache County are mainly sandstone and shale units and interbedded sandstone, siltstone, and shale, which were deposited in fluvial, nearshore, and shallow-marine conditions. These rocks overlie Proterozoic metamorphic and igneous rocks on an angular unconformity (Olson, 1974, 1976a, 1976b; Hedlund and Olson, 1974). Mesozoic clastic rocks are Jurassic and Cretaceous in age. The Junction Creek Sandstone is the oldest of these units and is overlain by the Morrison Formation (both Late Jurassic). The Dakota Sandstone (Early? and Late Cretaceous) and Burro Canyon Formation (Early Cretaceous) unconformably overlie the Morrison Formation, and the Mancos Shale (Late Cretaceous) is the youngest of the Mesozoic units. The thickness of Mesozoic rock units in Saguache County is about 2,100 ft. Mesozoic rocks are confined to the northwestern part of Saguache County in the Cochetopa Hills region (Olson, 1974, 1976a, 1976b; Hedlund and Olson, 1974).

In the northwestern part of Saguache County, Tweto and others (1976) grouped Jurassic rocks as the Morrison Formation and Junction Creek Sandstone. Tweto and his coauthors combined the Jurassic and Cretaceous units into one unit that contained the Dakota Sandstone and Burro Canyon Formation (Cretaceous) with the Morrison Formation and Junction Creek Sandstone (Jurassic). Each rock unit is described separately next.

Jurassic Rocks

Junction Creek Sandstone

The Junction Creek Sandstone of Late Jurassic age overlies Proterozoic metamorphic and igneous rocks in the Cochetopa Hills in the northwestern part of Saguache County (Olson, 1974, 1976a, 1976b; Hedlund and Olson, 1974). This unit was named for Junction Creek by Spencer and Goldman (1941), who considered the unit to be a member of the Morrison Formation, but no type locality was designated. Since that time, this sandstone has been assigned to several different formations and given different ranks by several geologists, and the name has not been consistently applied to the same stratigraphic interval (O'Sullivan, 1992). Eckel (1949) removed the "Junction Creek sandstone" from the Morrison Formation and raised it to formation rank. Hansen (1968) assigned the strata to the Junction Creek Member of the Wanakah Formation. Olson and Hedlund (1973) raised the rank of the Junction Creek to formation level, whereas Steven and Hail (1989) put the Junction Creek back into the Morrison Formation.

According to Olson (1974, 1976a, 1976b; Hedlund and Olson, 1974), the Junction Creek Sandstone is white- to light-yellowish-gray, fine- to medium-grained, quartzose sandstone. Silica cement is common, and the sandstone is locally crossbedded. The Junction Creek Sandstone overlies different units of Paleoproterozoic metamorphic and igneous rocks on an angular unconformity (Olson, 1976a, 1976b).

The Junction Creek Sandstone overlies different units of Paleoproterozoic metamorphic and igneous rocks on an angular unconformity (Olson, 1976a, 1976b).

The Junction Creek Sandstone is absent in some places in the Cochetopa Hills, but commonly this unit is 100 to 150 ft thick. The maximum thickness of the Junction Creek Sandstone is about 300 ft.

On the Colorado Plateau to the west of Saguache County, the Junction Creek Sandstone is interpreted to be eolian in origin (Peterson and Turner-Peterson, 1987). No paleoenvironmental studies have been reported on the unit in Saguache County.

Morrison Formation

The Morrison Formation of Late Jurassic age overlies the Junction Creek Sandstone in the northwestern part of Saguache County and is composed of interbedded reddish-gray and greenish-gray mudstone and siltstone and minor sandstone beds (Olson, 1974, 1976a, 1976b; Hedlund and Olson, 1974). The Morrison Formation was named for exposures near the town of Morrison, Colorado, by Eldridge (1896), but no type locality was designated. This unit appears to be conformable on the Junction Creek Sandstone; however, the Morrison Formation unconformably overlies Paleoproterozoic rocks at some places. The Morrison is widespread in the Rocky Mountains, and this unit has been studied in detail by numerous geologists who have subdivided it into many local members. In Saguache County, members were not separated by Olson (1974, 1976a, 1976b), by Hedlund and Olson (1974), or by Tweto and others (1976).

The Morrison Formation is composed mainly of variegated reddish-gray, grayish-green, light-gray, and grayish-purple shale, mudstone, argillaceous siltstone, and minor sandstone. Sandstone beds are lenticular and crossbedded (**fig. 13**). Rare limestone beds are light gray and moderate gray. Sandstone and limestone beds are as thick as 3 ft. The thickness of the Morrison varies between about 130 and 300 ft in the northwestern part of the county (Olson, 1974, 1976a, 1976b; Hedlund and Olson, 1974).

Cretaceous Rocks

Dakota Sandstone

The Dakota Sandstone of Early? and Late Cretaceous age overlies the Morrison Formation on a regional unconformity and is composed of conglomeratic sand-

Figure 13. Outcrop of crossbedded sandstone of Morrison Formation. Near Kathy Jo Mine, Cochetopa Hills district. Hammer is 16 in. long.

stone, sandstone, siltstone, and black shale. On some geologic maps in the region, the Dakota Sandstone includes the Burro Canyon Formation (Early Cretaceous) (Olson, 1976a, 1976b) at the base. The Dakota Sandstone was named from the town of Dakota, Nebraska (Meek and Hayden, 1862), and later a type locality was designated near Homer, Nebraska, in Dakota County (Condra and Reed, 1943). The following description is from Olson and Steven (1976a, 1976b), Olson and others (1975), and Olson (1976a, 1976b).

The Dakota Sandstone is mainly a light-gray to light-brown, moderately to well-cemented, medium- to coarse-grained, quartzose sandstone and conglomeratic sandstone near the base. Pebbles are gray and black chert. Crossbedding and channels are common. In the upper part, siltstone beds and flaggy sandstone beds are interspersed with coarser-grained sandstone. Locally, the Dakota Sandstone is carbonaceous and argillaceous.

The thickness of the Dakota Sandstone ranges between 50 and 330 ft and commonly is 150 to 230 ft thick.

Mancos Shale

The Mancos Shale of Late Cretaceous age overlies the Dakota Sandstone on a probably conformable contact and is composed mainly of black shale and minor sandstone lenses (Olson, 1976b; Olson and Steven, 1976a, 1976b). The Mancos Shale was named by Cross and Purington (1899) from exposures in the Mancos Valley and around the town of Mancos in southwestern Colorado. No type locality was designated. Numerous members were designated in the Mancos Shale in different sedimentary basins in the western United States (Molenaar and Baird, 1989), but members were not separated in the northwestern part of Saguache County (Olson, 1976b; Olson and Steven, 1976a, 1976b).

The top of the Mancos Shale is eroded in the northwestern part of the county where Tertiary volcanic rocks unconformably overlie the shale. The Mancos is dark-gray-brown silty shale. Lenses of friable dark-gray and gray sandstone are scattered through the shale, which also contains calcareous concretions. The shale is easily eroded and is the source of common landslides (Olson, 1976b; Olson and Steven, 1976a, 1976b).

In western Colorado, a complete sequence of Mancos Shale is as thick as 3,000 ft, but in the Cochetopa Hills region of Saguache County, only about 330 to 1,300 ft remain (Olson, 1976b; Olson and Steven, 1976a, 1976b).

Cenozoic Rocks and Deposits

Cenozoic rocks and deposits are distributed throughout Saguache County. The western part of the county is underlain by extensive volcanic rocks and associated intrusive bodies of the San Juan volcanic field, which is mainly west and south of Saguache County (**fig. 14**). The San Juan volcanic field is a complex of extinct volcanoes and calderas that had a principal period of activity between about 36 and 25 Ma. During this interval, more than 15,400 cu mi of magma were erupted (Lipman and others, 1970;

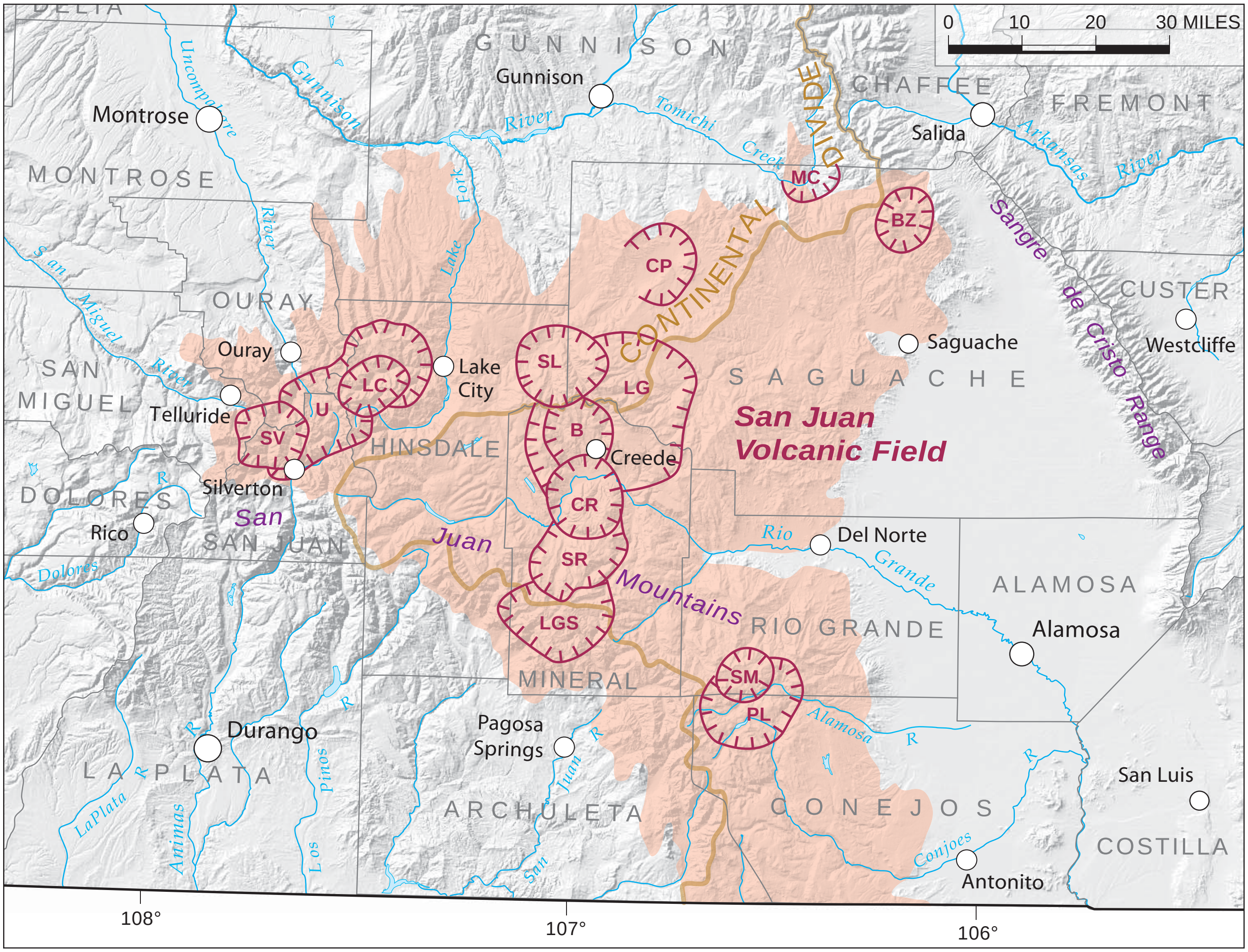


Figure 14. Calderas of the San Juan and Central Colorado volcanic fields. Abbreviations for caldera names: B, Bachelor; BZ, Bonanza; CP, Cochetopa Park; CR, Creede; LC, Lake City; LG, La Garita; LGS, La Garita South; MC, Marshall Creek; PL, Platoro; SL, San Luis; SM, Summitville; SR, South River; SV, Silverton; U, Uncompahgre (adapted from Steven and Lipman, 1976, Lipman, 2000, and McIntosh and Chapin, 2004).

Lipman, 1975, 1989). The San Juan volcanic field formed during three main stages:

- Early eruption of **intermediate-composition rocks** between approximately 36 and 31.1 Ma;
- Eruption of about 15 **voluminous ash-flow sheets** between 30 and 26 Ma from the southern, central, and western San Juan caldera complexes; and
- A period of **postcaldera eruptions** after 26 Ma characterized by bimodal volcanic rocks (Lipman, 1989).

The northeastern part of Saguache County, in the area of the Bonanza and Marshall Pass mining districts, is underlain by rocks of the Central Colorado volcanic field. These rocks are similar to those of the San Juan volcanic field: intermediate-composition rocks overlain by ash-flow sheets, followed by postcaldera bimodal volcanic rocks. However, the accurately dated ash-flow rocks of the Bonanza caldera and the Thorn Ranch Tuff from an unknown caldera indicate caldera collapse and ash-flow eruptions at 33.6 to 33.1 Ma, much earlier than in the San Juan volcanic field (McIntosh and Chapin, 2004).

The southeastern part of the county is underlain by rocks and unconsolidated deposits of late Cenozoic age that fill the San Luis Valley. These deposits are mainly clastic materials deposited in the rift basin that forms the modern San Luis Valley. The Santa Fe Group (Miocene and Pliocene) underlies much of the Quaternary alluvial, fluvial, and eolian deposits in the southeastern part of Saguache County.

Tertiary Volcanic and Intrusive Rocks

Early Intermediate-Composition Rocks

The assemblage of volcanic rocks that forms much of the eastern part of the Cochetopa Hills and La Garita Mountains adjacent to the San Luis Valley is composed mainly of rhyodacite, quartz latite, and andesite in flow, tuff, and breccia deposits that are combined in the Conejos Formation (Lisle, 1974; Lipman, 1976). The following description of these volcanic rocks is from Lipman (1976).

In the southwestern part of Saguache County, south of La Garita Creek in the La Garita Mountains, Lipman (1968, 1976) identified two volcanoes that erupted concurrently between 34.7 and 31.1 Ma (Oligocene). The heavily eroded Summer Coon and Baughman Creek volcanic centers are composed of flows, breccias, and dikes of rhyodacite, quartz latite, porphyritic rhyolite, rhyolite, and andesite. Andesite forms the largest volume of the main cones of these volcanoes and, at about 3,300 ft in thickness, is the thickest of the extrusive rocks on the volcanoes' flanks. The cone and outer apron of the Summer Coon volcano are composed mostly of crudely stratified breccia deposits. The breccia and flows are composed of alkali olivine andesite, 30 percent of which consists of small phenocrysts of plagioclase, clinopyroxene, and olivine (**figs. 15, 16, 17, and 18**). Lipman (1968) suggested that the breccia flows were formed by autobrecciation of andesite flows; however, Forkner (2001) suggested that most of the breccia produced by the Summer Coon volcano formed as lahars (mud flows).

The Summer Coon volcano has a spectacular outcrop of dikes radiating from the central intrusive complex. The earliest dikes are composed of andesite and tend to be 1 to 2 ft thick and as long as 500 ft; they have limited topographic expression. The middle-stage dikes are composed of mostly phenocryst-poor silicic rhyolite that crops out prominently. The late dikes, of rhyodacite to quartz latite, are 165 ft wide and 3 mi long in maximum dimensions; they form very prominent ridges (**figs. 19 and 20**) (Lipman, 1976; Mertzman, 1971). Lipman (1976) reported a potassium-argon date of 34.7 Ma for one of the Summer Coon rhyodacite dikes. A natural arch of scenic interest is formed in one of the dikes on the north side of the volcano (**fig. 21**).

Rhyodacite and quartz latite form lava flows and breccia deposits and are the

Figure 15. Outcrop of east-dipping laharic breccia. East side of Summer Coon volcano.

Figure 16. Outcrop of breccia overlying an andesite lava flow of Summer Coon volcano. Hammer is 16 in. long.

Figure 17. Close-up of breccia shown in Figure 16. Note poor sorting of angular to subrounded blocks of andesite of Summer Coon volcano. Hammer is 16 in. long.

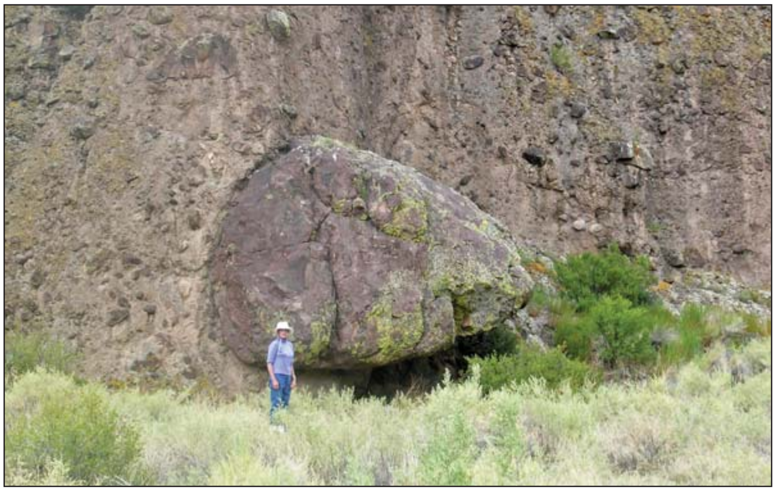


Figure 18. Outcrop of a large subrounded block of andesite in breccia related to the Summer Coon volcano, north of Shaws Warm Spring (see fig. 63 for location).

Figure 19. Outcrop of a quartz latite dike on south side of Summer Coon volcano. Juniper trees in the foreground are about 8 ft tall.about 8 ft tall.

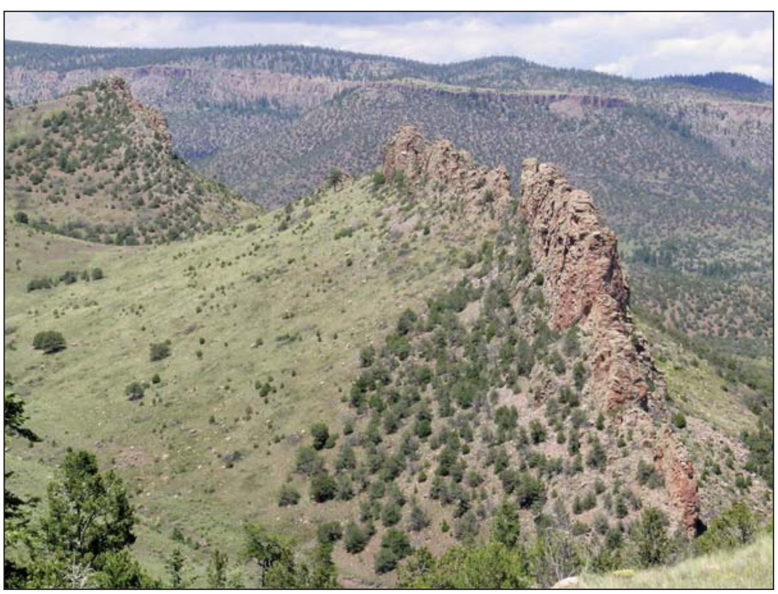


Figure 20. Outcrop of quartz latite dike on north side of Summer Coon volcano. Width of the dike is about 20 ft.

youngest eruptive rocks on Summer Coon volcano. Rhyodacite contains 10 to 30 percent phenocrysts of plagioclase, augite, and hornblende, and this unit is as thick as 985 ft. Quartz latite contains 20 to 40 percent phenocrysts of plagioclase, biotite, and augite, and this unit is as thick as 660 ft. Porphyritic rhyolite and rhyolite are as thick as 500 ft and form local lava flows on the flanks of the volcanoes. The porphyritic rhyolite contains 5 to 10 percent phenocrysts of plagioclase and biotite, and the rhyolite is a flow-laminated, crystal-poor lava flow.

Several intrusive bodies are found in the Summer Coon and Baughman Creek volcanic centers:

(1) Fine-grained mafic rocks range from andesite to diorite in composition and form an outer ring in the eroded summit crater.

(2) A porphyritic diorite stock mainly composed of plagioclase and clinopyroxene is exposed in the eroded summit crater.

(3) Hydrothermally altered quartz monzonite to granodiorite porphyry crops out in the eroded summit crater; Mertzman (1972) suggested that the alteration is related to the intrusion of a rhyolite dike.

(4) A tuff breccia appears to be the youngest part of the central intrusive complex.

North of La Garita Creek, Lipman (1976) assigned early intermediate-composition volcanic rocks to the Conejos Formation. Volcanic rocks of similar affinity extend northward from the Summer Coon and Baughman Creek volcanic edifices in a broad expanse of volcanic rocks to the vicinity of the town of Saguache and the Cochetopa Hills. Lipman (1976) identified the following flow units in the Conejos Formation: (1) an upper lava unit of porphyritic dark andesite and rhyodacite flows and flow breccia; (2) vent facies composed of aphanitic to porphyritic andesite, rhyodacite, and quartz latite lava flows and flow breccia; (3) conglomerate, sandstone, and mudflow breccia that accumulated on the flanks of stratovolcanoes; (4) rhyolite lava flows and domes; and (5) intrusive dikes and small plugs of intermediate composition. Hedlund and Olson (1974), Olson and others (1975), Olson (1976a, 1976b), and Olson and Steven (1976a, 1976b) described similar early intermediate-composition flows and breccias that they considered equivalent to the Conejos, Lake Fork, and San Juan Formations

Figure 21. Natural arch formed in one of the prominent quartz latite dikes on north side of Summer Coon volcano. Trees in the foreground are 8 to 10 ft tall.

and other early intermediate-composition rocks in the San Juan volcanic field. These aphanitic to finely porphyritic rock units are quartz latite and rhyodacite tuff breccia, flow breccia, and lava flows. Steven and others (1974) divided the early intermediate-composition lavas and breccias into a near-source facies and a volcaniclastic facies and included in this unit the Conejos, Lake Fork, San Juan, and Picayune Formations, Biedell Quartz Latite, and Tracy Creek Quartz Latite. In the northern part of Saguache County, similar early intermediate-composition volcanic rocks rest on Paleoproterozoic rocks, lower Paleozoic rocks, and Mesozoic rocks (Burbank, 1932; Mayhew, 1969; Perry, 1971), and these andesite and latite flow rocks are probably equivalent to the Conejos, Lake Fork, and San Juan Formations. Intermediate-composition rocks associated with the Bonanza caldera in the northeastern part of Saguache County consist of the andesitic lavas and breccias of the Rawley Andesite (**fig. 22**) as named by Burbank (1932) for exposures along Rawley Creek and in the Rawley Mine (**fig. 23**) about 2 mi north of the town of Bonanza. The most abundant and typical rock type found in the Bonanza caldera is augite-biotite andesite, which typically consists of a dark fine-grained matrix and phenocrysts of plagioclase; textures are fine grained nonporphyritic to conspicuously porphyritic (Burbank, 1932). Other volcanic rocks in the Rawley Andesite include augite andesite, biotite andesite, and locally near the base, latite flows. Vesicles and amygdules filled with chlorite, calcite, and chalcedony are common (fig. 22). The white phenocrysts of plagioclase are most conspicuous in their variation in size and proportion to the groundmass. Phenocrysts of augite and biotite are usually small and not abundant. The feldspar phenocrysts are calcic, usually labradorite,

Figure 22. Vesicular Rawley Andesite, near Queen City Mine, Copper Gulch, Bonanza district.

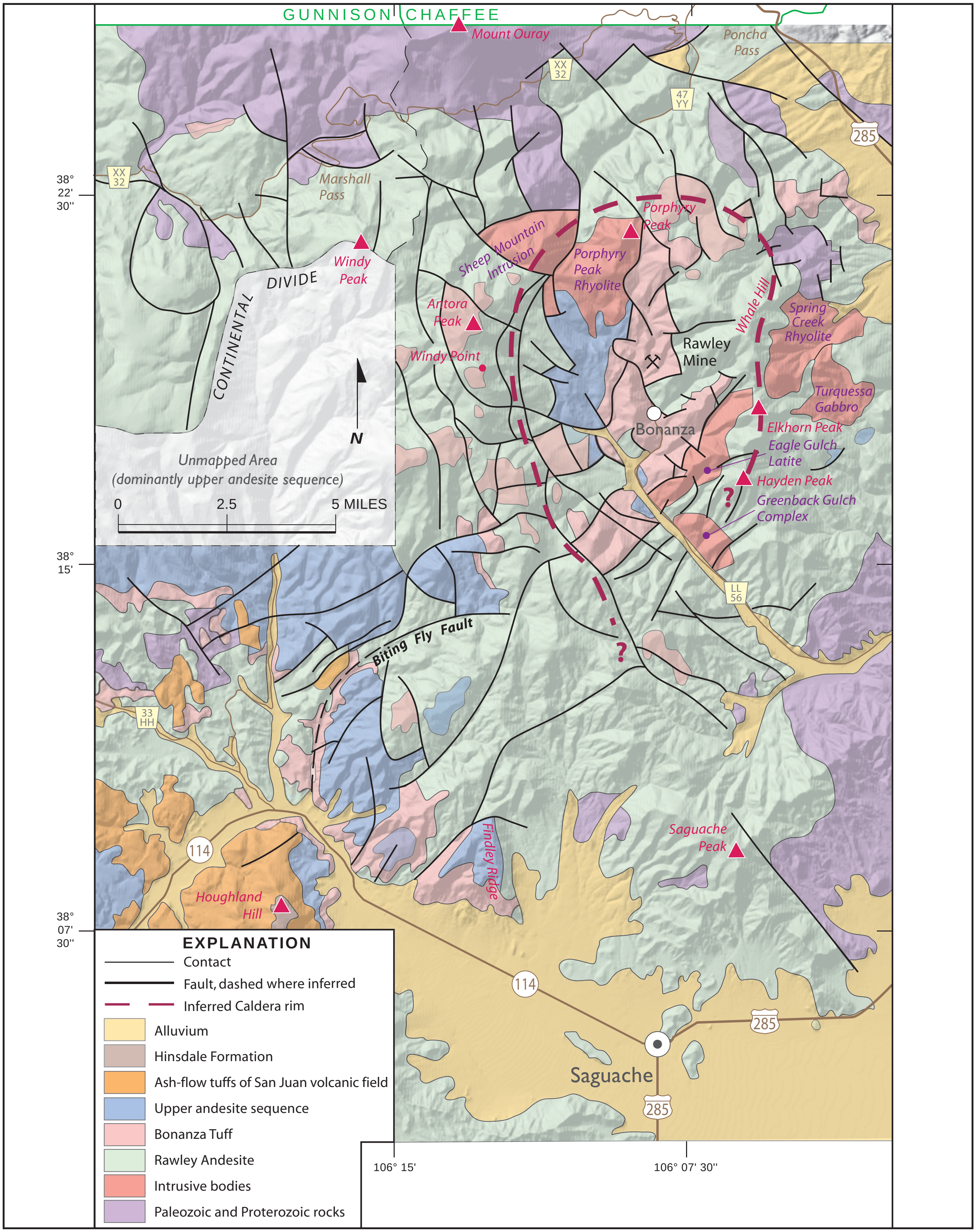


Figure 23. Simplified geologic map of Bonanza district (adapted from Varga and Smith (1984), and Bruns (1971).

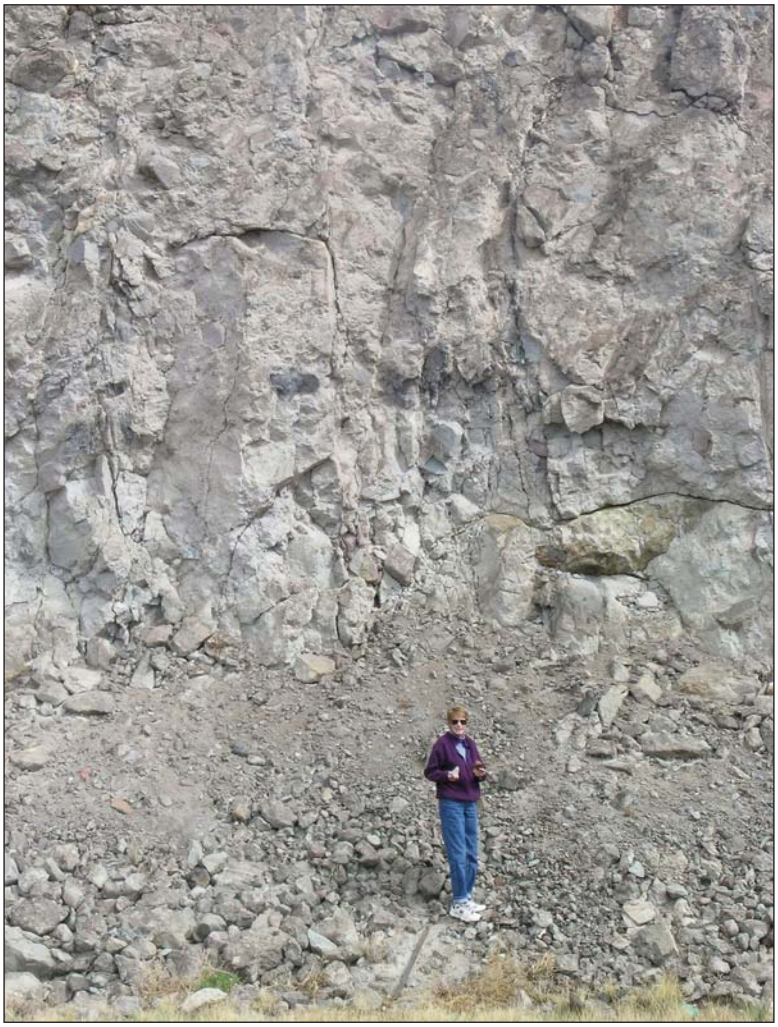


Figure 24. Roadcut of Rawley Andesite laharic breccia. About 1 mi east of Saguache on U.S. Highway 285.

Figure 25. Rawley Andesite laharic breccia. Fragments are typical andesite of the Rawley Andesite. About 1 mi east of Saguache on U.S. Highway 285.

but andesine is locally present in the latites. The thickness of the Rawley Andesite is not known with great accuracy, but is estimated to be 1,600 to 2,000 ft in the Bonanza caldera (Burbank, 1932).

In the southwestern part of the Bonanza caldera complex, the Rawley Andesite consists primarily of gray, hornblende andesite and red-brown, hornblende-biotite latite, andesitic auto-breccia, and lapilli tuff (Marrs, 1973) Volcaniclastic rocks within the Rawley Andesite include laharic breccia (**figs. 24 and 25**) and water-laid and air-fall tuff (**figs. 26 and 27**) (Marrs, 1973, p. 37–39). Lipman and others (1970) obtained $^{40}K/^{39}Ar$ dates of 34.2 ± 1.6 Ma from plagioclase from a lower flow unit of the Rawley Andesite and 33.4 Ma from plagioclase and biotite from an upper flow unit of the Rawley Andesite. Varga and Smith (1984) reported apparent whole-rock ages from the Rawley Andesite of 37.7 ± 3.0 and 37.3 ± 2.6 Ma.

The Hayden Peak Latite partially overlies and interfingers with the Rawley Andesite. The Hayden Peak Latite was first described by Patton (1916) for flows on Hayden Peak. The Hayden Peak Latite is composed mostly of latite, quartz latite, and “andesite with labradorite phenocrysts” (termed “calcic-andesitic latite” by Burbank, 1932). Phenocrysts of plagioclase and orthoclase are also common. The typical Hayden Peak Latite contains less than 10 percent plagioclase, biotite, and a trace of potassium feldspar. The groundmass is aphanitic and composed mostly of plagioclase microlites. The Hayden Peak Latite is compositionally similar to the Rawley Andesite and was probably deposited at the same time, but in different locations (Mayhew, 1969, p. 20–21). Geologists of the Colorado School of Mines (Bridwell, 1968; Kouther, 1969; Mayhew, 1969; Perry, 1971; Bruns, 1971; Marrs, 1973) mapped in the area around Burbank’s (1932) study of the Bonanza mining district. They did not break out the Hayden Peak Latite from either the Rawley Andesite or Bonanza Tuff.

Caldera-Collapse Volcanic Deposits

A distinctive feature of the San Juan volcanic field is the prominence of ash-flow tuffs and flow breccias formed during collapse of intermediate-composition volcanic edifices. Collapse of the roof of the volcanoes and the concomitant forceful eruption of voluminous, pyroclastic material formed calderas and massive ash-flow tuff deposits. The ash-flow tuffs were emplaced by incandescent, super-

Figure 26. Roadcut through Rawley Andesite autobrecciated andesite lava flow overlain by whitish-gray pumice lapilli tuff overlain by upper andesite lava flow. Note thinning of the pumice lapilli tuff on sloping toe of lowermost lava flow. About 3 mi south of Saguache on U.S. Highway 285.

Figure 27. Roadcut through Rawley Andesite whitish-gray pumice lapilli tuff overlain by upper andesite lava flow. Note baked upper contact of lapilli tuff with upper andesite lave flow. About 3 mi south of Saguache on U.S. Highway 285.

heated, turbulent mixtures of volcanic gas and ash that flowed over the landscape on a laminar flow base. After these superheated clouds came to rest, parts of the flows were hot enough to cause the merging of the viscous ash particles composed of glass shards and dust, pumice and scoria fragments, crystals, and xenoliths to form layers of welded tuff. The degree of welding may range from incipient stages marked by the cohesion of glassy fragments to complete welding of glassy fragments marked by their deformation, loss of porosity, and ultimate homogenization of the glass (Smith, 1960, p. 821–823). Later, fumaroles formed as hot gas and liquids were expelled vertically through the column of volcanic ash. Nonwelded tuff in the upper part of each flow was cemented by silica-rich minerals. These catastrophic eruptions covered thousands of square miles in the region of the San Juan volcanic field and lasted for millions of years. Following periods of eruption of voluminous ash-flow tuffs, resurgent volcanic domes commonly developed in the collapsed caldera roof as magma intruded and deformed the roof. Mapping and interpretation of ash-flow tuffs, flow breccias, lava flows, and landslide breccias in complex calderas that evolved through time constitute a difficult exercise, and the following summary deals with these complexities in a most generalized fashion.

Volcanic deposits from two of the three main clusters of calderas in the San Juan volcanic field are found in the western part of Saguache County (Steven and others, 1974; Lipman, 1989). The three main clusters of calderas (see fig. 14) are the southeastern (Platoro) caldera complex (Lipman, 1975; Dungan and others, 1989), the central San Juan caldera complex (Lipman and others, 1989), and the western San Juan caldera complex (Hon and Lipman, 1989). Volcanic rocks from the southeastern (Platoro) caldera complex (Dungan and others, 1989) have been mapped near the south boundary of the county, but welded tuffs and flow breccias from this complex do not extend into Saguache County. Volcanic rocks from calderas that compose the central San Juan caldera complex are widely exposed in the western part of the county. However, only the La Garita, San Luis, Cochetopa Park, and Bonanza calderas and the recently recognized Marshall Creek caldera (McIntosh and Chapin, 2004) are actually located within the county boundaries (fig. 14). All of these are in the western part of the county. Volcanic rocks derived from the western San Juan caldera complex extend into the northwestern part of the county. Lava flows and caldera-collapse breccia are associated with ash-flow tuffs of the calderas, as well as postdating the main events of caldera collapse (Steven and Lipman, 1976; Lipman and Sawyer, 1988; Lipman and others, 1989).

Central San Juan Caldera Complex

Ash-flow tuffs form the most voluminous volcanic deposits, and these are described first in the following section. Coeval and postcaldera lava flows, lava domes, and landslide breccia deposits are described at the end of this section.

The oldest of the ash-flow sheets is the Masonic Park Tuff, which has a $^{40}K/^{39}Ar^{40}K/^{39}Ar$ age of 28.4 Ma (Lipman and others, 1989, table 3-1). A thin layer of this tuff extends for less than 0.5 mi into the southwestern corner of Saguache County northeast of South Fork (Steven and others, 1974). The Masonic Park Tuff was erupted from the Mount Hope caldera (fig. 14) southwest of the county (Lipman and others, 1989), and the ash-flow tuff is truncated against the southwest side of the early intermediate-composition Baughman Creek volcanic center. The Masonic Park Tuff is a gray, nonwelded, and yellow-brown, partly welded, rhyolite and dacite ash-flow tuff (Dungan and others, 1989) that contains 40 to 50 percent phenocrysts of plagioclase, biotite, and augite and xenoliths of andesite (Lipman, 1976).

Overlying the Masonic Park Tuff is the Fish Canyon Tuff, which has an age of 27.8 Ma (Lipman and others, 1989, table 3-1). This tuff is exposed in north-trending patches from South Fork, Colorado (fig. 1) (Steven and others, 1974), into the Cochetopa Hills region and Cochetopa Park (figs. 1 and 2) (Hedlund and Olson, 1974; Olson and others, 1975; Olson, 1976a, 1976b), and along the east-facing mountain front of the La Garita Mountains (fig. 2) (Steven and others, 1974). The Fish Canyon Tuff is absent at places in the western part of the county, and it has a maximum thickness of about 380 ft (Olson, 1976a). This tuff was erupted from the La Garita caldera, which occupies the western part of the county (fig. 14). The collapse of the La Garita caldera is the largest recognized volcanic eruption in earth’s history. The ash flows and lavas erupted from La Garita have a volume of 1,200 cubic miles, enough to bury the state of California to a depth of over 35 ft. The Fish Canyon Tuff is a light-gray, nonwelded to tan, moderately welded quartz latite ash-flow tuff that contains 35 to 50 percent phenocrysts of plagioclase, sanidine, biotite, hornblende, and sparse resorbed quartz (Lipman, 1976).

The Carpenter Ridge Tuff, which was erupted from the Bachelor caldera (fig. 14) at 27.4 Ma (Lipman and others, 1989), overlies the Fish Canyon Tuff. The Carpenter Ridge Tuff is exposed (1) in a series of isolated patches that trend northeast of the Continental Divide along the South Fork of Saguache Creek and (2) in a north-trending set of outcrops on the western edge of the San Luis Valley adjacent to the east-facing mountain front of the La Garita Mountains (Steven and others, 1974). This unit has a maximum thickness of about 245 ft and consists of light-gray, nonwelded to reddish-brown, densely welded rhyolitic ash-flow tuff that contains 2 to 3 percent plagioclase, sanidine, and biotite. The Carpenter Ridge Tuff has a conspicuous black vitrophyre at the base and a central lithophysal zone (Lipman, 1976).

The Wason Park Tuff, overlying the Carpenter Ridge Tuff, was erupted from the South River caldera (fig. 14) at 27.2 Ma. Exposures of this welded tuff trend northward along the east and west sides of the South Fork of Saguache Creek (Steven and others, 1974), but the northern extent of this ash-flow unit is not known because it was not broken out by Tweto and others (1976) or Hedlund and Olson (1974). Olson and others (1975) and Olson (1976a, 1976b) did not show this unit in the northwestern corner of the county. This ash-flow unit is a grayish-red rhyolite and silicic dacite (quartz latite) that contains 10 to 30 percent phenocrysts that are composed of plagioclase, sanidine, biotite, and augite. This unit has a densely welded lower part and a less welded upper part and is as thick as 655 ft (Lipman and Sawyer, 1988).

The Rat Creek Tuff, which is above the Wason Park Tuff, was erupted at 26.4 Ma from the San Luis caldera complex (fig. 14). This ash-flow tuff was thought to be exposed in a north-trending band through the La Garita Wilderness along the east and west sides of the South Fork of Saguache Creek (Steven and others, 1974). Hedlund and Olson (1974), Olson and others (1975), and Olson (1976a, 1976b) mapped an ash-flow tuff in the northwestern part of Saguache County that they equated with the Rat Creek Tuff. However, mapping by Lipman (2006) indicates that there is no Rat Creek Tuff in this area.

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The Rat Creek Tuff is compositionally zoned: rhyolite forms the lower part and silicic dacite (quartz latite) and dacite form the upper part (Lipman and Sawyer, 1988). Contacts between the different compositions are gradational. The Rat Creek Tuff is as thick as 330 ft. Typically, the silicic dacite (quartz latite) is a partly welded tuff that contains 20 to 40 percent phenocrysts of plagioclase, biotite, augite, and rare sanidine (Lipman and Sawyer, 1988). Rhyolite contains 5 to 15 percent phenocrysts of sanidine, plagioclase, biotite, and sparse augite. Glassy, black, flattened pumice fragments are common in the silicic dacite (quartz latite), and lithic fragments of andesite and rhyolite are common in the basal rhyolite.

The Nelson Mountain Tuff overlies the Rat Creek Tuff. The Nelson Mountain Tuff was erupted from the San Luis caldera complex at 26.8 Ma (Lipman, 2006). The tuff is exposed on several peaks in the headwaters of the South Fork of Saguache Creek in the La Garita Mountains and in the northwestern part of Saguache County. Olson and others (1975), Olson (1976a), and Hedlund and Olson (1974) described the tuff of Long Gulch and the tuff of Cochetopa Creek as possible correlatives of the Nelson Mountain Tuff. The Nelson Mountain Tuff grades upward in composition from rhyolite at the base to dacite and silicic dacite (quartz latite) at the top. Lipman and Sawyer (1988) described eight subunits in the Nelson Mountain Tuff that are generalized here into a lower rhyolite and an upper dacite:

1. The lower (rhyolite) group of subunits consists of basal gray, nonwelded tuff, overlain by a light-gray, densely welded, phenocryst-poor tuff that contains collapsed pumice fragments and a light-gray to light-reddish-brown welded tuff that contains partly collapsed pumice fragments at the top. Phenocrysts form 3 to 5 percent of the rock and are composed of sanidine, plagioclase, biotite, and rare augite.

2. The upper (dacite) group of subunits consists of brownish-gray welded tuff that is transitional from rhyolite below to dacite above and contains 10 to 20 percent phenocrysts of plagioclase, sanidine, biotite, and sparse augite and quartz. This tuff is overlain by dark-gray silicic dacite (quartz latite) tuff and dacite welded tuff composed of 20 to 35 percent phenocrysts of plagioclase, biotite, and augite. The top unit is yellow-tan and gray, nonwelded, crystal-rich silicic dacite (quartz latite) and dacite composed of phenocrysts of plagioclase, biotite, and augite. The top of the unit is eroded, but Olson (1976a, 1976b) reported a maximum thickness of 460 ft.

Lava flows, lava domes, flow breccia, and landslide breccia have been documented to represent coeval phases of the caldera cycles (Lipman and Sawyer, 1988), as well as being postcaldera volcanic deposits. Dacite of McKenzie Mountain, which was previously thought to represent a late lava flow in the Creede caldera (Steven and Ratte, 1965; Steven and Eaton, 1975), has been reinterpreted as an early phase of the evolution of the San Luis caldera complex (Lipman and Sawyer, 1988). In the San Luis caldera, syncaldera lava flows of McKenzie Mountain are tan to brown, flow-layered dacite that contains 20 to 30 percent phenocrysts of plagioclase, biotite, and augite (Lipman and Sawyer, 1988). Other syncaldera lava flows are the silicic dacite (quartz latite) of the Captive Inca Mine (located in Mineral County, not shown in this report), which is a tan to brown lava dome that contains 15 to 25 percent phenocrysts of plagioclase, biotite, and hornblende. Other rocks associated with these flow rocks are flow breccia, dikes, vent necks, and conglomeratic mudflows (Lipman and Sawyer, 1988).

Late-stage volcanic rocks associated with the San Luis caldera are grouped in "Andesite of Stewart Peak" (26.9 to 25.7 Ma), "Volcanics of Stewart Peak," and "rhyolite of Mineral Mountain" (Lipman and Sawyer, 1988; Lipman, 2006); these rocks are andesitic and dacitic lava flows and associated volcaniclastic rocks that fill the moat area of the caldera (shown on fig. 28 as "intracaldera lavas"). Andesitic lavas are dark gray and dacitic lavas are light gray. These rocks contain 5 to 25 percent phenocrysts composed of plagioclase and augite or hornblende. Volcaniclastic rocks are mainly mudflow deposits and coarse breccias derived from coarsely porphyritic andesite and dacite lava domes (Lipman and Sawyer, 1988).

The La Garita and San Luis calderas accumulated lacustrine and fluvial sediment in the moats surrounding the resurgent domes of the collapsed roofs, but little of these deposits are preserved in the La Garita caldera (Steven and Lipman, 1976).

Western San Juan Caldera Complex

Tuffs that erupted from the Uncompahgre caldera (fig. 14) at 29 to 28 Ma in the western San Juan caldera complex extend into the northwestern part of Saguache County where the Sapinero Mesa Tuff was described and mapped by Olson (1976a, 1976b), Olson and others (1975), and Hedlund and Olson (1974). This tuff is reddish brown to light brownish gray, densely welded, and devitrified and contains 5 to 12 percent phenocrysts composed of calcic oligoclase, sanidine, quartz, and biotite. The matrix is eutaxitic, and collapsed pumice is

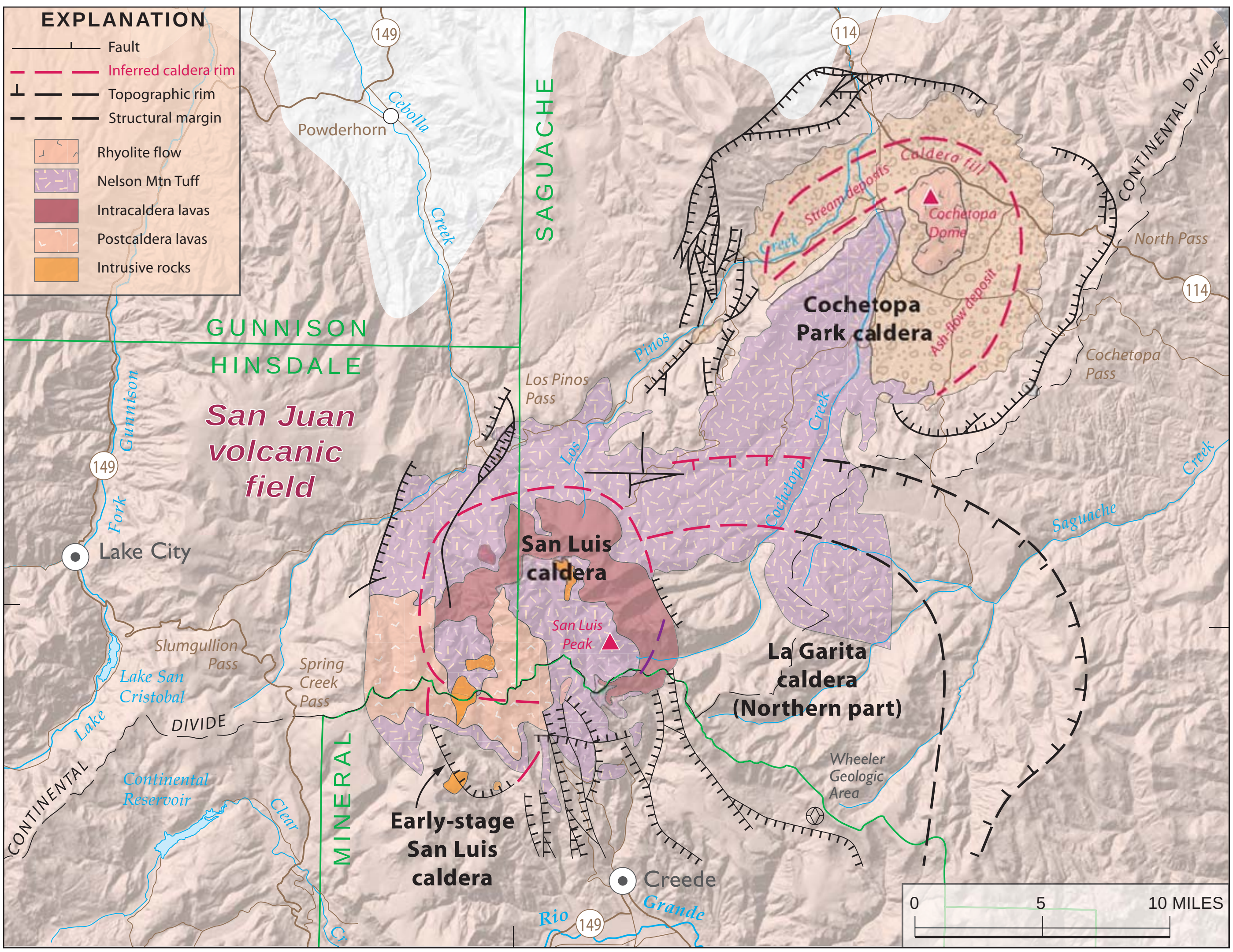


Figure 28. Geologic map of Cochetopa Park and San Luis calderas (adapted from Steven and Lipman (1976). The La Garita caldera extends about 30 mi to south of the figure.

common. Locally a thick black vitrophyre is found at the base (Olson, 1976b). This unit ranges from about 80 to 660 ft thick (Olson, 1976a, 1976b; Olson and others, 1975; Hedlund and Olson, 1974). The Sapinero Mesa Tuff does not extend to the south and southeast into the drainage of the South Fork of Saguache Creek.

Cochetopa Park Caldera

The Cochetopa Park caldera (**fig. 28**) has been studied in less detail than other eruptive centers in the San Juan volcanic field; however, preliminary work released by Peter Lipman (2003) indicates that all of the material described by Steven and Lipman (1976) as the Cochetopa Park Tuff is, in fact, the Nelson Mountain Tuff and not related to the collapse of the Cochetopa Park caldera. No mappable ash-flow unit related to the collapse of the Cochetopa Park caldera has so far been discovered. Instead, the collapse of that caldera is related to the eruption of the 26.8 Ma Nelson Mountain Tuff from an "underfit" depression within the San Luis caldera complex some 20 mi to the southwest (Lipman, 2003).

Olson (1976a, 1976b) described his "tuff of Cochetopa Creek," which Lipman (2003) considered to be the Nelson Mountain Tuff, as a light-gray to reddish-brown, densely to moderately welded tuff composed of 20 to 30 percent phenocrysts in the upper part and 8 to 20 percent phenocrysts in the lower part. This welded tuff is a composite cooling unit. Phenocrysts are sanidine, plagioclase, quartz, and some biotite in an aphanitic eutaxitic matrix that contains shards and small pumice fragments. This tuff contains inclusions of older Cenozoic volcanic rocks, lapilli, and minor granite clasts. Locally at the base of this welded tuff is a vitrophyre that is as thick as 16 ft. The "tuff of Cochetopa Creek" ranges between 200 and 330 ft thick in the northwestern part of the county. However, according to Peter Lipman (personal communication, 2004), Olson's "tuff of Cochetopa Creek" includes Fish Canyon Tuff, Carpenter Ridge Tuff, Tuff of Saguache Creek, and even Wall Mountain Tuff, but no recognizable Nelson Mountain Tuff.

Bonanza Caldera

The Bonanza caldera is the easternmost caldera and one of the oldest calderas in the San Juan volcanic field; however, it has been studied in less detail than other caldera complexes in this volcanic field. During late Eocene time, eruption of the Rawley Andesite built a large volcanic cone. The Bonanza Tuff is the principal ash-flow tuff that has been linked with the Bonanza caldera (Mayhew, 1969; Perry, 1971), and the ash-flow tuffs of the Bonanza Tuff were erupted during the collapse of the Bonanza volcano and caldera formation. The Gribbles Park Tuff, which is exposed mainly to the east of the Bonanza caldera, is

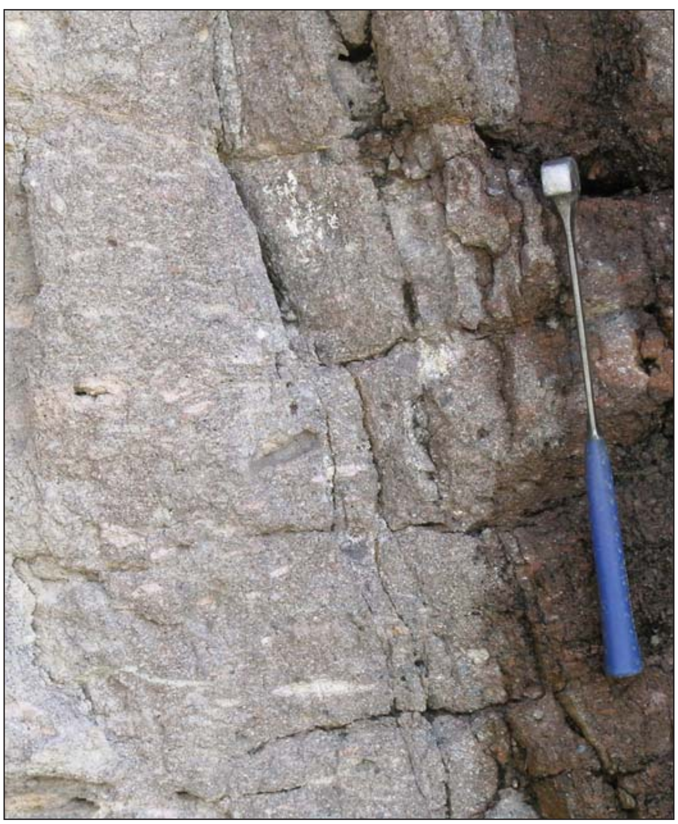


Figure 29. Outcrop of Bonanza Tuff outflow facies, showing distinct flow foliation. Saguache Creek near Houghland Hill.

Figure 30. Bonanza Tuff. Note lithic fragments of Rawley Andesite. From an outcrop near the Rawley 12 tunnel, north of Bonanza.

now recognized to have been erupted from the Bonanza caldera and is correlative with the upper Bonanza Tuff (McIntosh and Chapin, 2004).

The Bonanza Tuff was named the “Bonanza Latite” by Patton (1916) for latites with a prominent flow foliation and containing inclusions of and overlying the Rawley Andesite. Mayhew (1969, p. 25) renamed the unit the Bonanza Tuff (**figs. 29 and 30**).

Burbank (1932) described the Bonanza Tuff within the Bonanza mining district and, for the most part, inside the topographic walls of the caldera. His Bonanza Tuff consists of primarily greenish-gray to blackish-gray, biotite latite ash flows with platy foliation. The groundmass is very fine grained and contains abundant phenocrysts of plagioclase and orthoclase. Microscopic study of the Bonanza Tuff indicates most of the plagioclase to be andesine with lesser amounts of orthoclase. Quartz forms rounded, resorbed grains. Biotite is common and is usually altered to chlorite, calcite, and magnetite. The strongly foliated texture is typical of welded ash-flow tuffs. Purple-gray lithic fragments of Rawley Andesite are as large as 1 ft in diameter. Burbank (1932) divided his Bonanza Latite into two members, a lower dacitic unit and an upper rhyolitic unit; he interpreted a combined thickness of approximately 900 to 1,000 ft.

The Bonanza Tuff changes character outside the topographic rim of the Bonanza caldera (Bridwell, 1968; Kouther, 1969; Mayhew, 1969; Perry, 1971; Marrs, 1973). The outflow facies is a brown, brownish-gray, gray, and blackish-gray, densely to poorly welded, silicic dacite, quartz latite, and rhyolite that contains 20 to 30 percent phenocrysts of plagioclase, sanidine, and distinctive golden-brown to black biotite. In the southwestern part of the Bonanza caldera complex at Findley Ridge, Marrs (1973) divided the 488-ft-thick outflow facies of the Bonanza Tuff into eight separate flow units, which vary with intensity of welding, presence or absence of vitrophyre, and abundance of crystals and lithic fragments (**figs. 31 and 32**).

McIntosh and Chapin (2004) obtained $^{40}Ar/^{39}Ar$ ages of 33.21 ± 0.12 Ma on biotite and 33.32 ± 0.16 Ma on sanidine from the lower unit and a sanidine age from the upper sequence of 32.89 ± 0.09 Ma. $^{40}K/^{39}Ar$ dates on biotite from the lower Bonanza Tuff range from 35.7 ± 1.8 to 36.2 ± 1.6 Ma (Varga and Smith, 1984, table 2).

Marshall Creek Caldera

Gregory and McIntosh (1996) recognized the possible presence of a previously undescribed caldera northwest of the Bonanza caldera near the Pitch Mine in the Marshall Pass area. The Thorn Ranch Tuff is a simple cooling unit of nonwelded to moderately welded tuff. It is a high-silica rhyolite containing 15 to 25 percent phenocrysts of sanidine, plagioclase, quartz, and biotite. Abundant Precambrian lithic fragments and brown aphanitic lithic fragments in a matrix of devitrified glass shards and pink and white pumice give the Thorn Ranch Tuff a distinctive appearance (McIntosh and Chapin, 2004). Five $^{40}Ar/^{39}Ar$ measurements on sanidine give an average date of 33.66 ± 0.14 Ma (McIntosh and Chapin, 2004).

Postcaldera Volcanic and Intrusive Rocks

After caldera eruptions ceased in the San Juan volcanic field, a period of postcaldera eruptions began at about 26 Ma that was characterized by bimodal volcanic eruptions (Lipman, 1989). The dominant compositions of these postcaldera volcanic rocks are trachyandesite and silicic rhyolite (Lipman, 1989), but only isolated patches of the andesitic and basaltic phases of this bimodal suite are found in the La Garita Mountains and in the headwaters of Saguache Creek (Steven and others, 1974; Tweto and others, 1976). Steven and others (1974) assigned these basalt flows to the Hinsdale Formation of Miocene to Pliocene age (23.4 to 4.7 Ma). The basalt flows are fine-grained, silicic, alkali olivine basalt and basaltic andesite, generally containing olivine phenocrysts. Xenocrysts of quartz and feldspar are locally abundant. These units are shown as Tial and Tbb on plate 1. Lipman (1989) related eruption of the bimodal assemblage of flows and flow breccia to inception of regional extension of the Rio Grande rift zone.

Postcaldera volcanic rocks in the area of the Bonanza caldera are included in the “upper andesite sequence” (fig. 23), and they include the Squirrel

Figure 31. Outcrop of outflow facies of the Bonanza Tuff at Findley Ridge, about 5 mi west of the town of Saguache. Outcrop is about 500 ft high. Tr, Rawley Andesite —laharic breccia and volcaniclastic deposits; units 1a–8 are cooling units of the Bonanza Tuff from Marrs (1973).

Figure 32. Outcrop of Bonanza Tuff, unit 5 on Findlay Ridge (refer to fig. 31). Note strong flow foliation. Hammer is 16 in. long. The view in the photograph is looking northeast across Findley Gulch toward the area near Ute Pass (pl. 1).

Gulch Latite (Burbank, 1932; Perry, 1971) and Hayden Peak Latite (Burbank, 1932; Perry, 1971). The Squirrel Gulch Latite is mostly exposed on the western perimeter of the Bonanza district. It consists of massive flows of hornblende-biotite latite. The rock is glassy, black, and porphyritic and is characterized by pronounced columnar jointing. These units form an assemblage of flows and flow breccia. A potassium-argon date of 31.1 ± 5.6 Ma was obtained from the Squirrel Gulch Latite by Varga and Smith (1984). This imprecise date does not give confidence in the placement of these "upper andesite sequence" rocks in the bimodal suite.

The Porphyry Peak rhyolite formed a postcollapse exogenous dome, composed partly of intrusive and flow rocks in the caldera (Perry, 1971). The Porphyry Peak rhyolite is composed of phenocrysts of quartz, sanidine, and biotite in a matrix of intermixed alkali feldspar and quartz. At some places, the Porphyry Peak rhyolite underwent acid sulfate alteration, and the sanidine was converted to alunite (Lenz, 2004).

Burbank (1932) described other younger volcanic units in the heart of the Bonanza district: They include the Brewer Creek latite, a younger andesite of Brewer Creek, the Eagle Gulch Latite, and small bodies of granite porphyry and diorite, monzonite dikes, and intrusive rhyolite and latite. The stratigraphic relationships of these younger volcanic rocks to the Bonanza caldera are poorly understood (Perry, 1971).

Sedimentary Rocks of Late Cenozoic Age

The southeastern part of the county is underlain by rocks and unconsolidated deposits of late Cenozoic age that fill the San Luis Valley. These deposits were originally named the Santa Fe Group (Miocene and Pliocene?) and the Alamosa Formation (Pliocene and Pleistocene?) and are mainly clastic debris deposited in the rift basin that forms the modern San Luis Valley. Kottlowski (1953) proposed the name Santa Fe Group and subdivided several units in north-central New

Mexico, and by the late 1970s, use of the term "Santa Fe Group" was common in New Mexico. On his regional geologic map, Johnson (1969) indicated that the valley fill in the southeastern part of Saguache County was composed of Paleogene, Neogene, and Quaternary strata of the Santa Fe Group. Bruce and Johnson (1991), Johnson and Bruce (1991), Lindsey (1995a, 1995b), Wallace and Lindsey (1996), and Wallace (1997a, 1997b) extended use of Santa Fe Group nomenclature into the San Luis Valley, and Brister and Gries (1994) included the Alamosa Formation as the uppermost unit in the Santa Fe Group in the northern part of the valley.

Detailed geologic maps that might separate Paleogene and Neogene units from Quaternary units are lacking in the northern part of the San Luis Valley. Although Johnson (1969) showed a combined Neogene and Quaternary unit as the Santa Fe Group, Steven and others (1974), Scott and others (1978), and Tweto and others (1976) showed only Quaternary gravel units at the surface. In the northern part of the San Luis Valley, local relief is so small that little information can be gained about units in the Santa Fe Group at the surface. Drill-hole data, mainly from water wells, provide the best lithologic information of the Santa Fe Group.

The Santa Fe Group was named from the vicinity of Santa Fe, New Mexico, by Hayden (1869); his original name was "Santa Fe marls," and no type locality was designated. Siebenthal (1910) redefined the Santa Fe Group in Costilla and Conejos counties, Colorado, which are south of Saguache County. Siebenthal (1910) included sand dunes of the Great Sand Dunes National Park in the Santa Fe Group, so the current uncertainty regarding separation of Paleogene and Neogene and Quaternary deposits was established at an early date. Near Fort Garland, Colorado, along the eastern edge of the San Luis Valley, about 300 ft of red sand and gravel below Cenozoic basalt flows is assigned to the Santa Fe Group; lava is also interbedded with the coarse clastic deposits (Siebenthal, 1910; Robinson and Waite, 1937). Geologic mapping in the region of Fort Garland in the San Luis Valley resulted in the subdivision of the Santa Fe Group into a basal basaltic andesite unit (Miocene), basalts of the Servilleta Formation (Pliocene), a volcanic clast–rich conglomerate facies (Oligocene), and sandstone and pebble to boulder conglomerate of the main unit of the upper Santa Fe Group (Oligocene to Quaternary?) (Wallace and Soulliere, 1996; Wallace, 1997a, 1997b). Wallace (1997a) reported that the thickness of the main unit may exceed 3,800 ft and that the base of this coarse clastic unit is older than basalt feeder dikes whose age is 18.86 ± 0.01 Ma, based on an $^{40}Ar/^{39}Ar$ whole-rock age (early Miocene). An $^{40}Ar/^{39}Ar$ whole-rock age on the Servilleta Formation in the upper part of the Santa Fe Group gave an age of 3.66 ± 0.01 Ma (early Pliocene). Interpretation of data from oil exploration wells and seismic data in the central part of the San Luis Valley north of the town of Center suggests that the Santa Fe Group is at least 11,000 ft thick along the easternmost part of the valley (Brister and Gries, 1994). Above the Santa Fe Group, Siebenthal (1910) described the Alamosa Formation from a section at Hansen's Bluff near the town of Alamosa, Colorado. There, he described about 60 ft of sand and clay and lesser amounts of conglomerate and gravel. Water wells have penetrated 1,200 to 1,300 ft of Alamosa Formation, and Siebenthal (1910) determined that the Alamosa Formation overlies the Santa Fe Group unconformably. Brister and Gries (1994) interpreted seismic and drill-hole data from the San Luis Valley in the southern part of Saguache County. They determined that the Alamosa Formation of the Santa Fe Group thickened from west to east under the Quaternary cover and that the formation was at least 1,500 ft thick in the east side of the valley near Great Sand Dunes National Park and Preserve. The age of the Alamosa is thought to be as old as Pliocene and as young as Pleistocene (Brister and Gries, 1994).

Combined Paleogene, Neogene, and Quaternary deposits have been mapped in the northern part of the San Luis Valley because the problem of separation of the Alamosa Formation from Quaternary deposits has not been solved. Consistent lithologic criteria have not been developed to separate poorly consolidated and unconsolidated gravel, sand, silt, and clay deposits that could be gradational from Paleogene to early Quaternary time. Along the west side the San Luis Valley, Steven and others (1974) showed old alluvial gravels as dissected remnants that crossed the Neogene and Quaternary time boundary. The stratigraphic relationships between these old gravels and deposits of the Santa Fe Group are not known. Steven and others (1974) also showed the west side of the San Luis Valley in Saguache County mapped as Quaternary alluvium, some of which could be the Alamosa Formation. The unit Qba of Scott and others (1978) is a basin-fill alluvium and generally similar to Quaternary alluvium of Steven and others (1974); at places in the northern San Luis Valley, this unit may include the youngest parts of the Alamosa Formation.

Quaternary Deposits

Quaternary deposits have not been mapped systematically in detail in the San Luis Valley (Madole, 2004), and although several studies describe some of their aspects, no studies have addressed the widespread

Quaternary deposits in the part of the valley that lies in Saguache County. In general, Quaternary deposits in Saguache County form the following units:

- **Gravel, sand, silt, and clay deposits** in the central San Luis Valley;
- **Coarse gravel fans** along the range fronts of the Sangre de Cristo Range, La Garita Mountains, and Cochetopa Hills;
- **Glacial deposits** in the higher reaches of the Sangre de Cristo Range and La Garita Mountains;
- **Dunes and dune fields** in the southeastern part of the county; and
- **Mass-movement deposits** scattered through the western part of the county.

Alluvial deposits in the central part of the San Luis Valley have been mapped and described as many different types and ages of deposits by different geologists, and no synthesis of these disparate interpretations is possible, given the absence of detailed Quaternary maps in the northern part of the valley.

Older Quaternary gravel deposits were mapped along the west flank of the Sangre de Cristo Range (Scott and others, 1978) and along the east flank of the Cochetopa Hills and La Garita Mountains (Tweto and others, 1976; Steven and others, 1974), but no consensus is obvious among the authors regarding the age and origin of these deposits. Tweto and others (1976) considered some of these old gravels and alluvial deposits to be pre–Bull Lake in age, and other deposits were considered to be till of pre–Bull Lake age. Steven and others (1974) grouped old Quaternary gravel deposits with older Cenozoic gravel deposits. Scott and others (1978) showed pre–Bull Lake fans composed of pebbly gravel in the Villa Grove area.

McCalpin (1982) identified pre–Bull Lake Quaternary deposits in his work on neotectonics of the northern San Luis Valley. There, the pre–Bull Lake deposits range from as old as 700,000 yr B.P. to as young as 140,000 to 120,000 yr B.P. Some of the pre–Bull Lake deposits may be of glacial origin, inasmuch as alpine glacial events have been identified elsewhere in the Rocky Mountains (Scott and others, 1978; McCalpin, 1982), and Scott and others (1978) related several dissected alluvial terraces to continental glacial events that affected the alpine terrains.

In Saguache County, mainly in the mountainous areas of the Sangre de Cristo Range and La Garita Mountains, glacial and periglacial deposits include till, rock glaciers, and lacustrine deposits. Along the mountain fronts, till and outwash fans are common (Johnson, 1969; Tweto and others, 1976; Steven and others, 1974; Scott and others, 1978). Till is composed of unsorted, nonstratified to poorly stratified, boulder gravel in a pebbly, sandy, and silty matrix. The composition of the till is closely related to the lithology of the rocks in the glacial valley. Rock glaciers are composed of unsorted, angular boulders derived from adjacent rock outcrops. Some rock glaciers are ice cored, whereas others contain a sandy, silty, and pebbly matrix at depth. Lacustrine deposits are dominated by sand, silt, and clay, which are laminated or massive and commonly rich in organic material. Glacial outwash is stratified boulder and cobble conglomerate in a pebbly, sandy, and silty matrix interbedded with crossbedded sand and laminated silt. Outwash fans were formed in a braided-stream regime. The size of clastic material depends mainly on the proximity to the glacial front and the slope of the outwash fan. According to the standard Rocky Mountain chronology (McCalpin, 1982), the Bull Lake glacial period started at about 155,000 yr B.P. and ended at about 125,000 yr B.P. Deposits from the Bull Lake glacial event are generally located along the fringes of the younger deposits of the Pinedale glacial event (23,000–12,000 yr B.P.), and the glacial landforms are more subdued than those of the younger event. The Bull Lake glacial event was separated from the younger Pinedale glacial event by an interglacial period. The Pinedale glacial event left the most prominent glacial deposits in the mountains of Saguache County, and most of the high parts of the mountain ranges were scoured by alpine glaciers that left terminal and lateral moraines in many of the U-shaped canyons of the Sangre de Cristo Range and La Garita Mountains. In the eastern part of the county, outwash fans are located at the mouths of canyons that drain to the west, and outwash deposits extend into the flats of the San Luis Valley. In the La Garita Mountains, till and outwash extend several miles northeastward, along Saguache Creek; the deposits moved down canyons from the topographic divide that forms the southwestern boundary of Saguache County.

Eolian deposits form prominent dunes, dune fields, and sheet sands in the southeastern part of Saguache County in the region of the Great Sand Dunes National Park and Preserve. Eolian deposits reflect intermittent sand transport as alpine glaciers retreated in nearby mountain ranges, which resulted in lower groundwater levels. Johnson (1969) distinguished three ages of eolian units based on dune morphology, and these are the units shown on his geologic map: (1) Pleistocene parabolic dunes; (2) older Holocene parabolic dunes; and (3) younger Holocene barchan dunes, transverse dunes, and parabolic dunes, reversing dunes, plus gravel lag deposits in deflation pits. Carbon-14 ages permitted Madole (2004) to separate four ages of the eolian deposits, including dunes, sheet sands, and dune fields, in the region of Great Sand Dunes National Park and Preserve (**fig. 33**). The ages of the eolian units are independent of morphology, and the following summary is from Madole (2004):

1. The oldest dunes, of Pleistocene age, underlie the three younger eolian deposits and are exposed only in stream banks and blowouts; Pleistocene mammal bones and Folsom and Clovis artifacts are found in this oldest sand deposit. Shafer (1989) reported a ^{14}C age of 11,060 ± 160 yr B.P. for peaty sediment about 20 in. beneath the floor of Head Lake.

2. The next younger eolian deposit forms sand sheets and subdued broad dunes that are 20 to 30 ft high. These sand sheets and dunes are composed of fine- to medium-grained sand that is calcareous in the upper part. Surface soil is weakly developed. M.A. Jodry (written communication to R.F. Madole, 2001) determined ^{14}C ages of 6,640 to 6,300 cal yr B.P. and 4,830 to 4,540 and 4,990 to 4,840 cal yr B.P. from charcoal found in hearths and a pit house. [Ages with the designation “cal” are tree-ring–calibrated ages determined from conventional ^{14}C ages (Madole, 2004)]. A poorly constrained minimum age for the end of deposition of this sand tract is a ^{14}C age of alluvium at 2,980 to 2,760 cal yr B.P.

3. Most of the next younger eolian deposit is brown, noncalcareous, very fine to medium-grained sand that forms high, compound parabolic dunes and elongate, simple parabolic dunes. Soils are absent or poorly developed on these dunes. Radiocarbon studies of sediment beneath the dunes give ^{14}C ages of 928 ± 45 yr B.P. and 920 ± 60 yr B.P. The ^{14}C age of the 920 ± 60 yr B.P. age gives a calibrated age of 950–700 cal yr B.P., and Madole (2004) concluded that the dunes are likely to postdate 700 yr B.P.

4. The youngest sand deposit has mobilized within historic time. These dunes are composed of pale-brown to brown, noncalcareous fine-grained sand. This sand forms the surface of the dunes in most of the Great Sand Dunes National Park and Preserve. Most of the subdued relief on the floor of the San Luis Valley is the product of wind erosion and deposition (Madole, 2004).

Landslide deposits probably span the period from the latter part of Quaternary time to the present, but landslides older than the Bull Lake glacial event are probably not recognizable because the uneven surface morphology typical of landslides would be muted. In the Sangre de Cristo Range, landslides are rare

Figure 33. Great Sand Dunes National Park and Preserve is set against the Sangre de Cristo Mountains. (photos from Robert Kirkham and Larry Scott).

(Johnson, 1969; Scott and others, 1978; Lindsey and others, 1985d, 1986b; Lindsey and Soulliere, 1987; Johnson and others, 1989), but in the La Garita Mountains and Cochetopa Hills, where poorly welded tuffs and other volcanic ash deposits are unstable, mudflows, cohesive block slip, and debris flows are common. In the La Garita Mountains, volcanic units such as the Fish Canyon Tuff, Wason Park Tuff, Rat Creek Tuff, and Nelson Mountain Tuff yield to downslope mass movement. In the Cochetopa Hills, early intermediate-composition volcanic rocks, such as poorly consolidated tuffs and ash, provide unstable materials that respond to downslope mass movement.

Alluvium is common in modern streams and rivers in mountainous areas and in the San Luis Valley. Alluvium is composed of unconsolidated, stratified and poorly stratified, pebble-to-boulder gravel, and matrix-supported gravel in which the matrix is composed of sand and silt. Interbedded layers of cross-bedded sand and laminated silt and clay form laterally discontinuous layers in the gravel.

The structural geology of Saguache County is naturally divisible into three main provinces, each of which has a distinctive structural history and pattern of faults and folds. (1) The Sangre de Cristo Range forms the easternmost structural province in Saguache County, and this province is characterized by a thrust-faulted terrane that has tight, isoclinal folds between thrust faults. (2) The San Luis Valley structural province bounds the Sangre de Cristo structural province on the west, and the Sangre de Cristo fault separates the two provinces. The San Luis Valley is a structural basin within part of the north-trending Rio Grande rift system. The basin is characterized by steep normal faults and gently dipping Cenozoic and Quaternary deposits; the hinge zone is on the west side of the valley. (3) The westernmost structural province in the county is the block-faulted Paleoproterozoic terrane and the overlying San Juan volcanic field, which is characterized by volcanic edifices that are cut by step-graben and half-graben systems and by the circular and arcuate normal faults that bound the calderas.

SANGRE DE CRISTO STRUCTURAL PROVINCE

The Sangre de Cristo structural province (**fig. 34**) is dominated by steeply west dipping thrust faults and tight, isoclinal folds. This province is bounded on the west by the Sangre de Cristo fault, a steeply west dipping normal fault along which the San Luis Valley was down-dropped. The eastern boundary of the province is on the western side of the Wet Mountain Valley (fig. 1), which is formed in a graben (fig. 34). However, the crest of the Sangre de Cristo Range forms a political (county) boundary to the province. According to Lindsey and others (1986a), the Uncompahgre uplift (**fig. 35**) was thrust eastward against basin fill of the Central Colorado trough during Late Cretaceous to Eocene time to form a fold-and-thrust terrane that involved the length of the Sangre de Cristo Range. During Late Cretaceous and Eocene time, rocks in the Sangre de Cristo Range were subjected to high heat flow during burial and compressional tectonics, and at about 19 Ma (Miocene time), the rocks cooled abruptly, probably in response to uplift and erosion during early formation of the Rio Grande rift (Lindsey and others, 1986a).

Faults

Thrust faults are the dominant structures in the Sangre de Cristo Range, and most of these faults are steep- to medium-angle reverse faults that dip to the west and flatten at depth (Lindsey and others, 1983). Total shortening is about 5 mi in the northern part of the range and about 8.6 mi near the Great Sand Dunes National Park and Preserve (Lindsey and others, 1983). The main thrust faults are shown on a simplified structural map of the Sangre de Cristo Range (**fig. 36**) and on accompanying cross sections (**fig. 37**). The Deadman Creek thrust fault juxtaposes Paleoproterozoic gneiss against Paleoproterozoic quartz monzonite and overlying lower Paleozoic rocks. A cross section that crosses the Deadman Creek thrust fault (fig. 37IV) shows that the thrust is folded. The Crestone thrust fault superposes a plate of Paleoproterozoic gneiss and quartz monzonite on the Crestone Conglomerate Member, Sangre de Cristo Formation, and Minturn Formation (Pennsylvanian and Permian strata; see fig. 3). The Crestone thrust fault is a complex zone of imbricate thrust strands that dip to the west at angles as low as 35° (figs. 37I and 37II) (Lindsey and others, 1986a). Farther to the east, and partly east of Saguache County, is the Spread Eagle Peak thrust fault, along which rocks of the Crestone Conglomerate Member, upper Sangre de Cristo Formation, and Minturn Formation were emplaced over autochthonous rocks of the sandstone facies of the upper Sangre de Cristo Formation (fig. 37III). Scattered through the Sangre de Cristo Range are other less continuous thrust faults, such as the Sand Creek thrust fault (fig. 37IV). Along this fault, located in the southwestern part of the range, Paleoproterozoic gneiss has been emplaced over the Sangre de Cristo Formation.

Folds

Compressional tectonics that dominated in the Sangre de Cristo Range during Late Cretaceous to Eocene time formed large-scale folds in sedimentary rocks on the upper plates of thrust faults (fig. 36). In the south part of the range, the Deadman Creek thrust fault is folded into an asymmetric, east-verging anticline (fig. 37IV). East of the Deadman Creek thrust fault, above the Sand Creek thrust fault, the Sand Creek syncline is

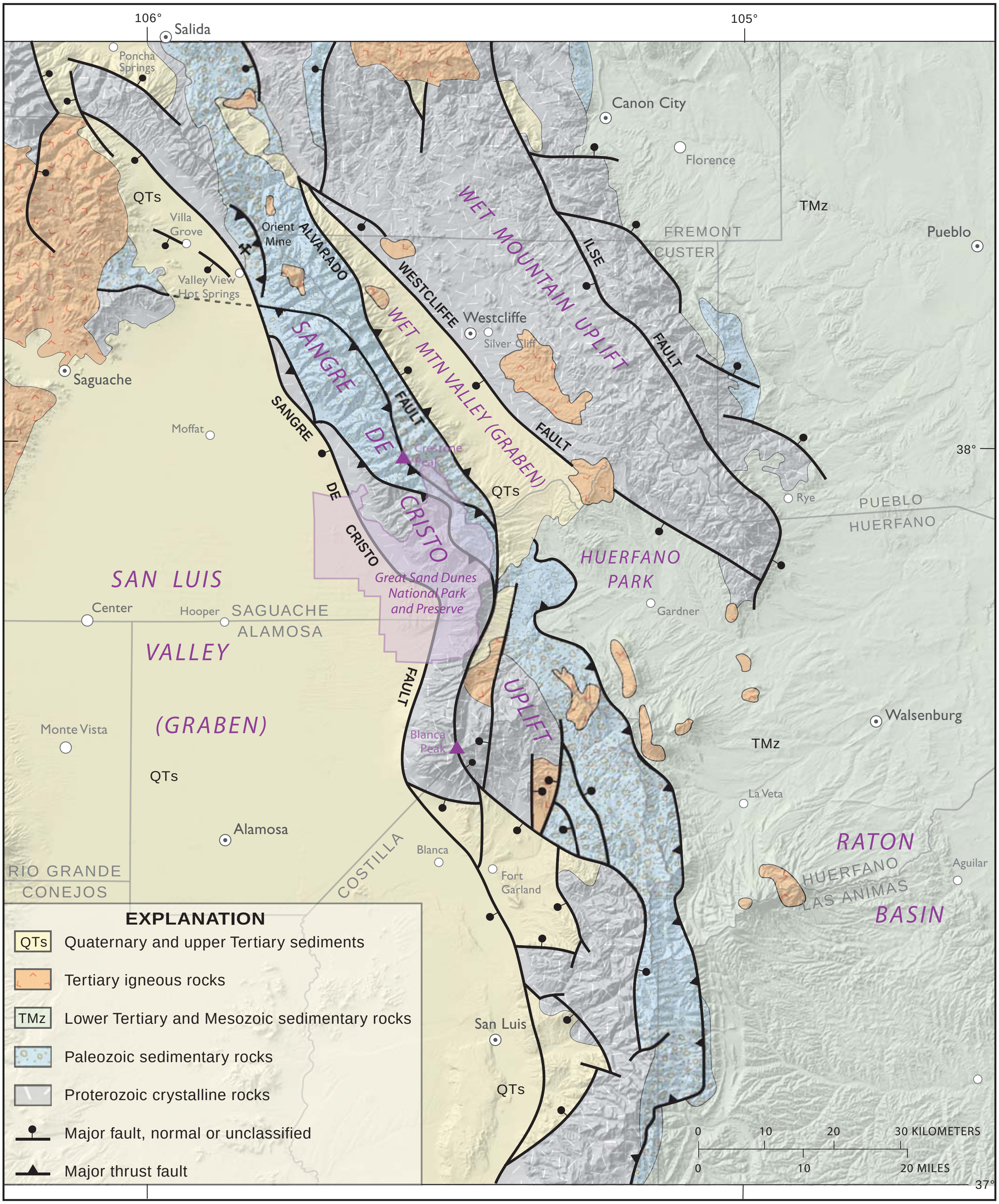


Figure 34. Sangre de Cristo structural province, northern San Luis Valley (after McCalpin, 1982 and Balleweg, 1990).

a broad, open fold in the Crestone Conglomerate Member (Lindsey and others, 1986b). Farther to the north, the upper plate of the Spread Eagle Peak thrust contains the Gibson Peak syncline, which is a broad, open fold in the upper part of the Sangre de Cristo Formation, and the Cotton Lake anticline and an unnamed syncline to the east, which are tight, east-verging folds in the lower Minturn Formation (Lindsey and others, 1985d). In the autochthon along the east edge of the Saguache County boundary, between the Spread Eagle Peak thrust fault and the Alvarado fault system, an unnamed set of folds form (from west to east) an anticline-syncline-anticline set of broad open folds in the upper Sangre de Cristo Formation (Lindsey and others, 1984). North of the Spread Eagle Peak thrust fault is a syncline-anticline pair that folds the Minturn Formation: The west limb of the isoclinal Nipple Mountain syncline is overturned to the east, and the Rito Alto anticline, which is east of the Nipple Mountain syncline, is a tight, upright structure (Lindsey and others, 1985c).

Thermal History and uplift of the Sangre de Cristo Range

Lindsey and others (1986a) determined that the rocks of the Sangre de Cristo Range were heated initially during burial in Middle Pennsylvanian time, and increased heat flow continued during Late Cretaceous and Eocene thrust faulting. Uplift and erosion that began in Eocene time and accelerated in Oligocene and Miocene time resulted in gradual cooling of the thrust-faulted terrane. The following interpretation of the thermal history of the Sangre de Cristo Range is summarized from Lindsey and others (1986a).
Sawatch Quartzite.

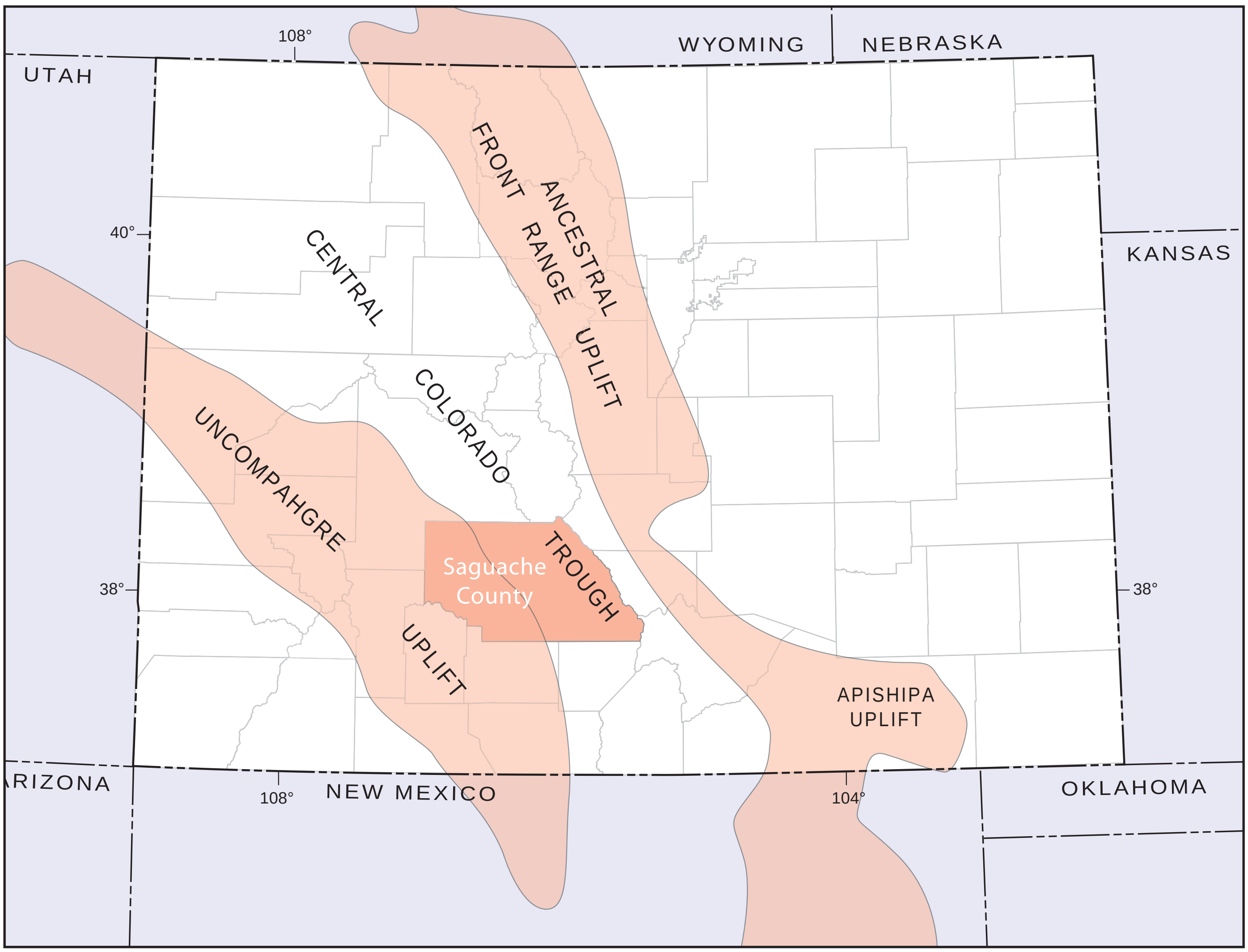


Figure 35. Regional map showing Middle Pennsylvanian to Early Permian depositional troughs and highlands in central Colorado (from Lindsey and others, 1986a, p. 1140).

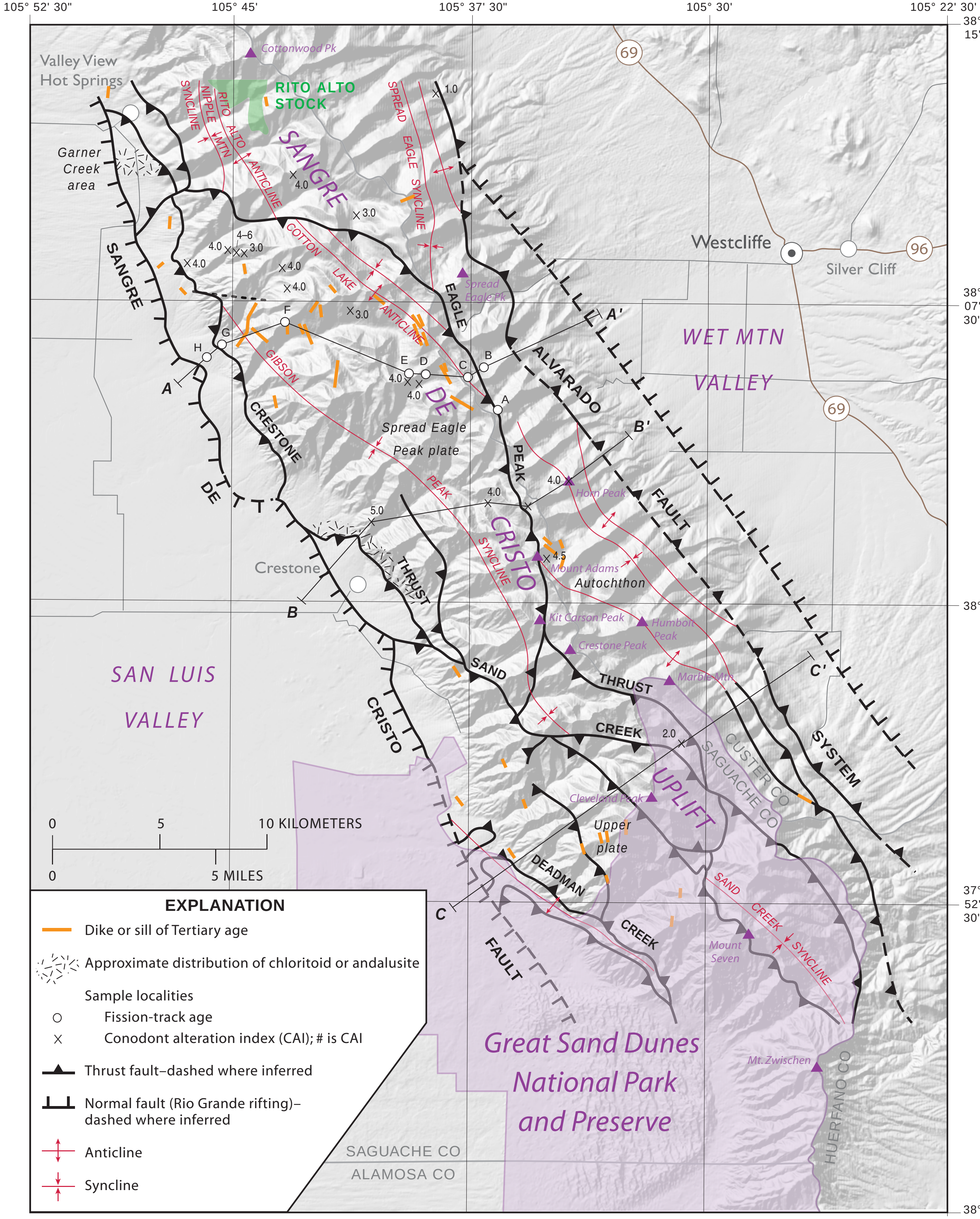


Figure 36. Sketch map showing main thrust faults and folds in Sangre de Cristo Range (after Lindsey and others, 1986a).

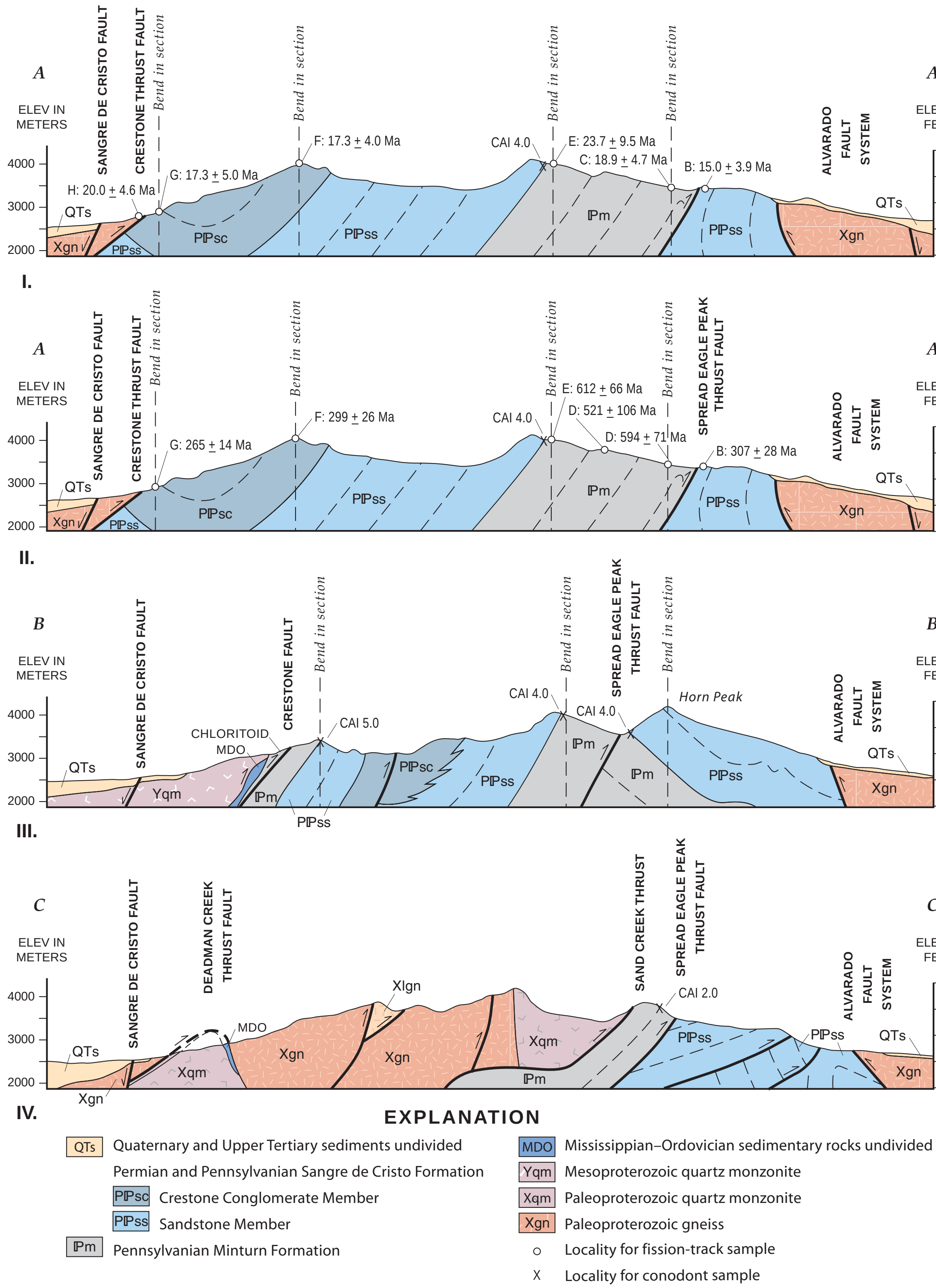


Figure 37. Cross sections showing principal thrusts in Sangre de Cristo Range. Sections show structural and stratigraphic positions of conodont and fission-track samples.

- **I.,** Section A–A', showing apatite dates by the fission-track method and conodont locality at the top of the Minturn Formation.
- **II.,** Section A–A', showing zircon dates by the fission-track method.
- **III.,** Section B–B', showing position of chloritoid and conodont locality near Crestone thrust fault and conodont localities near the Spread Eagle Peak thrust fault.
- **IV.,** Section C–C', showing upper thrust plate and conodont locality at Marble Mountain. Dikes not shown on sections; CAI—conodont alteration index. Location of lines shown in Figure 36 (After Lindsey et al., 1986a).

Paleozoic rocks in the northern part of the Sangre de Cristo Range contain randomly oriented muscovite and chlorite, and these mica minerals grew in the rock after compaction and lithification. Lindsey and others (1986a) termed these new mica minerals as "metamorphic" in origin, although the ~200° C temperature suggested for crystallization of new muscovite and chlorite is well within the temperature range of diagenesis. No shallow intrusive bodies are known from the area that contains the new muscovite and chlorite. Interpretation of alteration data from conodonts in the Spread Eagle Peak thrust plate in the northern part of the range suggest a conodont alteration index (CAI) of 4.0, which gives a temperature range of 190° to 300° C (figs. 36 and 37). If heating lasted from Eocene to early Miocene time (30 m.y.), the CAI is estimated at ~200° C. Other localities have CAI values of ~130° C, ~310° C, and ~70° C for the same 30-m.y.-long period. The high temperatures are from the west side of the range below Late Cretaceous thrust faults, and the lower temperatures are from the eastern part of the Sangre de Cristo Range where rocks were probably not buried deeply. Heating of rocks in the Sangre de Cristo Range was followed by rapid cooling during uplift in early Miocene time. Fission-track data from apatite (figs. 36 and 37) suggest that rocks cooled abruptly below 120° C, the blocking temperature for apatite, at about 19 Ma (early Miocene).

SAN LUIS VALLEY STRUCTURAL PROVINCE

In the central part of Saguache County, the San Luis Valley was down-dropped synchronously with the uplift of the Sangre de Cristo Range during late Tertiary time. The San Luis Valley is a complex rift basin that is hinged on the west side of the valley, and the east side of the valley is bounded by the Sangre de Cristo fault, which also bounds the east side of the Rio Grande rift in this region.

The modern San Luis Valley structural province began development before the Rio Grande rift started extensional subsidence at about 27.4 Ma (Brister and Gries, 1994; Lindsey and others, 1983). Interpretations of seismic data and of regional geologic relationships by Brister and Gries (1994) showed that a sequence of welded tuffs from the San Juan calderas occupies the San Luis sedimentary basin at depth. Brister and McIntosh (2004) dated single crystals of sanidine and biotite from samples of ash-flow tuffs in well cuttings in the northern San Luis sedimentary basin and confirmed the presence of the 32.9 Ma upper Bonanza Tuff (Gribbles Park Tuff) through the 27.3 Ma Carpenter Ridge Tuff at depth in the basin. They also confirmed the thinning of intermediate-composition lavas (Conejos Formation and possibly Rawley Andesite) from the Monte Vista graben (**fig. 38**) of the western San Luis sedimentary basin to the eastern half of the San Luis sedimentary basin.

Brister and Gries (1994) used an isochron map of contoured seismic two-way traveltime intervals to show the pre–Rio Grande rift structure in the southern part of the county (fig. 38). A series of faults forms a graben in the central part of the San Luis Valley where the thickest accumulation of tuffs and sediment is found. Similarly, Brister and Gries (1994) mapped faults that formed during extension of the Rio Grande rift after caldera eruptions ceased (**fig. 39**). They interpreted seismic and drill-hole data from a seismic line just south of the southern boundary of Saguache County (**fig. 40**), and they mapped the Baca half graben in the eastern part of the valley, the Alamosa horst in the middle part of the valley, and the Monte Vista graben in the western part of the valley. Kluth and Schaftenaar (1994) showed these structures to extend northward into Saguache County (**fig. 41**). The Baca half graben is hinged on the west. The half graben was down-dropped more than 9,800 ft along the Sangre de Cristo fault on the east, which resulted in the accumulation of a thick, westward-thinning wedge of Santa Fe Group above welded tuffs of the San Juan volcanic field. Several small faults cut Oligocene ash-flow tuffs, the Santa Fe Group, and Quaternary alluvium; this observation records active extensional tectonics from Oligocene to Quaternary time. The Monte Vista graben is hinged on the east and is bounded on the west by several faults along which blocks were down-dropped. A large-separation bounding fault on the west side of the graben, such as the Sangre de Cristo fault, is absent in the Monte Vista graben. Faults in the Monte Vista graben cut the Eocene Blanco Basin Formation and offset ash-flow tuffs of the San Juan volcanic field.

Watkins (1996) described a northwest-trending, west-dipping, low-angle normal fault along the northeastern margin of the San Luis sedimentary basin in the Baca Land Grant area. The fault is marked by a thin layer of generally green-gray clay gouge and is interpreted as a detachment fault linked to early stages of the formation of the Rio Grande rift and San Luis Valley. The Baca 1 and Baca 2 wells encountered highly faulted Mancos Shale in the hanging wall of the detachment fault and hydrothermally altered Proterozoic gneiss in the footwall (fig. 4 in Watkins, 1996). Erosional remnants of the detachment footwall breccia are exposed at several locations along the west flank of the Sangre de Cristo Range (fig. 3 in Watkins, 1996). Benson and Jones (1996) described a similar detachment fault and hydrothermally altered breccia along the eastern margin of the valley in the area of the San Luis gold mine in Costilla County.

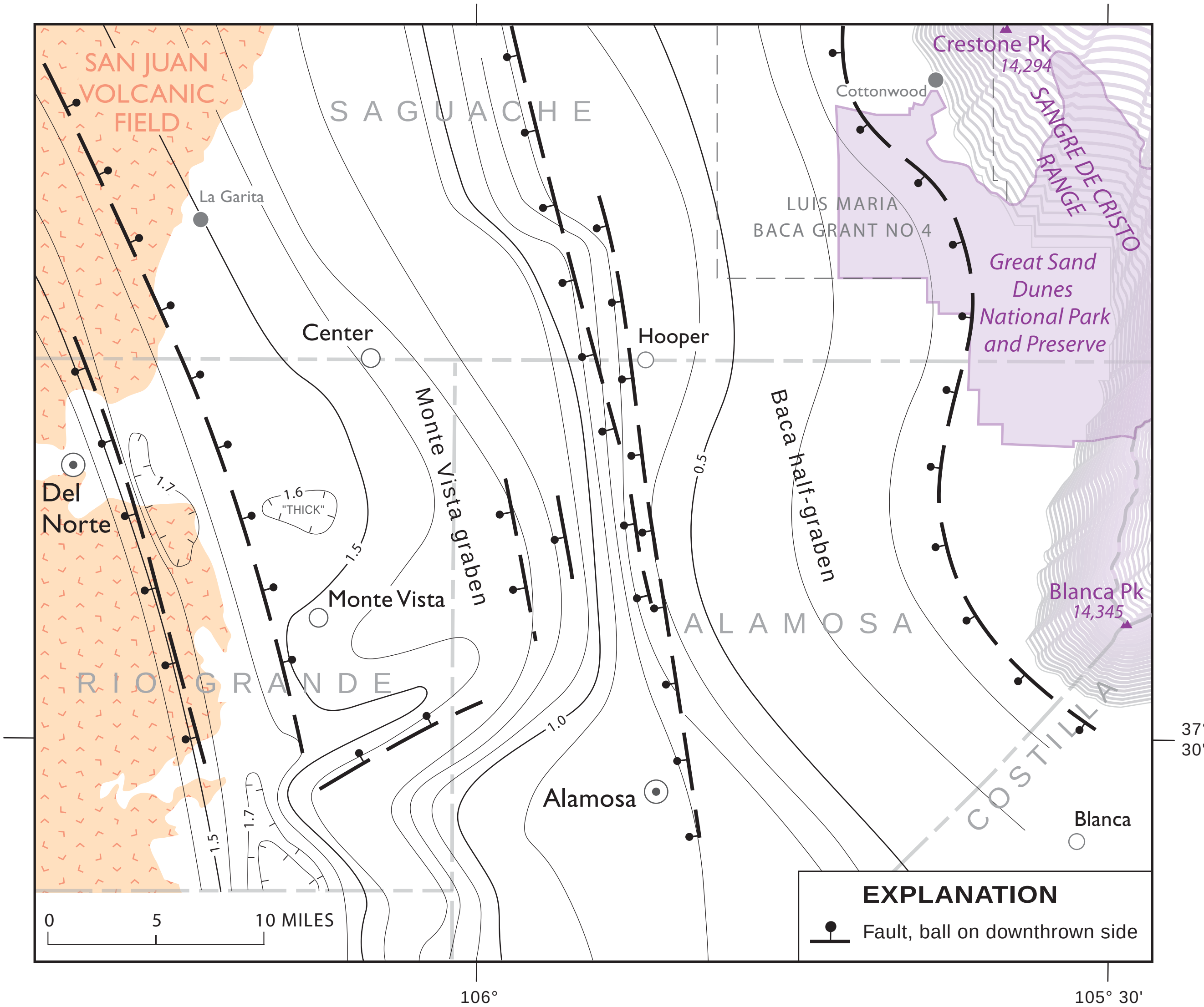


Figure 38. Pre–Rio Grande rift structure of the northern San Luis Valley. Isochron map is contoured two-way traveltime interval between the top of Oligocene ash-flow tuff reflections and the top of the Precambrian reflections. Fault zones along which prerift normal displacement has been demonstrated are shown by a dashed line with ball and bar on the downthrown side. Contour interval is 0.1 s (Brister and Gries, 1994).

Fault segments in two fault zones have been active during Quaternary time in the southeastern part of Saguache County, and detailed study by McCalpin (1982) of neotectonics along the east side of the San Luis Valley demonstrated multiple periods of slip on these fault zones. The following summary of neotectonics in Saguache County is from the comprehensive report by McCalpin (1982). The two main young fault zones in the northern part of the San Luis Valley are the Villa Grove and Sangre de Cristo fault zones. The Villa Grove fault zone (**fig. 42**) is composed of about 40 discontinuous, parallel scarps that trend northwest between the town of Villa Grove and Valley View Hot Springs. The fault zone is about 6 mi long and between 1,500 and 4,000 ft wide. Most fault scarps face toward the southwest, and interpretation of seismic data suggests that the scarps are the surface expression of a buried graben. Single seismic events have had displacements of between 2.5 and 4.6 ft, and total displacements on some scarp segments are as much as 16 ft. According to McCalpin (1982), some segments of the Villa Grove fault zone have been recurrently active from about 300,000 yr B.P. to about 80,000 to 60,000 yr B.P., and the recurrence interval is about 60,000 to 100,000yr. The magnitude of earthquakes that caused these scarps has been estimated at 6.6 to 7.0. Earthquakes of this intensity, therefore, are capable of occurring at 60,000- to 100,000-yr intervals along the Villa Grove fault zone. The northern Sangre de Cristo fault is one of three faults in Colorado that are included in the U.S. Geological Survey National Earthquake Hazard Map.

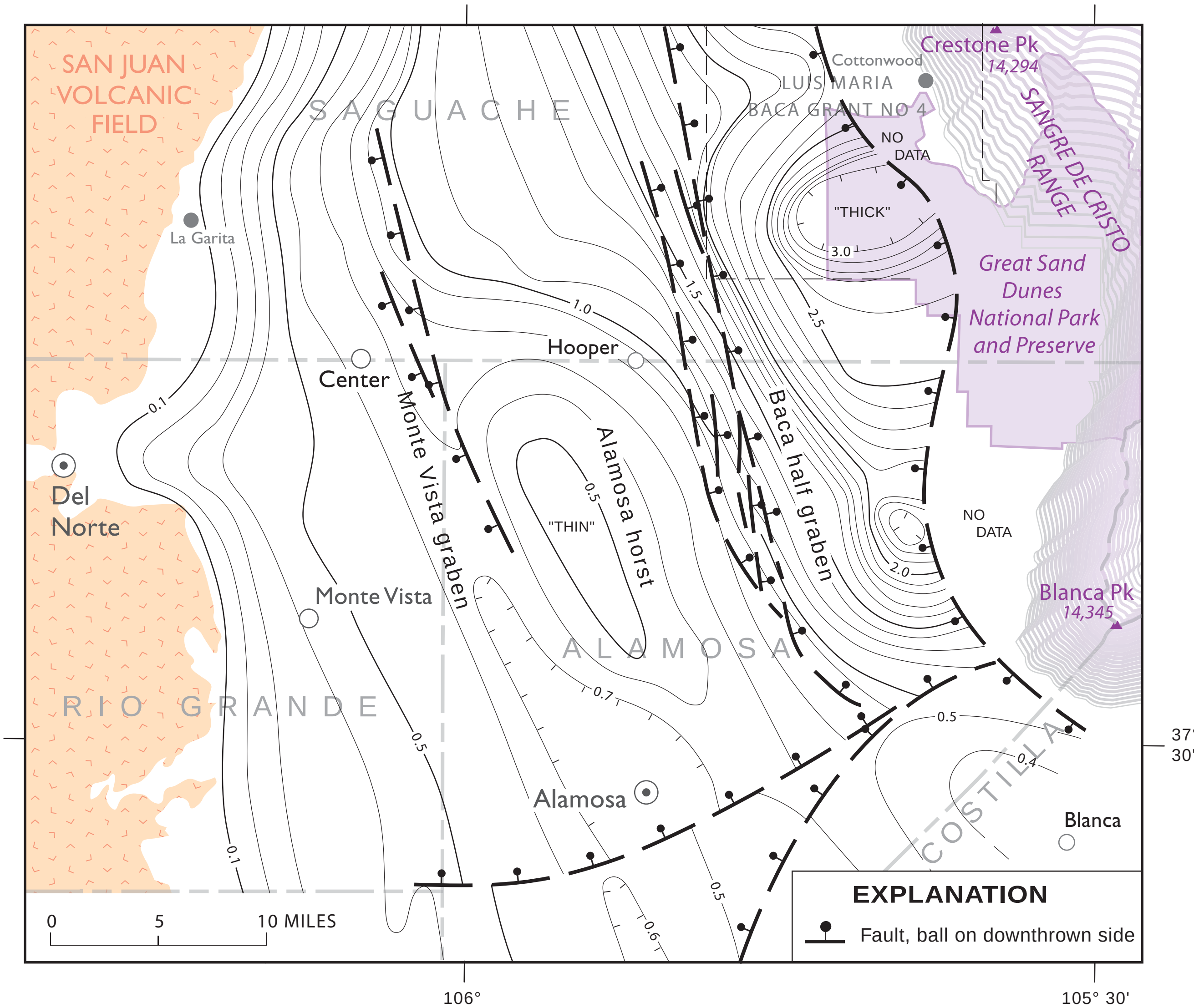


Figure 39. Syn–Rio Grande rift structure of the northern San Luis Valley. Isochron map is contoured two-way traveltime interval between surface datum and the top of Oligocene ash-flow tuff reflections. Fault zones along which synrift normal displacement has been demonstrated are shown by a dashed line with ball and bar on the downthrown side. Contour interval is 0.1 s (Brister and Gries, 1994).

The Sangre de Cristo fault zone is a range-front fault (**fig. 43**) that separates the Sangre de Cristo Range from the northern part of the San Luis Valley. The fault zone is composed of numerous fault segments along the range front from Alder at the north end to southwest of Blanca Peak at the south end (fig. 1). The fault zone is represented by numerous scarps along the range front that are 800 to 10,500 ft long; the blocks are dominantly down on the west. Cumulative separation between the Sangre de Cristo Range and the San Luis Valley caused by normal displacement along the fault zone is as much as 23,000 ft. Displacements associated with single seismic events along the fault zone range between 3 and 7.5 ft on some fault scarps. Faults have been recurrently active in the Sangre de Cristo fault zone for the past 400,000 yr. Segments of the fault zone exhibit different activity patterns; during the past 120,000 yr, scarps in the northern part of the fault zone have a recurrence interval from 5,000 to 11,700 yr, but scarps in the southern part of the fault zone show recurrence intervals of 25,000 yr. McCalpin (1982) indicated that earthquakes of magnitude 6.8 to 7.4 occurred along the Sangre de Cristo fault zone and that the recurrence interval averaged 25,000 to 30,000 yr, although some seismic events may have occurred within as short an interval as 2,500 yr. Historical records and analysis of seismograms have revealed no earthquakes in the northern San Luis Valley region since 1870 (McCalpin, 1982).

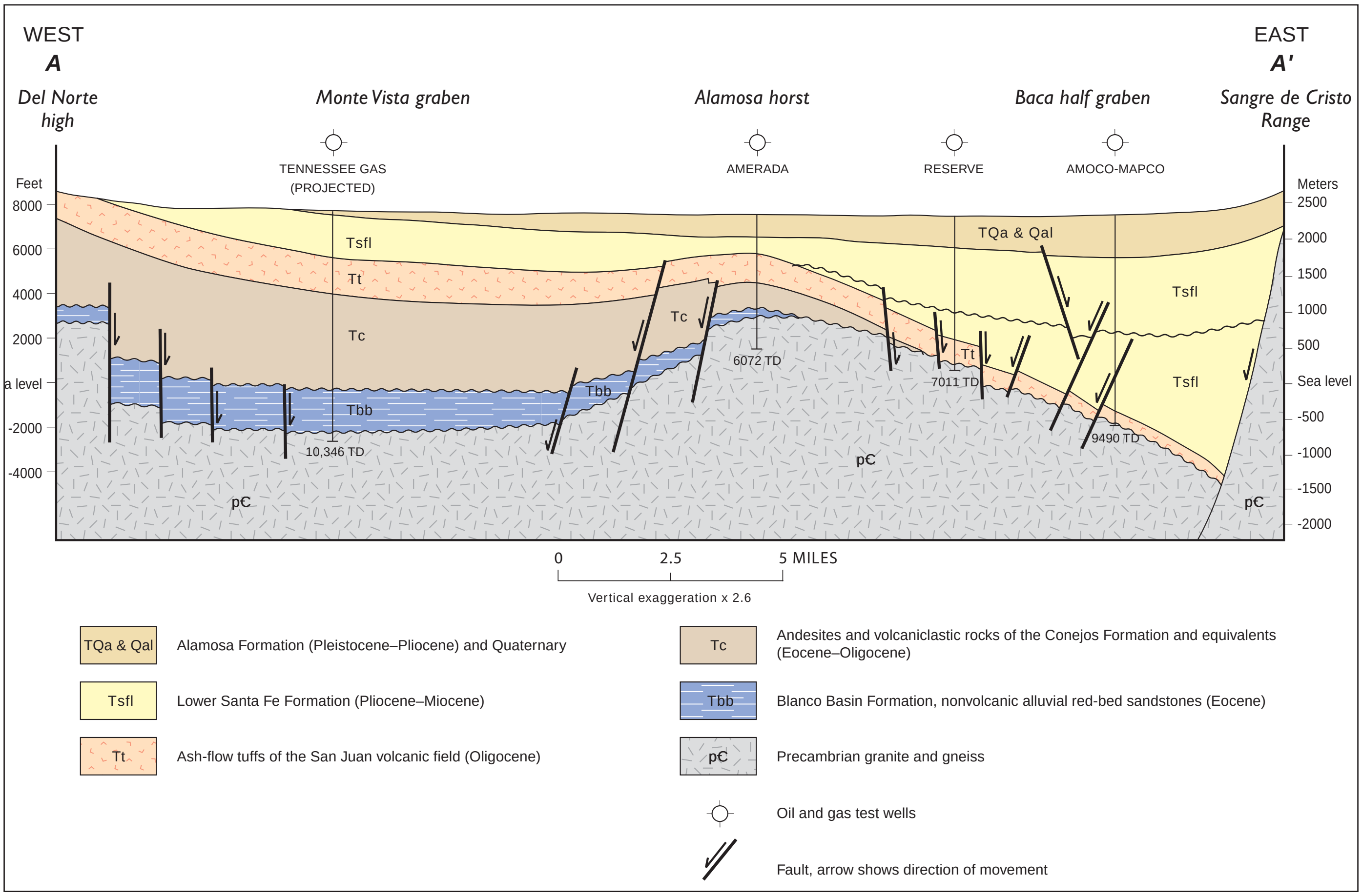


Figure 40. Interpretive cross section across northern part of San Luis Valley; location of section indicated in Figure 41. TD, total depth of well in feet (Brister and Gries, 1994).

SAN JUAN VOLCANIC FIELD AND CENTRAL COLORADO VOLCANIC FIELD STRUCTURAL PROVINCE

The San Juan volcanic field defines a unique structural province in the western part of Saguache County. The structural grain of the underlying Proterozoic and Paleozoic sequence projects upward into the volcanic edifice along the eastern edge of the volcanic field where the volcanic rocks are thin. In the Proterozoic and Paleozoic terrane of the northern Sangre de Cristo Range near Valley View Hot Springs (fig. 34), however, west-trending thrust faults juxtapose Mesoproterozoic rocks over Paleozoic rocks, and at least one such fault may be traced westward into the volcanic field structural province. All the same, this structural province on the west side of Saguache County is dominated by caldera structures and extensional block faults that form horsts and grabens in ash-flow tuffs and lava flows.

North of the town of Saguache, structures are mainly north- and northwest-striking normal faults along which (1) Proterozoic and Paleozoic rocks are displaced, (2) Tertiary volcanic rocks are brought into contact with Proterozoic metamorphic and igneous rocks, and (3) different units of Tertiary volcanic rocks from the San Juan volcanic field are offset (Tweto and others, 1976). Structures in the San Juan volcanic field are dominated by north- and northwest-striking normal faults on which there is no consistent pattern of displacement. No consistent pattern of displacement has been documented along the north- and northwest-striking normal faults.

The most prominent structures in the San Juan volcanic field are the circular and arcuate normal faults that define the edges of collapsed calderas, the linear faults and fractures that radiate from caldera centers or are related to resurgent domes, and the horst-and-graben sets related to extension of the Rio Grande rift. The Cochetopa Park caldera, located in the northwestern part of the county, has a prominent circular normal fault along the east boundary (Tweto and others, 1976). Steven and Lipman (1976) showed a system of arcuate normal faults that define the north and west limits of the Cochetopa Park caldera, and this caldera is about 15 mi wide (fig. 28). The Cochetopa Park caldera subsided as a “trap-door” on the southwestern side along a horseshoe-shaped fault (Steven

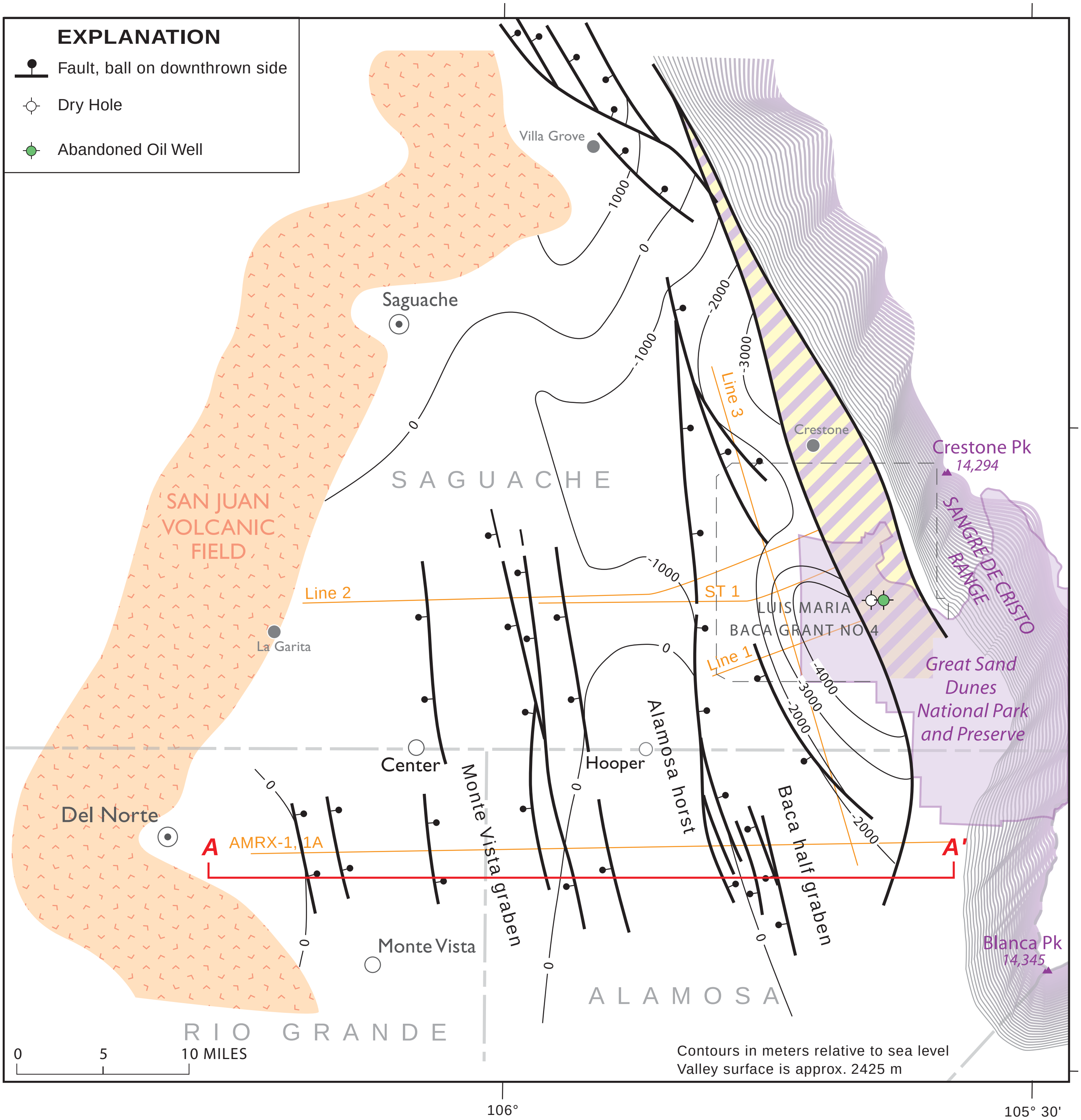


Figure 41. Structure contour map on top of the Precambrian basement surface in the northern Rio Grande rift. This map incorporates the interpretations of the seismic data and of published data (Gries, 1985b, Line AMRX-1, IA; Stoughton, 1977, Line ST-1; Davis and Stoughton, 1979). The diagonally ruled area on the west side of the Sangre de Cristo Mountains represents the Sangre de Cristo fault zone (Kluth and Schaftenaar, 1994).

and Lipman, 1976). The San Luis caldera is a generally circular structure, about 9 mi in width, which occupies the northwestern part of the La Garita caldera (fig. 28). The San Luis caldera developed during several periods of tumescence and collapse, and the main collapse event produced the Nelson Mountain Tuff. Only the eastern part of the San Luis caldera is in Saguache County. The La Garita caldera forms a prominent, mainly circular structure that is elongated in a north-south direction. The eastern half of this caldera is in the southwestern

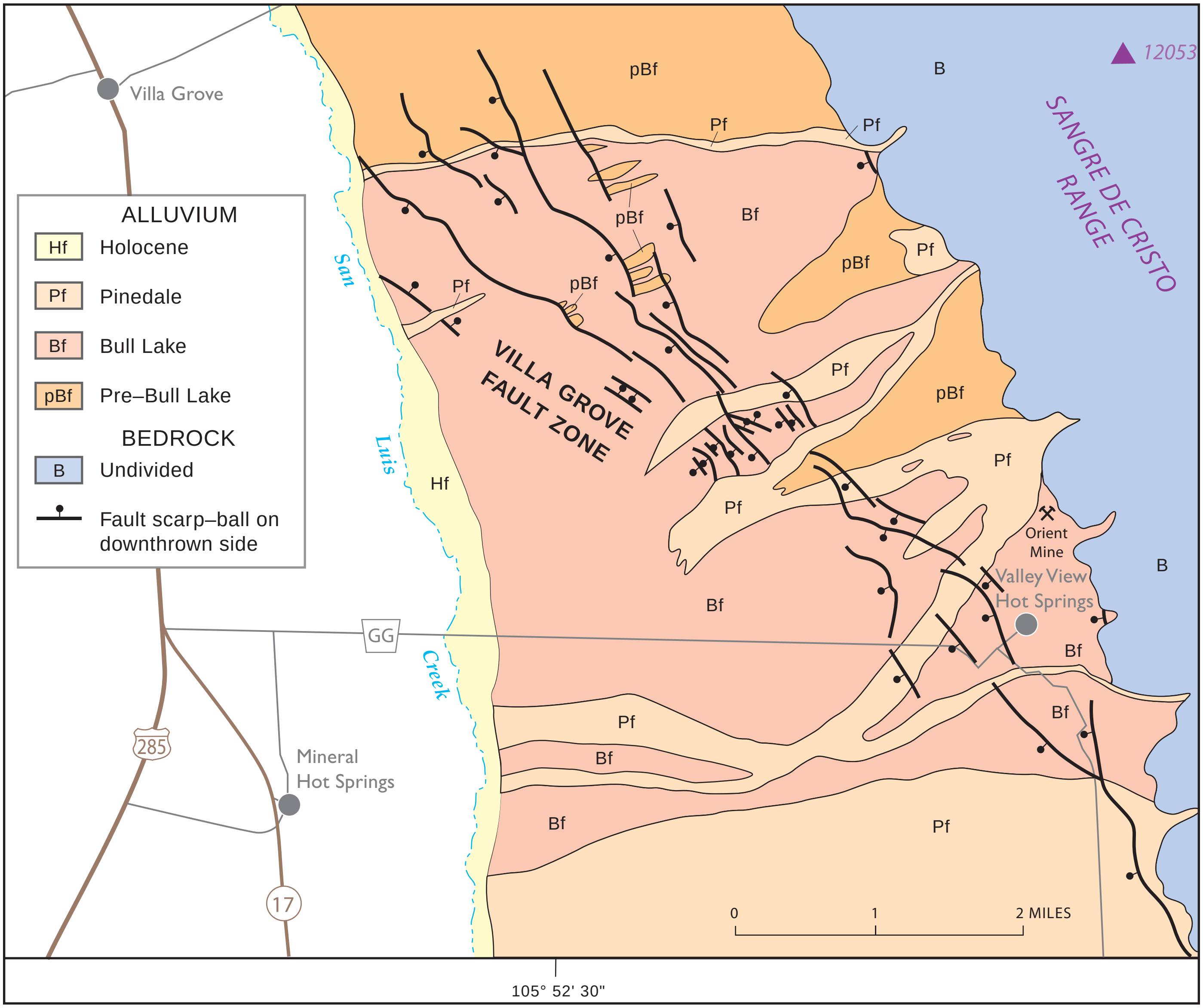


Figure 42. Villa Grove fault zone and Quaternary geology, northern San Luis Valley (McCalpin, 1982).

Figure 43. Aerial view of the Sangre de Cristo fault scarp, Butterfly Creek (pl. 1), 7 mi north of Villa Grove (image courtesy of Robert Kirkham).

part of Saguache County. The San Luis caldera later formed in the northwestern part of the La Garita caldera. The La Garita caldera (fig. 28) is about 21 mi by 45 mi across, which makes it the largest known caldera system in the world (Lipman, 2006). Rocks in the southeastern part of the San Juan volcanic field are offset along a prominent set of northwest-striking normal faults; these form a graben that Steven and Lipman (1976) considered an extension of the Rio Grande rift. Clusters of tightly packed horst-and-graben structures cut ash-flow tuffs of the San Juan volcanic field in the western and southwestern part of the county (Tweto and others, 1976; Steven and others, 1974).

Geophysical data by Karig (1965) and mapping by several authors (Burbank, 1932; Bridwell, 1968; Kouther, 1969; Mayhew, 1969; Perry, 1971; Marrs, 1973) show the location of the radial and arcuate normal-fault system of the Bonanza caldera. Figure 23 plots the major faults in the Bonanza area.

Karig (1965) collected gravity data from the Bonanza region, and his interpretation of those data indicated that the structure has a slightly elliptical outline that was about 10 mi in the longest direction. About 8,200 cu ft of low-density material filled the structure, possibly an intrusive complex that supplied the magma for the development of the Bonanza volcano. This geophysical evidence and structure contour maps of the contact between the Rawley Andesite and the Bonanza Tuff (**fig. 44**) depict a shallow-sided shield volcano with a collapsed caldera of about 4-km diameter at the apex. The caldera walls are steeper and the floor is deeper on the western side, which indicates a possible trap-door–style caldera floor (Varga and Smith, 1984).

In general, the volcanic units dip strongly to moderately to the west and to the south in the southern part of the district. Most of the fractures and fissures in the Bonanza district trend north-northwest to north-northeast and are probably related to dilatational stresses caused by the rotation of the caldera floor along a north-south axis during caldera collapse (Varga and Smith, 1984).

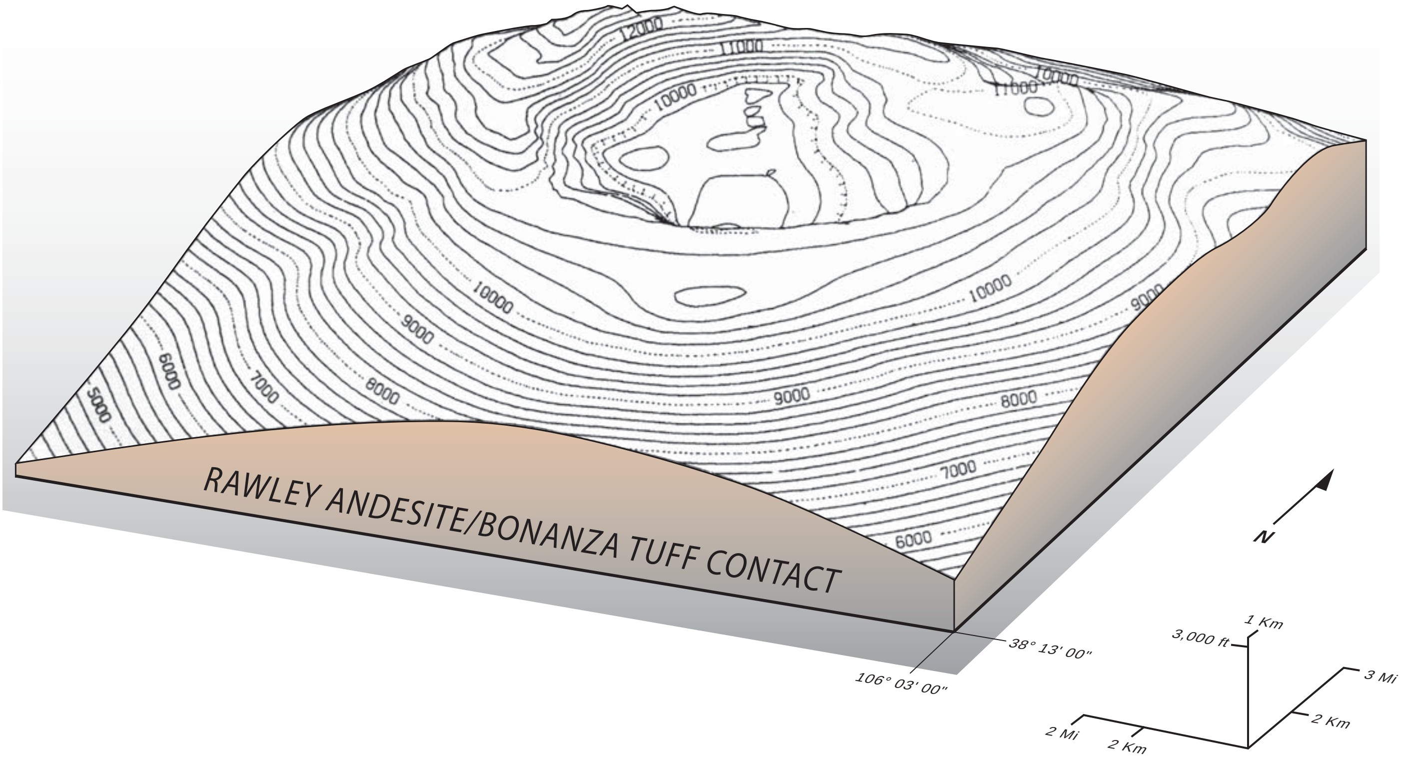


Figure 44. Computer-generated perspective showing the present-day configuration of the Rawley Andesite/Bonanza Tuff contact, with erosional effects removed. Contours (feet above sea level) were generated by interpolation between points where elevations of the contact are known. Note the generally conical shape of the contact, the large caldera in the middle of the Bonanza shield volcano, and the contrast in gradient between the steep western structural caldera margin and the relatively gently dipping eastern monoclinal caldera margin. The caldera floor dips about 10° to the west (Varga and Smith, 1984).

Precious and base metal mineral production in Saguache County is mostly from the Bonanza district. Production values for gold, silver, lead, copper, and zinc are illustrated in **figures 45 through 49**, respectively. The last reported metallic mineral (gold) production from Saguache County was in 1988 from Draco Mines' Crystal Hill Mine. The graphs and tables are derived from Henderson (1926), Vanderwilt (1947), Del Rio (1960), and the U.S. Bureau of Mines and U.S. Geological Survey Mineral Year Books. Plate 2 shows mineral occurances and mining districts of Saguache County.

BONANZA (KERBER CREEK) DISTRICT

In 1879, prospectors discovered the manganese and silver-lead mineralized outcrops along Kerber Creek, which cuts through the heart of the Bonanza district. By late 1880, the town of Bonanza had been settled, and mining, at least on a small scale, was proceeding. Silver was discovered at the outcrop of the Rawley Vein in 1880. The Rawley Mine, eventually the most productive mine of the district, was established in 1880 and was in production by 1882. Other important mines of the district that were productive during the early years include the Empress Josephine, Bonanza, Antoro (**fig. 50**), and Cocomongo mines.

By 1900, two concentrators had been built in the district. However, much of the ore produced in the district was sent directly to the mills and smelter at Leadville.

After the initial rush to the Bonanza district, miners found that the deeper ores contained less silver and more base metals. Many marginal mines and mills closed during the late 1880s and early 1890s. In 1893, the Federal Government stopped supporting the price

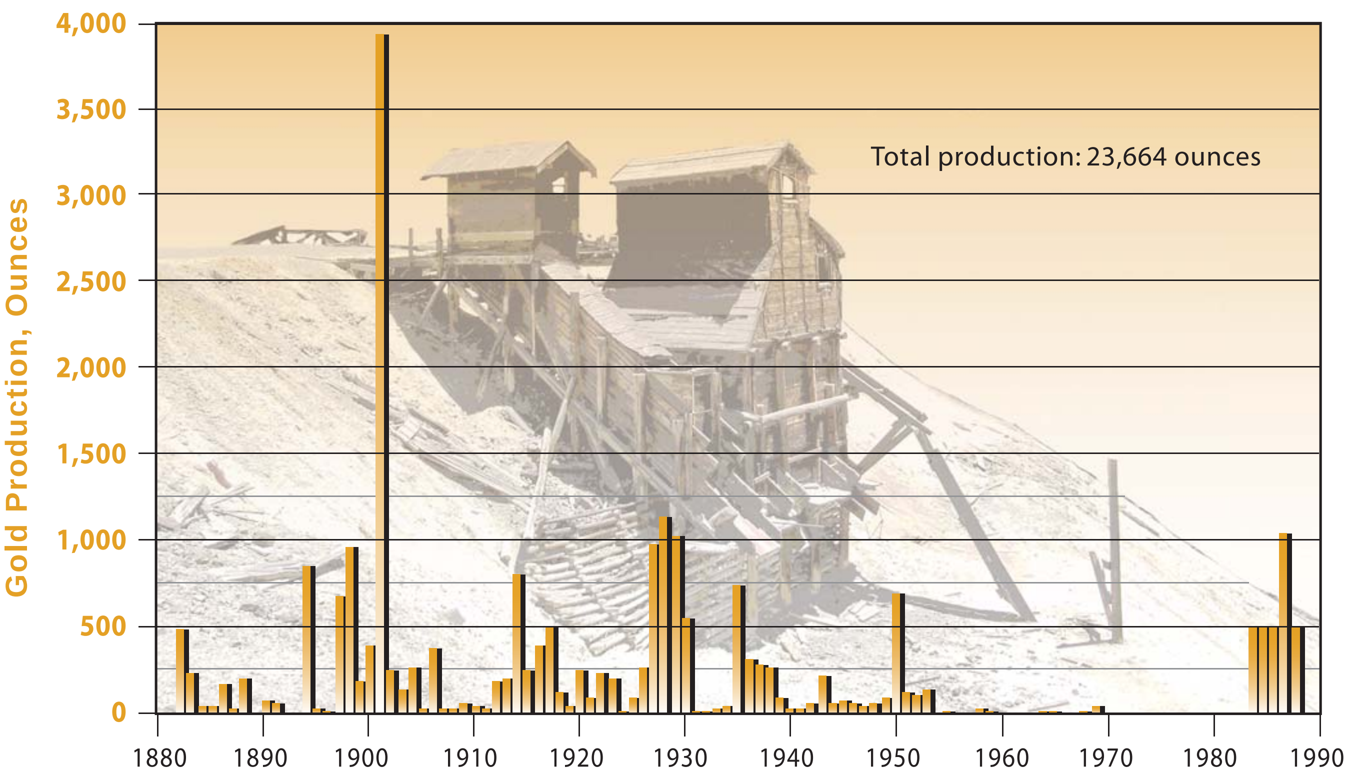


Figure 45. Gold production, Saguache County.

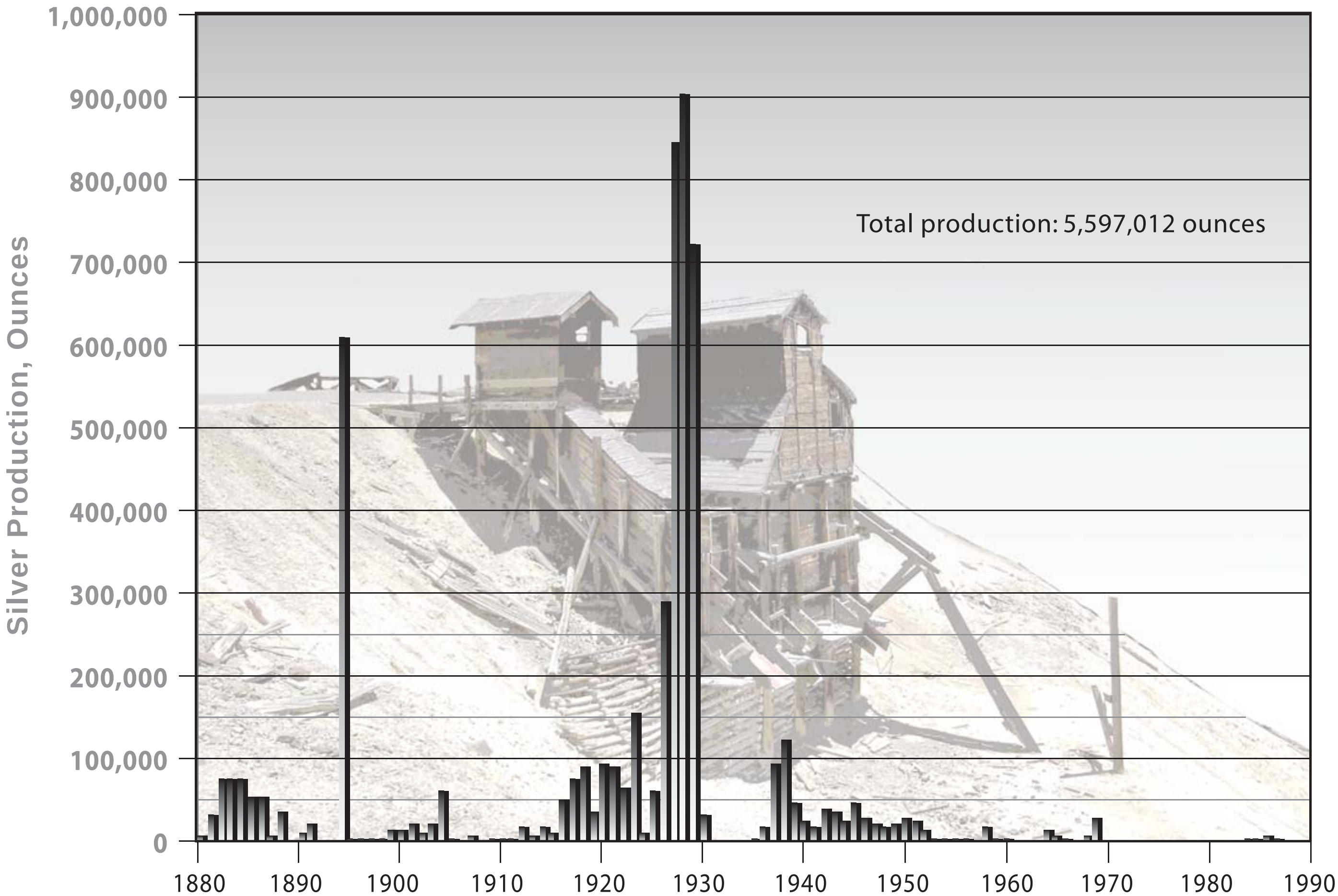


Figure 46. Silver production, Saguache County.

of silver, and the price fell from about a dollar per ounce to about 50 cents per ounce, which further contributed to mine closures.

The Rawley 12 drainage tunnel was constructed in 1911 and 1912 to dewater the Rawley Mine and to provide a production level. The tunnel was 6,200 ft long and drained into Squirrel Creek. The New Rawley Mill was built at the opening of the Rawley 12 tunnel. In 1917, electric locomotives replaced the mules that had been used to haul ore out of the Rawley 12 tunnel.

The peak years of mineral production in the district were from 1915 to about 1930. There was a mild resurgence of mining during World War II that lasted through the mid-1950s. Bear Creek Mining Company conducted an extensive exploration program from 1952 to 1954. The company conducted detailed mapping, geochemical surveys, several types of geophysical surveys, and core drilling. The results of the exploration program were not encouraging (Cook, 1960). Houston International Minerals Corporation conducted exploration for porphyry molybdenum deposits in the late 1970s. Two drill holes were completed in an area of silicified intrusive quartz latite and rhyolite in Greenback Gulch south of the main part of the Bonanza district (J. Lufkin, Metro State College, personal communication, 2003). The last recorded production from the district was in 1969 from U.S. Silver Mining Company's Rawley 200 project. In 2006, the town of Bonanza is a seldom-visited ghost town with a few year-round residents (**fig. 51**).

Most (about 99 percent) of the base and precious metal production of Saguache County was from the Bonanza district. The district produced an estimated 5.6 million oz of silver, 23,000 oz of gold, 45.6 million pounds of lead, 16.3 million pounds of copper, and 9 million pounds of zinc (Henderson, 1926; Vanderwilt, 1947; U.S. Bureau of Mines and U.S. Geological Survey Mineral Year Books). The total metal production has a present-day (2006) value of $158.5 million (**table 1** and figs. 45 through 49).

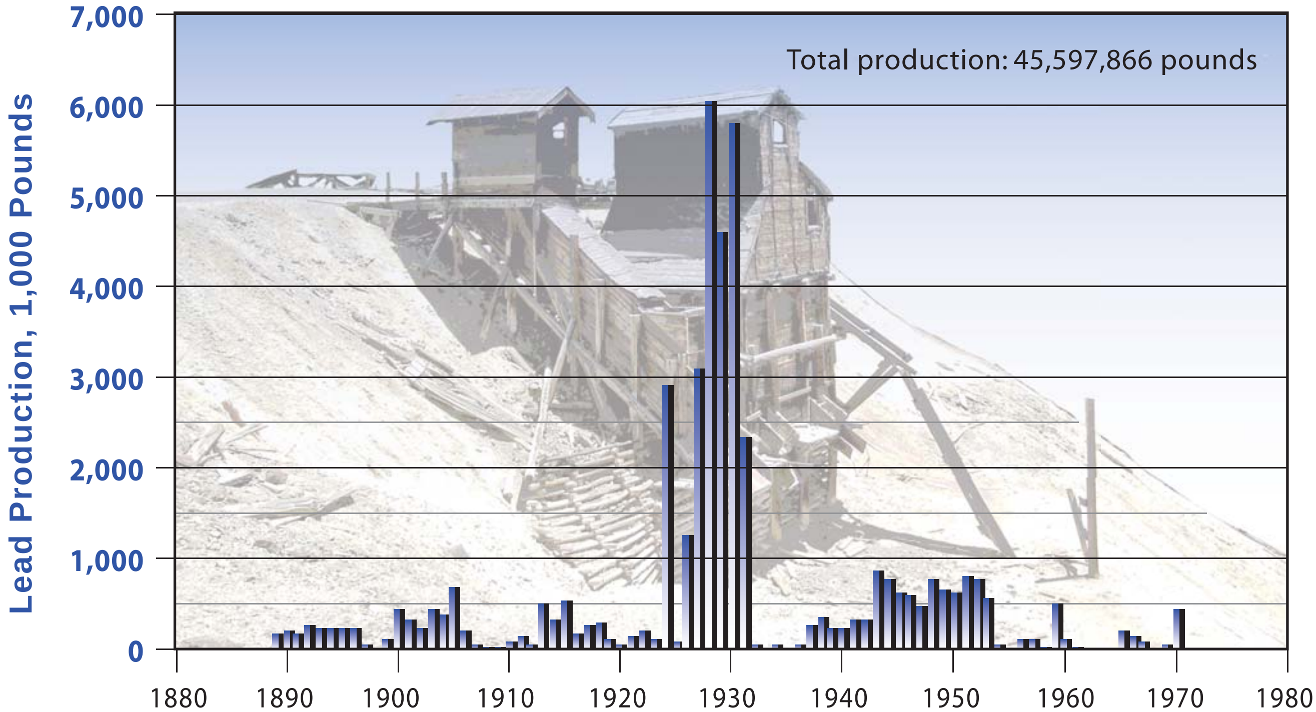


Figure 47. Lead production, Saguache County.

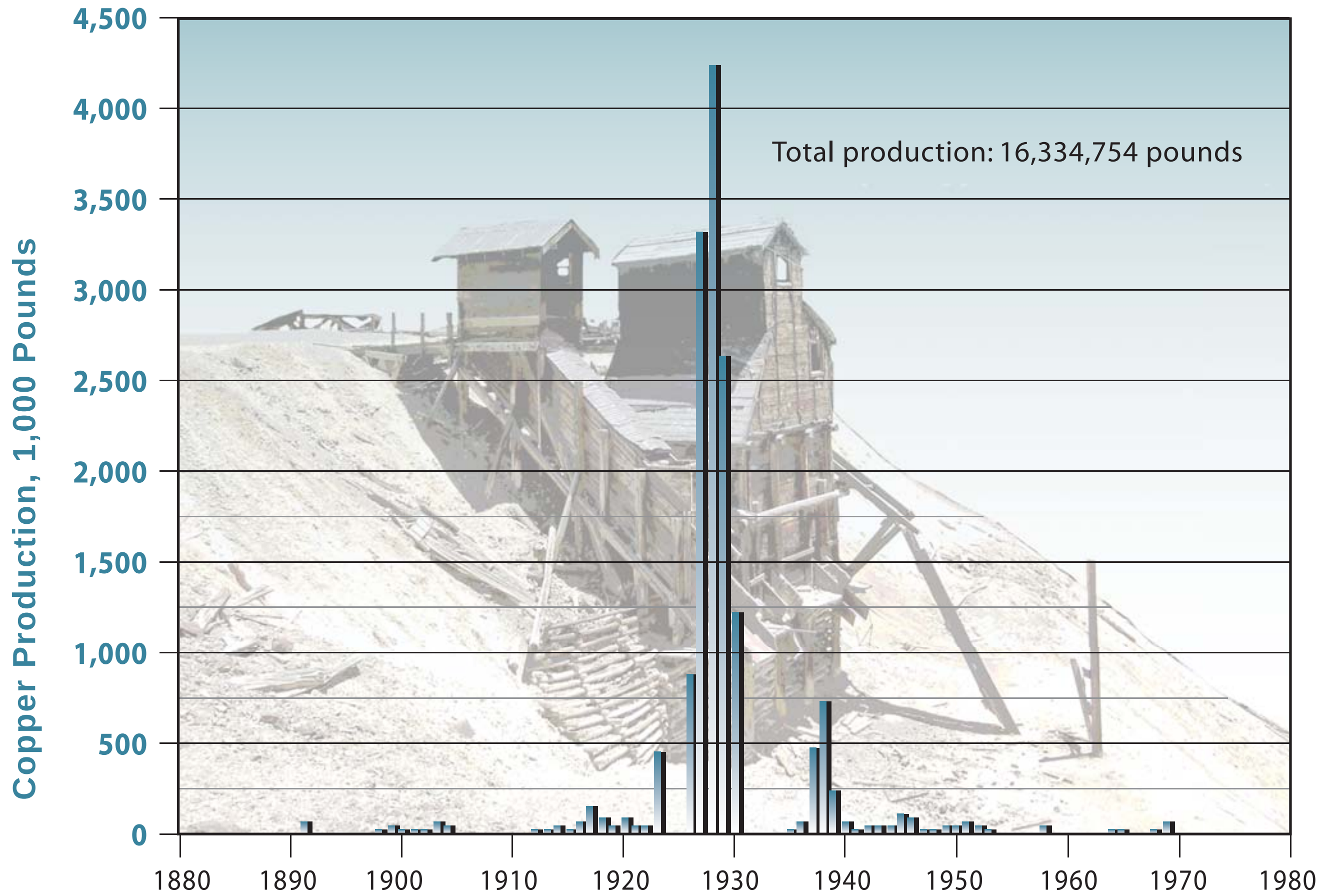


Figure 48. Copper production, Saguache County.

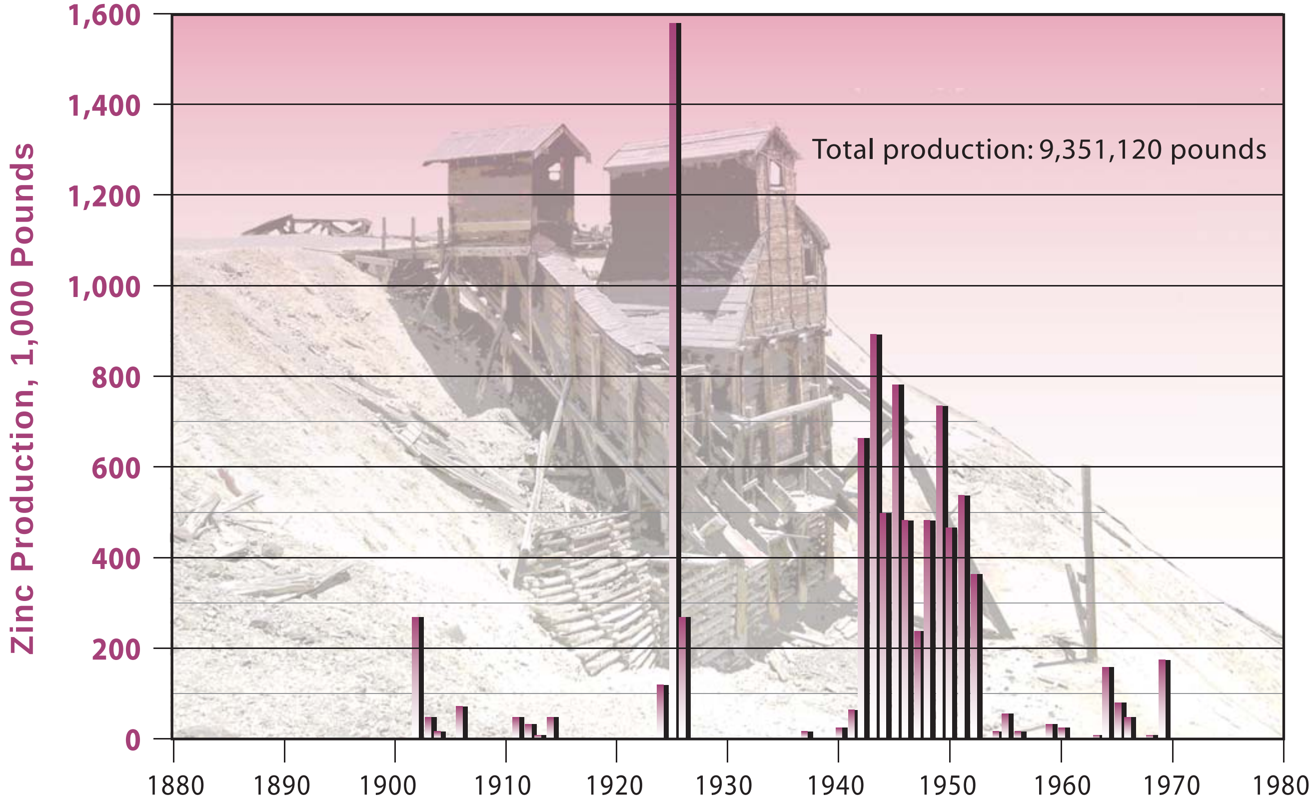


Figure 49. Zinc production, Saguache County.

Figure 50. Antero Mine, Bonanza district, loading facilities, spring 2004.

Figure 51. Town of Bonanza in 2006.

Ore Deposits

The mineral deposits of the Bonanza district are hosted, for the most part, in quartz veins occupying fractures and fissures in the Rawley Andesite, though mineralized fissures are found in Proterozoic rocks as well. The veins and fissures generally trend north-northeast to north-northwest. Silicification and sericitization are the most common alteration styles around the veins and fissures.

The lower Bonanza Tuff, which resembles the Rawley Andesite in its rheological characteristics, is the host rock for the Cocomongo Mine along Kerber Creek. Where mineralized, the lower Bonanza Tuff, a latite, is strongly altered. Chloritization, sericitization, and silicification are the most common alteration styles.

Lead, silver, copper, zinc, gold, and manganese have been produced from the district. The principal ore minerals of the veins are pyrite, sphalerite, galena, chalcopyrite, bornite, argentiferous tennantite (complex copper arsenic sulfide), and stromeyerite (argentiferous copper sulfide). Common gangue minerals include quartz, manganocalcite, rhodochrosite, and barite. The grade of the ore deposits is variable: silver concentrations range from 5 to 50 oz per ton and lead from 10 to 40 percent. Generally, small, high-grade ore bodies contained 10 to 15 percent combined lead and zinc and 2 to 8 oz of silver per ton. Gold contents for most of the district were negligible. Only the St. Louis Vein in Copper Gulch had high-grade gold contents ranging from 1 to 7 oz per ton.

Low-sulfide veins containing quartz, rhodochrosite, and fluorite were found in the southern part of the district in the area around Eagle, Chloride, Greenback, Express, and Manganese gulches. Minor amounts of manganese were produced at these deposits.

Timing of the mineralization is not known, but in other mining districts of the San Juan volcanic field, mineralization occurred 2 to 15 Ma after caldera collapse and ash-flow eruption (Steven and Lipman, 1976, p. 33–34; Lipman and others, 1976).

The chapters describing features of the ore deposits and the mines of the Bonanza district from Burbank's 1932 U.S. Geological Survey Professional Paper are included as **Appendix 1** at the end of this report.

VILLA GROVE (HALL) TURQUOISE MINE—BONANZA DISTRICT

The Villa Grove (Hall) turquoise mine (sec. 26, T. 47 N., R. 8 E.; pl. 1) is located in the intrusive Turquessa gabbro in the Rawley Andesite of the Bonanza volcanic complex; it was originally mined for copper as far back as the 1890s. J.S. Randall recognized turquoise minerals in 1893; however, the Villa Grove Mine was not developed for turquoise until 1936. The deposit was developed by a pit, open cuts, and underground drifts (Eckel, 1997). Pearl (1941) described the turquoise as veins and nodules filling openings in

Table 1. Historic annual precious and base metal production for Saguache County.

Year	Gold (ounces)	Silver (ounces)	Copper (ounces)	Lead (pounds)	Zinc (pounds)
1880	----	7,734	----	----	----
1881	----	30,938	----	----	----
1882	484	77,344	----	----	----
1883	242	77,344	----	----	----
1884	50	77,344	----	----	----
1885	50	55,920	----	----	----
1886	176	55,920	----	----	----
1887	36	7,196	----	----	----
1888	204	36,101	----	12,582	----
1889	----	----	----	180,272	----
1890	84	11,988	4,290	200,000	----
1891	69	21,285	68,047	176,193	----
1892	----	----	----	260,577	----
1893	----	----	----	250,000	----
1894	847	608,224	----	250,000	----
1895	26	3,939	----	250,000	----
1896	16	2,447	241	249,166	----
1897	665	2,482	2,975	65,465	----
1898	952	2,618	21,711	9,266	----
1899	188	14,306	35,319	132,462	----
1900	386	15,793	16,129	441,095	----
1901	3,869	20,507	15,253	316,061	----
1902	243	10,486	13,669	235,750	267,100
1903	143	22,424	67,410	454,995	44,000
1904	267	60,506	48,722	376,711	15,585
1905	34	4,401	1,135	699,312	2,917
1906	369	737	----	203,797	74,302
1907	31	6,194	1,260	49,141	----
1908	30	953	76	22,528	----
1909	58	2,260	3,769	27,715	----
1910	50	4,841	5,362	83,463	----
1911	25	4,664	4,984	161,068	46,561
1912	184	19,309	29,479	74,566	32,964
1913	205	8,694	13,277	504,845	8,941
1914	799	18,293	35,783	336,886	44,250
1915	255	11,266	23,360	534,872	----
1916	388	48,959	62,581	174,447	----
1917	501	76,016	144,978	255,449	----
1918	124	89,510	96,866	310,686	----
1919	40	37,767	36,344	108,253	----
1920	243	94,655	88,386	52,515	----
1921	90	90,871	49,512	150,063	----
1922	235	63,542	41,622	198,686	----
1923	205	155,723	459,477	111,782	----
1924	14	9,939	1,748	2,919,200	115,600
1925	96	63,036	1,500	86,375	1,582,000
1926	265	289,505	897,285	1,269,600	265,800
1927	968	845,044	3,378,504	3,085,200	----
1928	1,130	903,759	4,300,000	6,030,222	----
1929	1,018	722,319	2,667,000	4,600,000	----
1930	550	33,722	1,234,000	5,806,000	----
1931	8	1,507	5,000	2,343,000	----
1932	18	21	----	62,000	----
1933	28	1,500	3,000	----	----
1934	50	215	300	68,000	----
1935	738	4,640	18,000	2,000	----
1936	315	16,330	65,000	61,500	----

Year	Gold (ounces)	Silver (ounces)	Copper (ounces)	Lead (pounds)	Zinc (pounds)
1937	278	94,186	481,000	278,700	16,000
1938	258	124,825	736,000	361,000	----
1939	89	48,794	248,000	227,000	----
1940	30	27,059	62,000	240,000	26,000
1941	24	17,706	26,000	345,000	62,000
1942	60	41,313	36,400	320,000	663,600
1943	216	36,464	50,500	878,900	891,000
1944	70	27,149	45,000	796,000	500,000
1945	76	47,302	114,000	625,000	782,000
1946	57	28,396	86,000	599,000	480,000
1947	47	21,445	24,200	478,000	236,400
1948	60	19,473	18,000	793,900	482,000
1949	98	21,970	42,000	662,000	738,000
1950	689	30,342	48,000	638,000	464,000
1951	119	24,623	74,000	808,000	538,000
1952	106	14,745	48,000	784,000	364,000
1953	134	4,666	12,000	556,000	----
1954	4	2,938	2,000	72,000	18,000
1955	12	3,101	6,000	14,000	54,000
1956	----	2,958	8,000	112,000	14,100
1957	----	1,339	1,700	111,000	----
1958	34	16,866	40,000	26,600	----
1959	8	3,184	6,000	522,000	30,000
1960	3	2,261	4,000	116,000	20,000
1961	----	----	----	20,000	----
1962	----	----	----	----	----
1963	----	182	1,000	----	6,000
1964	21	14,320	24,000	2,000	160,000
1965	15	9,000	16,000	220,000	80,000
1966	7	4,471	10,000	160,000	46,000
1967	----	----	4,000	80,000	----
1968	9	7,332	18,000	----	8,000
1969	53	30,307	70,000	54,000	172,000
1970	----	----	----	444,000	----
1971	----	----	9,600	----	----
1972	----	----	----	----	----
1973	----	----	----	----	----
1974	----	----	----	----	----
1975	----	----	----	----	----
1976	----	----	----	----	----
1977	----	----	----	----	----
1978	----	----	----	----	----
1979	----	----	----	----	----
1980	----	----	----	----	----
1981	----	----	----	----	----
1982	----	----	----	----	----
1983	----	----	----	----	----
1984	500	3,000	----	----	----
1985	500	3,000	----	----	----
1986	500	6,257	----	----	----
1987	1,026	3,000	----	----	----
1988	500	----	----	----	----
1989	----	----	----	----	----
1990	----	----	----	----	----
Total	23,664	5,597,012	16,334,754	45,597,866	9,351,120
Price1	$635	$11.20	$3.55	$0.50	$1.52
Value	$15,026,640	$62,686,534	$57,988,377	$22,798,933	$14,213,702

felsite porphyry. Later workers (Mayhew, 1969) described the turquoise as a fracture filling in the Turquessa gabbro. The Turquessa gabbro visible at the mine in 2004 had a porphyritic texture and was strongly altered. The mine produced high-quality turquoise, essentially free from veining and having a sky-blue color (**fig. 52**). Peak production was in the 1940s, when turquoise sold for $15 to $45 a pound. Voynick (1994, p. 289) mentioned that the value of the production through the 1950s was $80,000. The mine is currently (2006) closed.

CRYSTAL HILL MINE—ESPERANZA DISTRICT

Several small prospects around the Crystal Hill Mine (secs. 27 and 28, T. 43 N., R. 6 E.; pl. 1) operated during the late 1800s. Some mining at Crystal Hill was conducted in the 1950s, resulting in production of 587 oz of gold. The modern Crystal Hill Mine was an open pit–heap leach operation that produced 27,000 oz of gold and 40,000 oz of silver between 1984 and 1986. The average grade of the orebody was 0.043 oz per ton gold and 0.33 oz per ton silver (Colorado Division of Minerals and Geology unpublished files, 2003).

Figure 52. Turquoise from the Turquessa gabbro, Villa Grove Mine, Bonanza district.

Geology

The Crystal Hill Mine ore deposit is in the Crystal Hill breccia pipe in the Biedell stock, a quartz latite intrusion dated at a mean age of 33.8 Ma by $^{40}K/^{39}Ar$ methods on biotite and plagioclase (Lipman and others, 1970) (**fig. 53**). The Biedell stock is a hypabyssal quartz latite that contains phenocrysts of plagioclase, biotite, quartz, and minor hornblende. Propylitic alteration is ubiquitous, and argillic alteration is locally intense along structures (Osterwald, 1977, p. 74).

The orebody is in a breccia pipe composed entirely of fragments of the quartz latite breccia pipe. The breccia pipe has plan dimensions of 600 by 400 ft, and the pipe extends at least 1,000 ft below the surface as indicated by drill-hole data (Pansze, 1987). The breccia fragments are mostly platy with dimensions of 1 to 12 in. The poorly indurated matrix consists of quartz, calcite, iron-manganese oxides, and rock flour. Quartz crystals are common in the upper part of the breccia pipe and give the locality its name (Pansze, 1987). Gold and silver minerals are found mostly below the zone of quartz crystals and are associated with manganese oxide in the matrix of the breccia. **Figure 54** is a schematic cross section of the Crystal Hill breccia pipe.

The breccia pipe is interpreted as a collapse feature on the basis of the following primary evidence, as listed by (Pansze, 1987): (1) orientation and imbrication of platy fragments, (2) a tilted quartz latite roof slab or "trap door," and (3) volcaniclastic sediments in the upper part of the pipe.

Other mines in the area of the Biedell stock include the Esperanza and Buckhorn mines; their production was small. These deposits are located on an east-trending fault, just north of the Crystal Hill breccia pipe (Osterwald, 1977).

BONDHOLDER—CASCADE DISTRICT

The Bondholder-Cascade (unsurveyed; pl. 1) district is located in southwestern Saguache County along Spring Creek. There is no production information from the district; however, reports indicate that development goes back to 1887 (Steven and Bieniewski, 1977). The district is 6 mi north of the highly productive Creede district in Mineral County and lies along the same north-northwest–trending fracture system as the Creede district.

The district lies within the San Luis caldera, the youngest of the calderas of the San Juan volcanic field. Rocks of the district include an unnamed flow-banded rhyolite, the Nelson Mountain Tuff, and a latite porphyry (**fig. 55**) (Thompson, 1992).

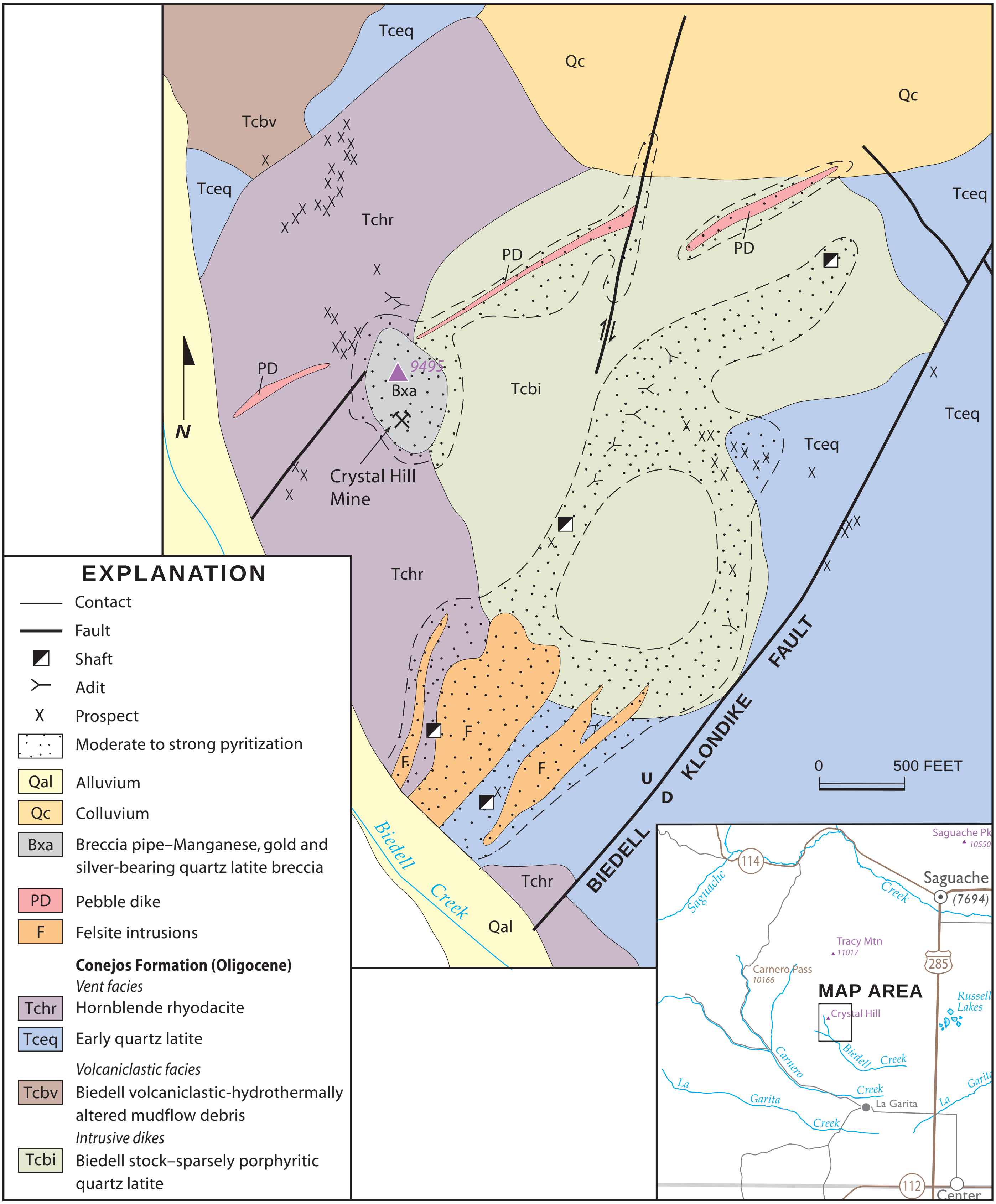


Figure 53. Geologic map of the Biedell stock and Crystal Hill Mine area.

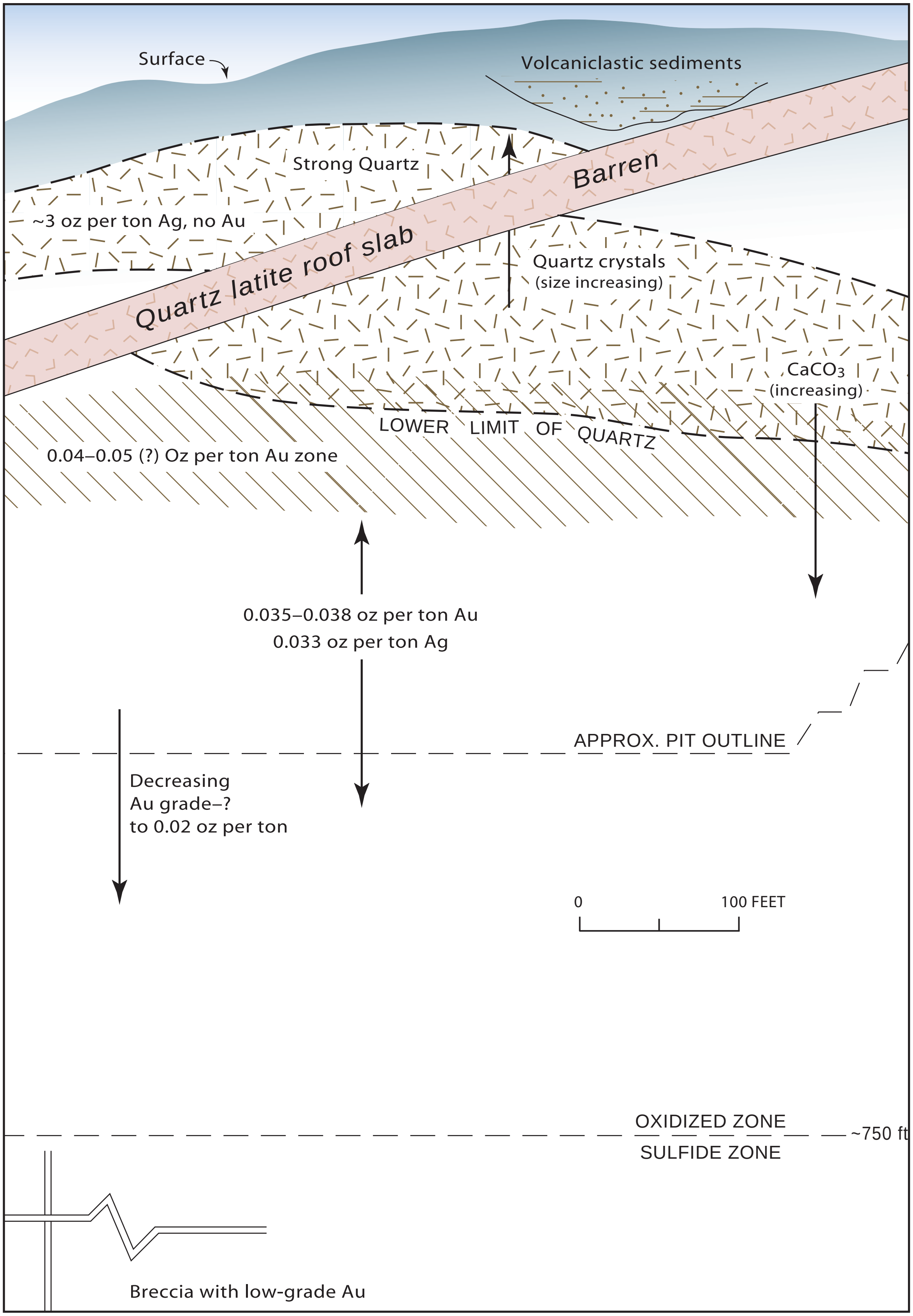


Figure 54. Schematic cross section of the Crystal Hill breccia pipe (Pansze, 1987).

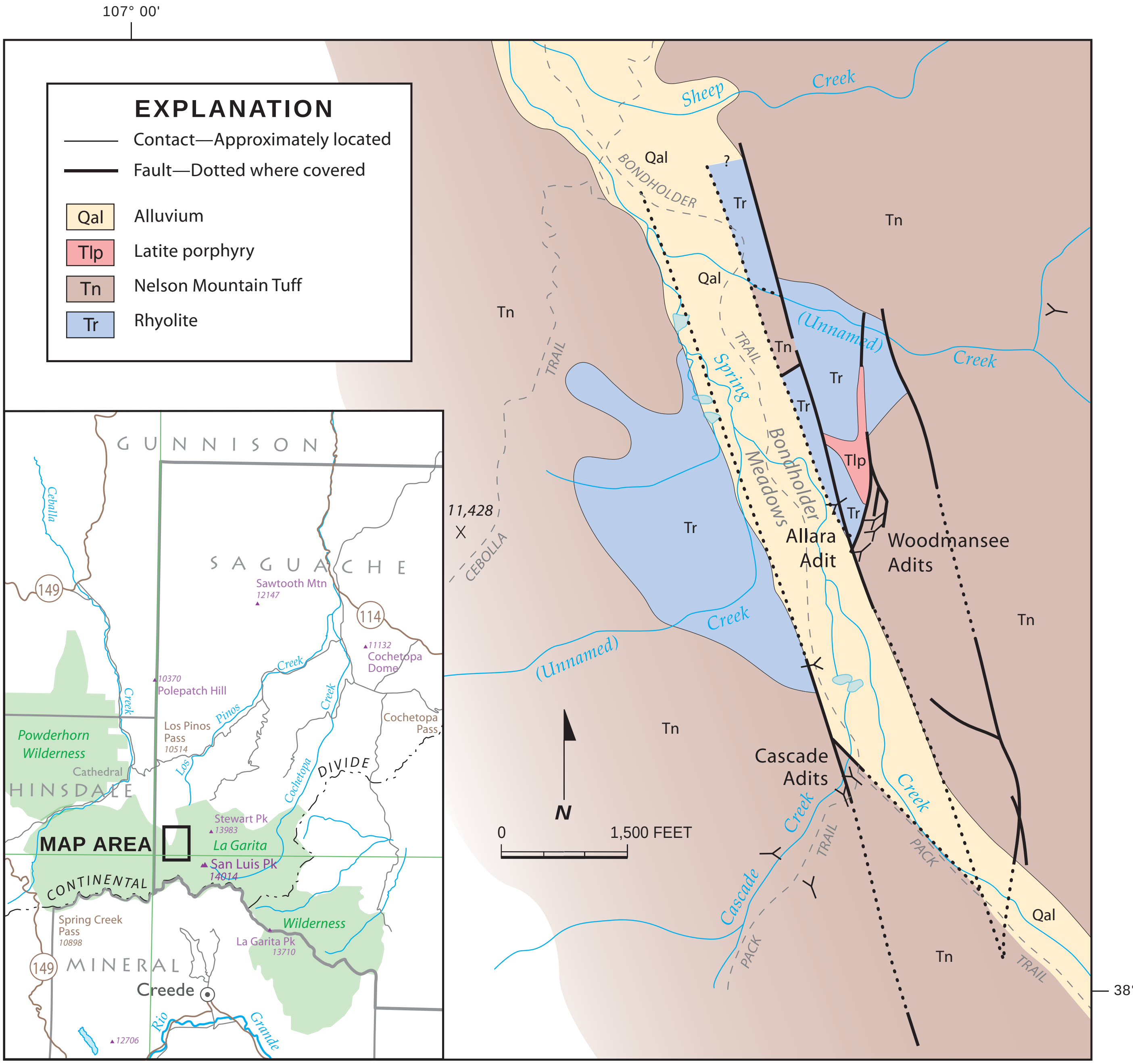


Figure 55. Geologic map of the Bondholder district (Thompson, 1992).

The Cascade Mine area has three short adits that expose veins and faults in hydrothermally altered rocks of the Nelson Mountain Tuff. One of the adits, the New Cascade adit, was driven in 1968–1970 (Steven and Bieniewski, 1977). The others were developed in the 1920s and 1930s. Veins in the Cascade area consist of quartz, galena, sphalerite, chalcopyrite, pyrite, rhodochrosite, fluorite, and other gangue minerals (Thompson, 1992). Sampling conducted by the U.S. Geological Survey (Steven and Bieniewski, 1977) indicates low metal concentrations in veins of the New Cascade adit. Sampling in the older adits indicates higher metal concentrations—14.65 percent zinc, 9.3 percent lead, and 0.32 percent copper— from a vein 3 in. wide (Steven and Bieniewski, 1977, p. 52).

The Allara adit was driven into mineralized rock in 1966 and 1967 about 2,000 ft north of the Cascade Mine area near Bondholder Meadow. There were no mineral deposits of note found in the Allara adit (Steven and Bieniewski, 1977). An older adit, the Woodmansee Mine, was opened in approximately 1915. Veins in this area have a mineral assemblage similar to that of the Cascade Mine area with the addition of pyrargyrite and no rhodochrosite and fluorite (Thompson, 1992). The U.S. Geological Survey sampled a 5-in. quartz vein that assayed 42.9 oz per ton silver, 0.01 oz per ton gold, 12.3 percent zinc, 8.6 percent lead, and some copper. Although this mine had some economic mineral deposits, there is no record of any production. Other prospects and adits in the area were poorly mineralized (Steven and Bieniewski, 1977).

SKY CITY MINE—WANNAMAKER DISTRICT

The Sky City Mine (unsurveyed; pl. 1) is located along Wannamaker Creek in southwestern Saguache County. There is no production information on the Sky City Mine. Sampling by the U.S. Geological Survey from the dump of the mine indicated small amounts of gold (0.01–0.02 oz per ton). Other prospects and adits in the area were barren (Steven and Bieniewski, 1977).

CRESTONE DISTRICT

The Crestone district is located within the unsurveyed Baca Land Grant, a Spanish land grant, along the western foothills of the Sangre de Cristo Range (pl. 1). According to Clement (1952), between 1890 and 1900, several prospectors began mining operations in the area and produced precious metals worth approximately $7 million to $8 million. The prospectors and miners were evicted in 1898, and the land came under the control of the heirs of Luis Maria Cabeza de Baca. Clement (1952) stated that the mineral deposits are associated with north-trending thrust faults. Silica and sericite are the main alteration products in the Proterozoic rocks. The dominant mineral deposits are quartz-hematite and quartz-pyrite-chalcopyrite veins. Some of the veins had grades as high as 5 oz per ton gold and 5 oz per ton silver (Clement, 1952). According to Vanderwilt (1947, p. 193), 1,337 oz of gold and 533 oz of silver plus minor copper and lead were produced from the Crestone district between 1932 and 1939.

In the late 1980s and early 1990s, Lexam Explorations Inc. conducted a gold exploration program in the area around Deadman Creek some 8 mi south of Crestone. Gold mineral deposits at this prospect are related to a low-angle detachment fault similar to that found at the San Luis Gold Mine, which is about 50 mi south in Costilla County (Benson, 1997). The Deadman Creek prospect is located in strongly silicified breccia of feldspar and quartz in a chloritic matrix. Gold grades are as rich as 0.13 oz per ton; the gold is associated with pyrite. Benson (1997) and Watkins (1996) interpreted the breccia to be in the footwall of a low-angle detachment fault.

Other places in the foothills of the Sangre de Cristo Mountains that have similar alteration, low-angle or flat-lying structures, and significant gold include the area at the mouth of Dimick Gulch, mines and prospects between the north and south branches of Wild Cherry Creek, the Copperhead Mine, and the areas around Garner Creek, Carr Gulch, and Bolton Creek (Benson, 1997).

GUNNISON GOLD BELT

The Gunnison gold belt is in Paleoproterozoic volcanic rocks consisting of the Dubois Greenstone and associated volcanic, subvolcanic, and sedimentary rocks. The Gunnison gold belt is as much as 6 mi wide and extends in a general east-west direction for about 30 mi from near Gunnison in Gunnison County to western Saguache County. There were several mines in the gold belt, the largest of which were the Vulcan and Good Hope mines, located just a few hundred yards west of the Saguache County line in Gunnison County. According to Drobeck (1981, p. 284), the Vulcan and Good Hope mines produced gold-silver ore worth about $500,000 between 1898 and 1902. The actual tonnage and grade are not reported. Approximately 100 tons of ore grading 2.5 oz per ton gold and 12 oz per ton silver were produced in 1919. The mine reportedly produced ore as late as the 1930s.

Geology

There are four main rock types included in the broad term "Dubois Greenstone": (1) metamorphosed arkose, graywacke, and siltite; (2) metamorphosed basalt to andesite, water-laid flows, and tuffs; (3) metamorphosed dacite to rhyolite tuffs, turbidites, and flows; and (4) syntectonic to late tectonic granite, granodiorite, and diorite. Metamorphism occurred between 1730 and 1650 Ma (Drobeck, 1981, p. 280).

Ore Deposits

The Denver City Mine is located in the Iris district in sec. 14, T. 48 N., R. 1 E. (pl. 1). The local rocks consist of steeply dipping felsic tuff and turbidite beds and thin, discontinuous, purple metachert beds. The gold was deposited along foliation planes of the host rhyolite porphyry. The gold deposit is composed of massive sulfide intercalated with calcite, quartz, and tuffaceous material. Sulfides include black sphalerite, pyrite, chalcopyrite, and small amounts of pyrrhotite. One sample of the massive sulfide ore had grades of 0.46 oz per ton silver and 0.04 oz per ton gold (Drobeck, 1981, p. 280).

The Yukon and Alaska mines are located just east of Cochetopa Canyon in sec. 28, T. 48 N., R. 2 E. The area is composed of fine-grained metamorphosed argillite, siltite, and graywacke. Metamorphic grade is low enough so that primary sedimentary structures are preserved. Quartz-feldspar-muscovite schist forms 7- to 25-ft-thick bands. Mineral deposits at both mines are discontinuous lenses of massive sulfide intermixed with quartz veins and schist. The sulfide consists of sphalerite, pyrite, pyrrhotite, and minor copper sulfide and galena. The Alaska Mine (**fig. 56**) produced only 10 tons of ore at a grade of 0.7 oz per ton gold, 15 tons of 11 percent copper ore, and four ore cars of 34 percent zinc ore (Drobeck, 1981, p. 281).

The Continental Mine area, sec. 11, T. 47 N., R. 1 W., was explored by FMC Gold Company (now Meridian Gold Company) during the mid-1980s. An offering letter from FMC Gold Company states that mineral deposits at the Continental Mine are in high-angle, quartz-vein structures within a tonalite sill. Microfractured tonalite is adjacent to the veins and hosts anomalous gold concentrations. The quartz veins contain tourmaline, chlorite, pyrite, and limonite. Gold minerals are primarily native gold and calaverite associated with pyrite, chalcopyrite, galena, and altaite (a lead telluride). Limonite is associated with higher-grade structures. Channel samples from the mineralized zone vary from 0.3 to 1.4 oz per ton gold (FMC Gold Company offering letter, 1986, in Sunshine Mining Company files).

The Vulcan and Good Hope mines were the most important producing mines in the Gunnison gold belt and so are worthy of note in this report even though they were in neighboring Gunnison County. Mineral deposits are in a lens of massive sulfide between bleached sericite schists. The hanging wall of the orebody contains opaline chalcedony veinlets that contain silver, gold, and copper tellurides as well as native tellurium (Drobeck, 1981, p. 284; Hunsaker, 1988).

EMBARGO CREEK DISTRICT

The Embargo Creek district (pl. 1) is located in southwestern Saguache County in T. 41 N., R. 4 E. Vanderwilt (1947, p. 194) reported minor gold along with silver, lead, and copper from veins in Conejos Formation andesites. Information from the U.S. Geological Survey Mineral Resource Data System database indicates that the Monon claims produced about 10,000 tons of ore and that the area of the Golden Income Group claims is underlain by an Oligocene granodiorite and had a value of $28 per ton of silver, gold, and lead ore (McFaul and others, 2000).

BLAKE, STEEL CANYON AND HAYDEN PASS MINING DISTRICTS

These small mining districts are in the foothills of the Sangre de Cristo Range north of the Orient Mine and south of Hayden Pass. According to Ellis and others (1983), production from these districts was 5 oz of gold, 7,000 oz of silver, 70,000 pounds of lead, and 8,000 pounds of copper. Mineralized structures in the Copper King and Victor mines in Steel Canyon consist of veins in fractured carbonate rock (Leadville Limestone?). The veins pinch and swell to 3 ft in thickness; they consist of silver-bearing galena and minor chalcopyrite in a gangue of quartz, calcite, and minor fluorite and barite (Lindsey and others, 1985b). Samples taken from the Copper King Mine during a wilderness assessment assayed from 0.006 to 0.043 oz per ton gold and 0.3 to 34.2 oz per ton silver and contained anomalous amounts of copper and lead (Lindsey and others, 1985b). Samples taken from the Victor Mine during the same wilderness assessment assayed from 0.3 to 10.3 oz per ton silver and contained anomalous amounts of copper and lead (Lindsey and others, 1985b).

Figure 56. Alaska Mine, Gunnison gold belt, 2005.

ORIENT MINE

The Orient Mine is located in the western foothills of the Sangre de Cristo Range at the northern end of the San Luis Valley (pl. 1). The mine is located less than 1 mi north of Valley View Hot Springs in sec. 25, T. 46 N., R. 10 E. (fig. 34). Colorado Fuel and Iron Company (CF&I) acquired the Orient Mine in 1880. Limonite production was substantially increased in 1881 with the building of a rail line to the mine site. During the period 1880 to 1905, the mine produced 1,370,000 tons of ore, all of which was shipped to the CF&I smelter in Pueblo. A community of approximately 400 people and

70 buildings was established at the Orient Mine during those years. CF&I closed the mine in 1905 because of apparent ore reserve exhaustion. Lessees produced an additional 116,000 tons of ore through 1921. A systematic exploration and reserve development program by CF&I allowed the reopening of the mine in 1922. During the period of 1922 to 1931, the mine produced an additional 250,000 tons of ore. The total production of the Orient Mine was 1,736,000 tons of limonite ore (Balleweg, 1990). The average grade of the ore produced during 1930 (assumed to be typical of the orebody) was 43.3 percent Fe, 1.43 percent Mn, 1.92 percent CaO, and 7.87 percent SiO_2 (Stone, 1934, p. 322).

CF&I conducted an exploration program for copper at the Orient Mine from 1973 to 1975. Four diamond drill holes were completed. No primary copper deposit was discovered; however, sporadic pockets of limonite were found at depths as much as 1,000 ft below the surface (Balleweg, 1990, p. 13). Estimated ore reserves in the underground mine, open pits, and dumps at the Orient Mine were estimated to be five million tons at 43 percent iron (Carr and Dutton, 1959, p. 97).

Geology

The Orient Mine is located in the foothills of the northern Sangre de Cristo Mountains, a Neogene, block-faulted mountain range. The stratigraphy in the region consists of lower to middle Paleozoic clastic and carbonate rocks of the Manitou Formation, Harding Quartzite, Fremont Dolomite, and Chaffee Group, which overlie Proterozoic metamorphic and igneous rocks. Upper Paleozoic formations include the Mississippian Leadville Limestone and the Pennsylvanian through Permian clastic rocks of the Kerber, Sharpsdale, Minturn, and Sangre de Cristo Formations. There are no known Mesozoic sedimentary rocks in the area. Cenozoic sedimentary deposits include glacial deposits and alluvium (**fig. 57**).

The Oligocene Rio Alto stock is located about 3 mi east of the Orient Mine and is composed of medium- to coarse-grained augite-hornblende-biotite tonalite (Toulmin, 1953). Lindsey and others (1985c) listed recalculated fission-track dates from the Rio Alto stock of 28.0 ± 3.4 Ma on zircon and 32.8 ± 2.4 Ma on sphene.

Within the mine area, several altered porphyry sills are found in 10- to 30-ft-thick bodies generally conformable to bedding in the Paleozoic carbonate rocks. The porphyry consists of strongly altered feldspar and minor biotite and hornblende phenocrysts in an aphanitic matrix. Feldspar phenocrysts are replaced by sericite throughout the area and by clay minerals (kaolinite) in the mine area. Biotite and hornblende are replaced by chlorite. Paragenetic relationships indicate that the argillic alteration postdates the sericitic alteration. Balleweg (1990, p. 63) suggested that the porphyry bodies are related to and are the same age as the tonalite of the 32–28 Ma Rio Alto stock. Balleweg also pointed out that the lack of quartz phenocrysts, the inference of plagioclase as the dominant feldspar, and the presence of titaniferous biotite suggest that the altered porphyry was originally andesite porphyry.

The north-northwest–trending Sangre de Cristo normal fault forms the western boundary of the Sangre de Cristo Mountains. The Villa Grove fault zone trends northwest and intersects the Sangre de Cristo fault near the Valley View Hot Springs, just 1 mi south of the Orient Mine (fig. 57).

Several north-northwest–trending thrust faults and parallel folds cut through the lower and middle Paleozoic rocks north of the Black Canyon and the Orient Mine (fig. 57). The main structure near the mine is the Orient syncline. The Leadville Limestone in the area of the mine dips 20° to 30° to the east. Several normal faults related to the Sangre de Cristo fault cut through the western part of the mine area.

Ore Deposits

The limonite deposits of the Orient Mine are found in the Leadville Limestone. They are oxidation products of a primary ankerite deposit in intraformational breccias and paleokarst features of the Leadville Limestone.

Stratigraphy of the Mine Area

Balleweg (1990) recognized three formal members of the Leadville Limestone in this area: From bottom to top, they are the Gilman Member, the Redcliff Member, and the Castle Butte Member (**fig. 58**). The following descriptions are from Balleweg (1990):

1. The Gilman Member is 20 to 30 ft thick in the Orient Mine and consists of gray dolomite; light-gray to white, finely crystalline stromatolitic limestone; tan to gray to cream, dolomitic mudstone; and intraformational breccia.

2. The Redcliff Member is 45 to 110 ft thick in the mine area and consists of gray, thinly bedded, lime mudstone; wackestone; and stromatolitic boundstone. Locally, thin chert beds are conspicuous within the carbonate rocks. The upper surface of the Redcliff Member is a strata-bound breccia layer. Most of the limonite deposits of the mine are in the Redcliff Member.

3. The basal part of the Castle Butte Member consists of a 10- to 50-ft-thick intraformational breccia. The upper part is tan to light-gray, finely crystalline dolomite mudstone. The thickness of the Castle Butte Member is 70 to 135 ft. Locally, the member consists entirely of intraformational breccia. The upper surface of the Castle Butte Member is an erosional contact with karst features.

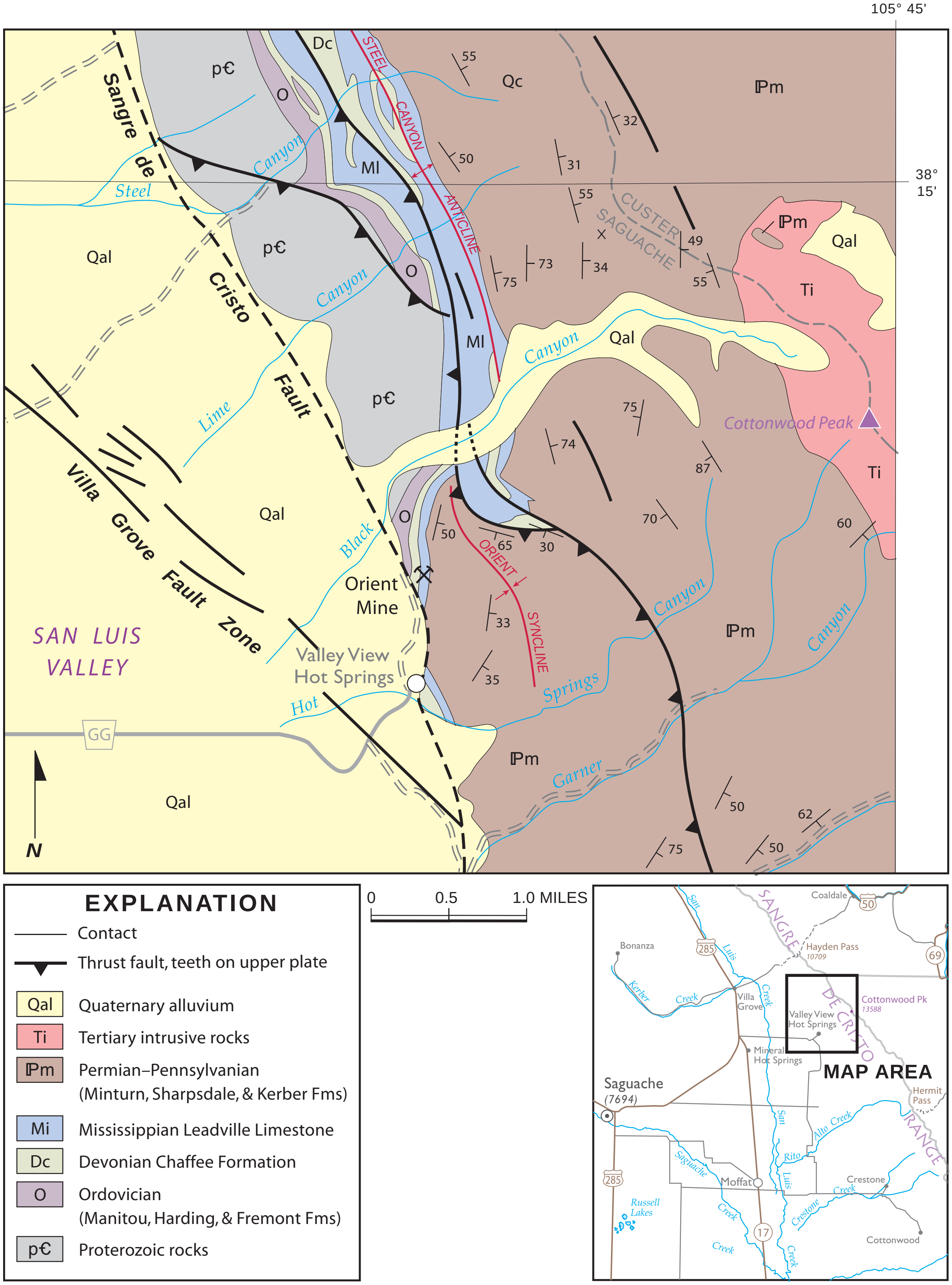


Figure 57. Geologic map of the Orient Mine area (Balleweg, 1990).

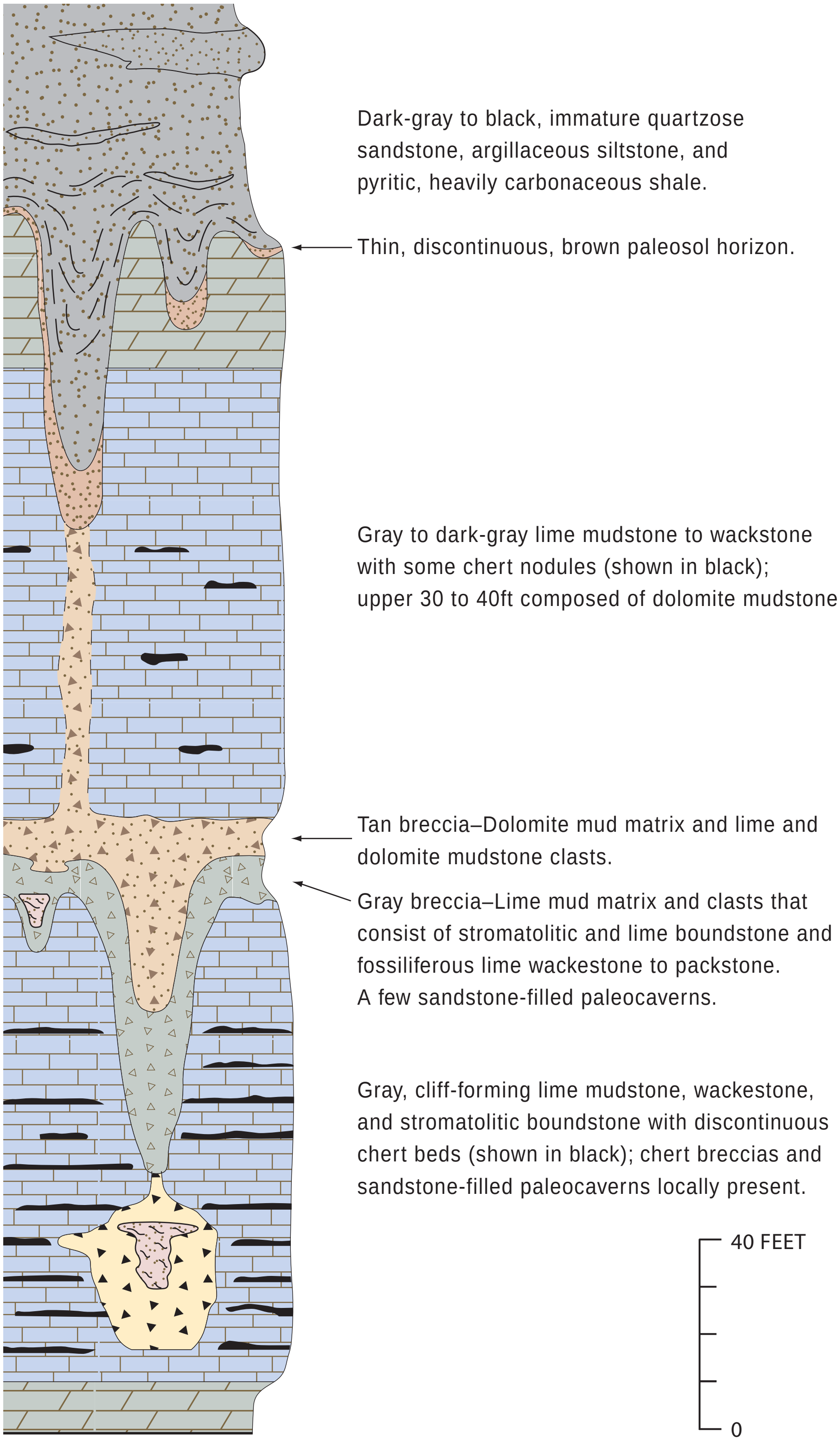


Figure 58. Composite stratigraphic section of the Redcliff and Castle Butte Members of the Leadville Limestone, showing relative position of intraformational breccia types and dissolution features (Balleweg, 1990).

Dissolution Features

Dissolution features in the Leadville Limestone are the primary host for the limonite deposits. These features include intraformational breccia, sandstone-infilled paleocaverns, and Quaternary dissolution features (Balleweg, 1990).

Intraformational breccias include the following: (1) clast-supported lime-mud-matrix breccia, composed of predominantly limestone clasts in a dark-gray lime-mud matrix; (2) clast-supported to matrix-supported dolomite-mud-matrix breccia, composed of clasts of predominantly dolomite mudstone in a tan to cream dolomite-mud matrix; (3) clast-supported to matrix-supported chert breccia with angular chert clasts in a matrix completely masked by the effects of later growth of ankerite and limonite minerals; and (4) dominantly matrix-supported, sandstone-matrix breccia with clasts of limestone and lime-mud-matrix breccia in a well-lithified quartz sandstone matrix. The chert breccia (no. 3) is found solely within the Redcliff Member, and all chert breccia bodies are strongly mineralized, which suggests a genetic link between them and the mineralization event.

Sandstone-infilled paleocaverns are irregular lenticular masses of well-stratified, thinly bedded, well-sorted, very fine grained to fine-grained quartz sandstone, siltstone, and shale located within bodies of lime-mud-matrix breccia of the Redcliff Member. Balleweg (1990) thought them to be infillings of paleocaverns because of dissolution superimposed on preexisting breccias.

Numerous karst dissolution features of presumed Quaternary age are present within the mine workings. These features include open and infilled caverns, solution-enlarged joints, and collapse breccias and are preferentially developed in the Dyer Dolomite (fig. 3) and, to a lesser extent, in the Leadville Limestone.

The lime-mud-matrix breccia, the chert breccia, and the sandstone-matrix breccia formed because of subaerial exposure of the Redcliff Member and the dolomite-mud-matrix breccia; the infilled paleocaverns formed as result of subaerial exposure of the Castle Butte Member. Balleweg (1990) emphasized the point that these breccias were formed prior to deposition of the Pennsylvanian strata and are not tectonic in origin.

Mineral Deposits

The limonite ore bodies of the Orient Mine are hypogene deposits that resulted from multiple mineralization events in favorable paleokarst sites in the Leadville Limestone (Balleweg, 1990). The earliest phase of mineralization resulted in deposition of ankerite plus or minus chalcopyrite, pyrite, specularite, and quartz. The early ankerite phase replaced chert breccias and lime-mud-matrix breccias. Crosscutting relationships indicate that the ankerite stage is later than the porphyry intrusion, which, if related to the Rito Alto stock, occurred at 32 to 28 Ma.

There are two types of iron oxide mineral deposits at the Orient Mine, brown lime replacement and ochre replacement. Brown lime replacement deposits consist of calcite and limonite. Ochre replacement deposits consist of an insoluble residue of limonite, silica, and clay, which remains after the leaching of calcite from the brown lime phase. Both types of limonite deposits replace the primary ankerite deposits; the orebody morphology reflects that of the ankerite ore bodies.

Balleweg (1990, p. 207) stated that the limonite, which formed the massive ore at the Orient Mine, is not a supergene mixture of ferric hydroxides and silica, but is composed of hypogene goethite. Specularite and quartz microveinlet stockworks are thought to have introduced the goethite-bearing solutions into the ankerite bodies. Locally, supergene limonite resulted from oxidation of sulfide minerals in the goethite bodies.

Normal faults related to the development of the San Luis Valley offset the hypogene ore bodies. Thrust faults in the mine area show conflicting paragenetic relationships with the goethite-limonite mineralization event. Balleweg (1990, p. 210) suggested that the mineral deposits at the Orient Mine originated in early Oligocene time coincident with the intrusion of the Rito Alto stock and associated porphyry sills. Balleweg further interpreted that both the deposits and the igneous rocks were formed by a hydrothermal system active during early development of the San Luis Valley, in an area of intersection of rift-related normal faults and low-angle thrust faults.

OTHER LIMONITE-IRON DEPOSITS

The Major Creek Mine (unsurveyed; pl. 1), also known as the Moffat and Bennet Mine, is located on Major Creek about 3 mi southeast of the Orient Mine. A sample assayed 53.7 percent iron, 0.17 percent phosphorous, 1.53 percent sulfur, 8.6 percent silica, and 0.1 percent manganese. Workings on the property consist of small prospect pits and three caved adits (Harrer and Tesch, 1959, p. 63).

The Alder limonite deposit is located about 2 mi east of the settlement of Alder in sec. 30, T. 48 N., R. 9 E. The deposit is a bog iron [“a soft, spongy, and porous deposit of impure hydrous iron oxides formed in bogs, marshes, swamps . . . by precipitation from iron-bearing waters” (Jackson, 1997, p. 75)] and consists of yellow, red, and brown to black limonite in sand and gravel. The deposit has dimensions of 800 by 100 ft and is as much as 8 ft thick. Fifty tons of this deposit assaying 45 percent iron were mined in 1943 (Harrer and Tesch, 1959, p. 59).

The Del Norte limonite deposit is located in sec. 30, T. 41 N., R. 6 E. It is a bog iron of hard brown to black limonite in sand and gravel. This deposit is 1,500 ft long by 250 ft wide and is as thick as 5 ft. A sample assayed 47.8 percent iron, 0.23 percent phosphorous, 1.13 percent sulfur, 11.8 percent silica, and 0.1 percent manganese (Harrer and Tesch, 1959, p. 61).

The Indian Creek limonite deposit is located in the Marshall Pass uranium district. This deposit consists of small replacement bodies in Paleozoic limestone as well as bog-iron deposits. A sample assayed 42.6 percent iron, 0.07 percent phosphorous, 0.43 percent sulfur, 20.8 percent silica, and 0.1 percent manganese (Harrer and Tesch, 1959, p. 61).

An unnamed small deposit of limonite is located near the Bonanza Road along Kerber Creek, sec. 22, T. 46 N., R. 8 E., and consists of yellow and reddish-brown limonite in a limestone breccia. A characteristic sample assayed 24.2 percent iron, 0.11 percent phosphorous, 0.34 percent sulfur, 48.6 percent silica, and 0.4 percent manganese (Harrer and Tesch, 1959, p. 62).

MARSHALL PASS URANIUM DISTRICT

Uranium deposits along the north-trending Chester fault (**fig. 59**) in northern Saguache County and southern Gunnison County were discovered in 1955. The early discoveries include the Little Indian No. 36 Mine, which is about 1,000 ft north of the Saguache-Gunnison County line. This mine produced several thousand tons of ore from the quartzites of the Harding Quartzite. Other prospects in the area that were discovered in 1955 include the Apache No. 4

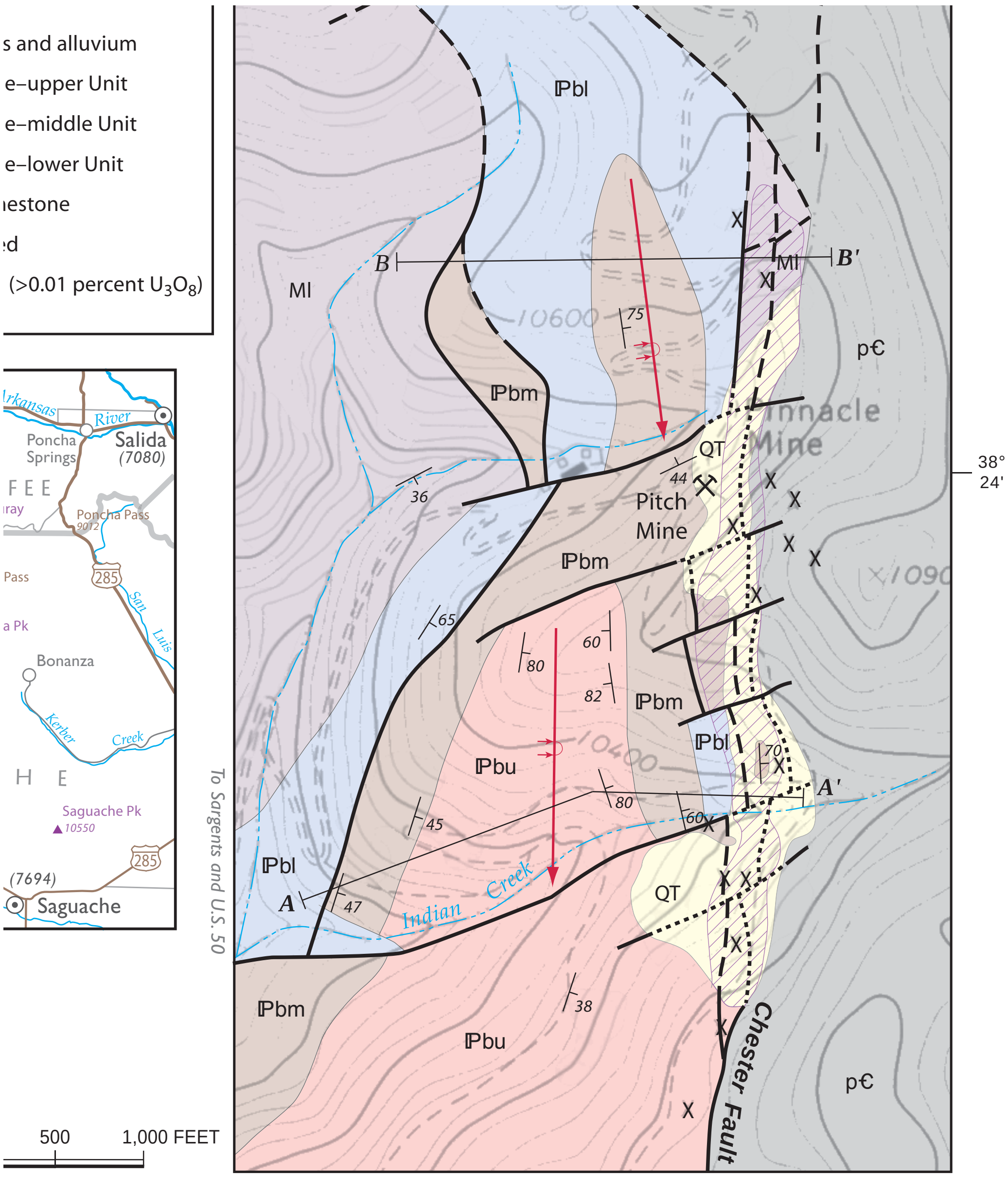


Figure 59. Preliminary geologic map of the area surrounding the Pitch Mine (formerly the Pinnacle Mine). Cross section A–A′ is shown in Figure 60, and cross section B–B′ is shown in Figure 61 (Nash, 1988).

deposit, which consists of uranium deposits in carbonaceous beds in the quartzites of the Harding Quartzite, and the Lookout No. 22 Mine, in which uranium deposits are in a fault zone in Proterozoic metamorphic rocks (Malan, 1959).

A unique set of uranium minerals was discovered in 1956 at the Lookout 22 claim. The host rock for this uranium deposit is Proterozoic schist. Uranium minerals include several forms of pitchblende and rare oxidation products such as schoepite ($2UO_2{\cdot}5H_2O$), ianthinite (similar composition as schoepite), becquerelite ($7UO_3 \cdot 11H_2O$), soddyite [$(UO_2)(SiO_4)_2(OH) 2 \cdot 5H_2O$], uranophane [$(H_3O)_2(UO_2)_2(SiO_4)_2 \cdot H_2O$], boltwoodite [$K_2(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$], and zeunerite and metazeunerite [$Cu(UO_2)_2(AsO_4)_2 \cdot 10–16H_2O$] (Gross, 1965). Some of the uranium deposits of the Marshal Pass district contained very high grade ore. The Lookout 22 deposit produced 42 tons of ore averaging 4.39 percent U_3O_8 and 360 tons of ore averaging 0.55 to 0.60 percent U_3O_8 (Gross, 1965).

Uranium deposits are found in carbonate rocks in the Pitch deposit (unsurveyed; pl. 1) (formerly known as the Erie No. 28 claim or Pinnacle deposit), which was discovered in 1955. The deposit was developed by two adits in 1959 through 1962 and produced about 100,000 tons of uranium ore at an average grade of 0.50 percent U_3O_8, equivalent to one million pounds of U_3O_8. An additional 100,000 pounds of U_3O_8 were produced through a solution-mining process. Malan (1959, p. 14) described the mineralization as being in Precambrian rocks and a limestone bed of the Belden Shale.

In 1972, Homestake Mining Company acquired the property and proceeded to develop an open-pit–minable resource of 2.1 million tons at an average grade of 0.17 percent U_3O_8, equivalent to 7,140,000 pounds of U_3O_8 (Nash, 1988, p. 1–2). As the exploration program proceeded, the company geologists recognized that they had discovered a previously unrecognized type of uranium ore deposit in brecciated dolomite of the Mississippian Leadville Limestone. Ore mined from 1959 to 1963 was probably also from the Leadville Limestone though that possibility was unrecognized. Homestake mined the deposit from 1975 to 1985. The ore was processed at Homestake's mill near Grants, New Mexico. Production from the mine is listed in **table 2**.

Geology

The geology of the Marshall Pass district was described in a geologic map (fig. 59) of the area by Olson (1983) and in a report on the uranium mineralization by Nash (1988). Paleozoic sedimentary rocks unconformably overlie Paleoproterozoic quartz monzonite and hornblende and mica gneiss. The youngest rocks of the Marshall Pass uranium district are sandy-textured tuffs that are part of a quartz latite ash-flow tuff sequence of Oligocene age (Nash, 1988, p. 5).

The main structural feature of the area is the north-trending Chester fault (fig. 59). The complex fault system dips about 70° to the east and has a net reverse displacement of 2,000 ft. In the mine area, Proterozoic pegmatitic granite is displaced over the Paleozoic section to the west (**figs. 60 and 61**). The Paleozoic rocks on the west side of the fault have been folded to an overturned syncline.

Table 2. Production for Homestake Mining Company operations at Pitch Mine, 1975–1985. (From Alan Cox, Homestake Mining Company, 2003).

Year	Ore (tons)	U_3O_8 (pounds)
1975	514	2,122
1976	—	—
1977	3,132	12,405
1978	52	186
1979	12,843	44,496
1980	90,770	441,737
1981	35,239	204,620
1982	24,800	239,446
1983	72,590	867,738
1984	30,610	179,572
1985	3,205	20,464
TOTAL	**273,754**	**2,012,786**

Ore Deposits

The Chester fault is the main feature that controlled ore deposition not only at the Pitch Mine, but also the nearby Little Indian deposit in Gunnison County. Movement along the Chester fault created fractures in the brittle dolomite rocks of the Leadville Limestone at the Pitch Mine and in the Harding Quartzite and the dolomites of the Fremont Dolomite and the Manitou Formation. Nash (1988, p. 33) suggested that iron sulfide minerals and organic material in the Leadville Limestone created a reducing environment, a favorable site for the deposition of uranium. Nash also suggested that the source of the uranium was the overlying volcanic rocks, the quartz latite ash-flow tuff and the Rawley Andesite, now both mainly eroded away in the mine area. Oxidizing ground water moved along and near the fault, and the ground water would have been able dissolve uranium from the volcanic rocks and transport it at low temperatures (<100° C) to favorable sites of reduction and precipitation in the fractures of the Leadville Limestone and other Paleozoic rocks of the district.

COCHETOPA URANIUM DISTRICT

The Cochetopa uranium district is located in northwestern Saguache County about 20 mi southeast of Gunnison. The original discovery of the district was made in 1954 at the Los Ochos claim, which eventually became the Thornburg Mine (sec. 4, T. 48 N., R. 2 E.; pl. 1). Production at the Thornburg Mine and the adjoining Kathy Jo and Irishmen's Dream claims totaled 551 tons from 1954 to 1962 (McFaul and others, 2000).

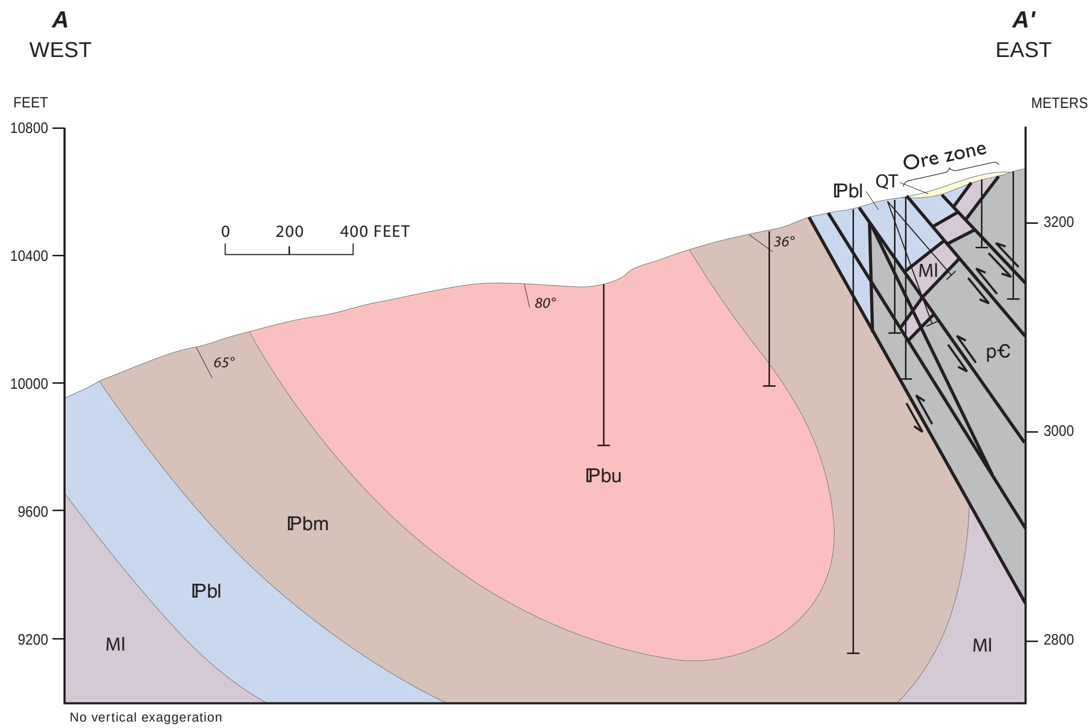


Figure 60. Schematic cross-section A–A′ of the Pitch Mine area. Line of section shown in Figure 59 (After Nash, 1988).

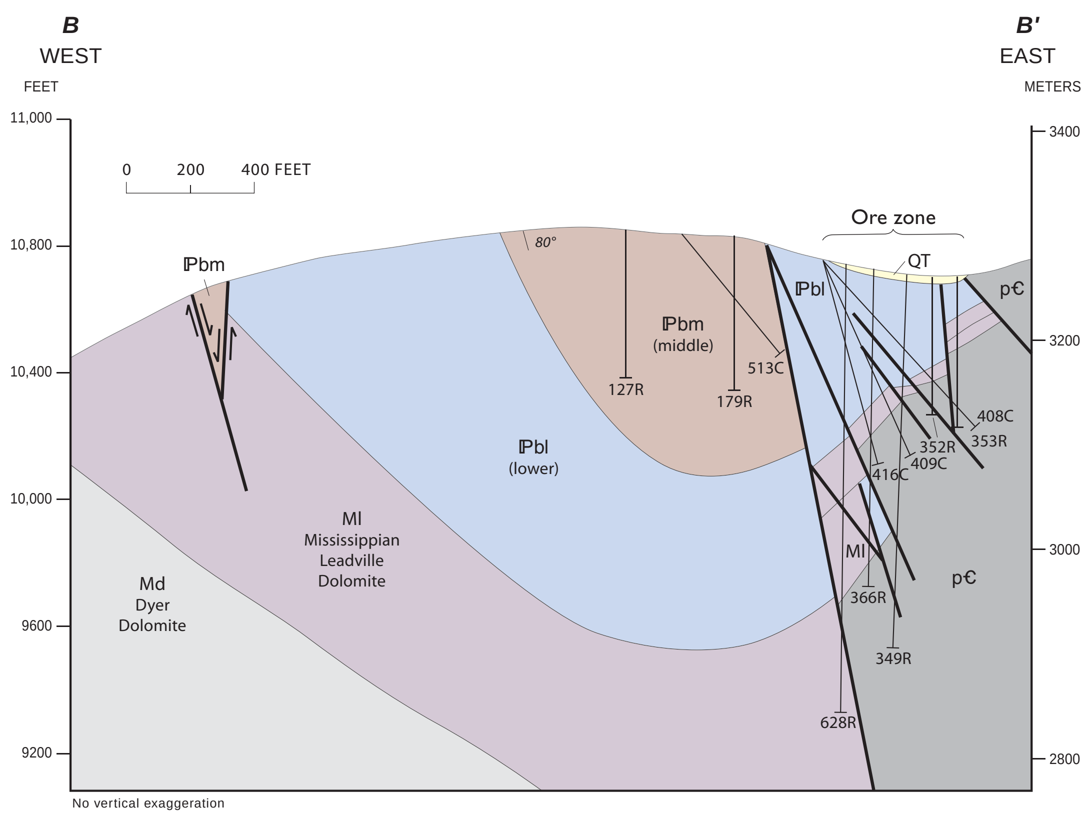


Figure 61. Schematic cross-section B–B′ of the Pitch Mine area. Line of section shown in Figure 59 (After Nash, 1988).

Geology

The oldest rocks of the district are Proterozoic metamorphic rocks that consist of quartz-biotite schist, hornblende gneiss, and minor ultramafic rocks, which were intruded by Proterozoic biotite granite and granite gneiss. The Upper Jurassic Morrison Formation, which in this area is about 300 ft thick, unconformably overlies the older metamorphic and igneous rocks. The Lower Cretaceous Dakota Sandstone and the Upper Cretaceous Mancos Shale overlie the Morrison Formation. Miocene volcanic rocks, including the Conejos Formation and younger quartz latites and rhyolites, are found in the southern part of the district (Malan and Ranspot, 1959, p. 4).

Northeast- and east-trending faults are the dominant structural features of the district. The east-trending Los Ochos fault is near vertical and displaces the Morrison Formation beds about 120 ft down to the north. Splits of the fault contain ore bodies in the Thornburg Mine. Another east-trending fault in the southern part of the district displaces Miocene volcanic rocks against Proterozoic igneous rocks (Malan and Ranspot, 1959, p. 6)

Ore Deposits

In the Thornburg Mine, the silicified and brecciated sandstone and mudstone of the Brushy Basin Member of the Morrison Formation contain black, sooty to semihard, fine-grained pitchblende in veinlets filled with marcasite and clay minerals and as finely disseminated grains in fractures and quartz gangue (Malan and Ranspot, 1959, p. 8). Surface exposures of the ore deposits contain secondary uranium oxide minerals, such as autunite and uranophane. Mineral deposits also are found in the Proterozoic schist and pegmatites. The Thornburg Mine (including the Irishmen's Dream and Kathy Jo claims) produced more than 1,253,000 pounds of U_3O_8 at an average grade of 0.14 percent U_3O_8 (Nelson-Moore and others, 1978).

Malan and Ranspot (1959, p. 7) suggested the following sequence of events in the formation of the ore deposit at the Thornburg Mine: (1) initial displacement along the Los Ochos fault; (2) invasion of the wall rocks and fault by solutions resulting in intense silica replacement of the sedimentary rocks along the fault; (3) renewed movement along the fault in which a linear zone of silicified rocks adjacent to the fault was extensively brecciated and fractured; and (4) introduction of marcasite and pitchblende.

OTHER URANIUM DEPOSITS

The Mercury-Alpine Mine is located just below Hermit Peak near the Saguache-Custer county line. At this deposit, uraninite is found in pockets of silty arkose in the Permian Sangre de Cristo Formation. Twenty-five tons of ore were mined from the Mercury-Alpine Mine at an average grade of 0.31 percent U_3O_8 (Nelson-Moore and others, 1978).

The Bonita Mine is located in sec. 23, T. 48 N., R. 72 E., just southwest of the abandoned town site of Shirley. Autunite and possibly other uranium minerals are found in a seam of black carbonaceous material along the contact between Proterozoic granite and overlying volcanic rocks of the Bonanza caldera (possibly the Rawley Andesite?). The ore host is strongly altered to hematite, kaolinite, and sericite and is thought to be a regolith. From 1955 to 1958, the mine produced 163 tons of ore at an average grade of 0.144 percent U_3O_8 (Nelson-Moore and others, 1978).

The Beginners Luck Mine is located in the NE¼ sec. 33, T. 45 N., R. 33 E. Pitchblende, coffinite, and autunite are found in small discontinuous fractures in the Harding Quartzite. In 1955, nine tons of ore were mined at an average grade of 0.15 percent U_3O_8 and 0.09 percent V_2O_5 (Nelson-Moore and others, 1978).

The Mocking Bird Mine is located along the foothills of the Sangre de Cristo Range in sec. 4, T. 46 N., R. 10 E. Uranium minerals of unknown type are found in a zoned pegmatite dike in Proterozoic gneiss. One sample assayed 0.271 percent U_3O_8. In 1954, six tons of ore were mined at an average grade of 0.20 percent U_3O_8 (Nelson-Moore and others, 1978).

Several small deposits of uranium and copper are found in the lower Sangre de Cristo Formation and the upper Minturn Formation along the crest of the Sangre de Cristo Range in Saguache and Custer counties. The deposits also contain anomalous amounts of silver, molybdenum, lead, vanadium, and zinc. The deposits contain from 0.01 to 0.025 percent U_3O_8 and from 0.025 to 0.085 percent copper (Lindsey and Clark, 1995; Clark and Walz, 1985).

Several other small uranium deposits in Saguache County are described in Nelson-Moore and others (1978).

Geothermal Resources

The central and eastern part of Saguache County—the geographic San Luis Valley—is in the Rio Grande rift. This geologic province is characterized by high heat flow (**fig. 62**), especially along the western edge of the rift (Reiter and others, 1975). Chapin (1971) proposed a thinning of the crust and an upward bulge of the mantle under the rift. Several geothermal springs are in the northern San Luis Valley of Saguache County (**fig. 63**). Valley View Hot Springs and Mineral Hot Springs are currently (2004) developed as spa resorts. Shaws Warm Spring and Fullinwider Warm Spring remain undeveloped. The Sand Dunes Swimming Pool is serviced by a deep water well and is currently open as a limited resort facility with a restaurant and RV parking. The well was originally drilled as an oil and gas test by San Luis Valley Oil and Gas Company and was completed on June 29, 1924, to a total depth of 4,308 ft. This artesian well flows at a rate of 340 gallons per minute and can be pumped at a rate of 1,480 gallons per minute; the temperature of the water flowing from the well is 111° to 115° F (Ed Harmon, Sand Dunes Swimming Pool, personal communication, 2004).

The geothermal resources of the State and Saguache County have been described in numerous publications: George and others (1920), Barrett and Pearl (1976, 1978), Cappa and Hemborg (1995), and popular guides such as Frazier (1996) and Cahill (1986).

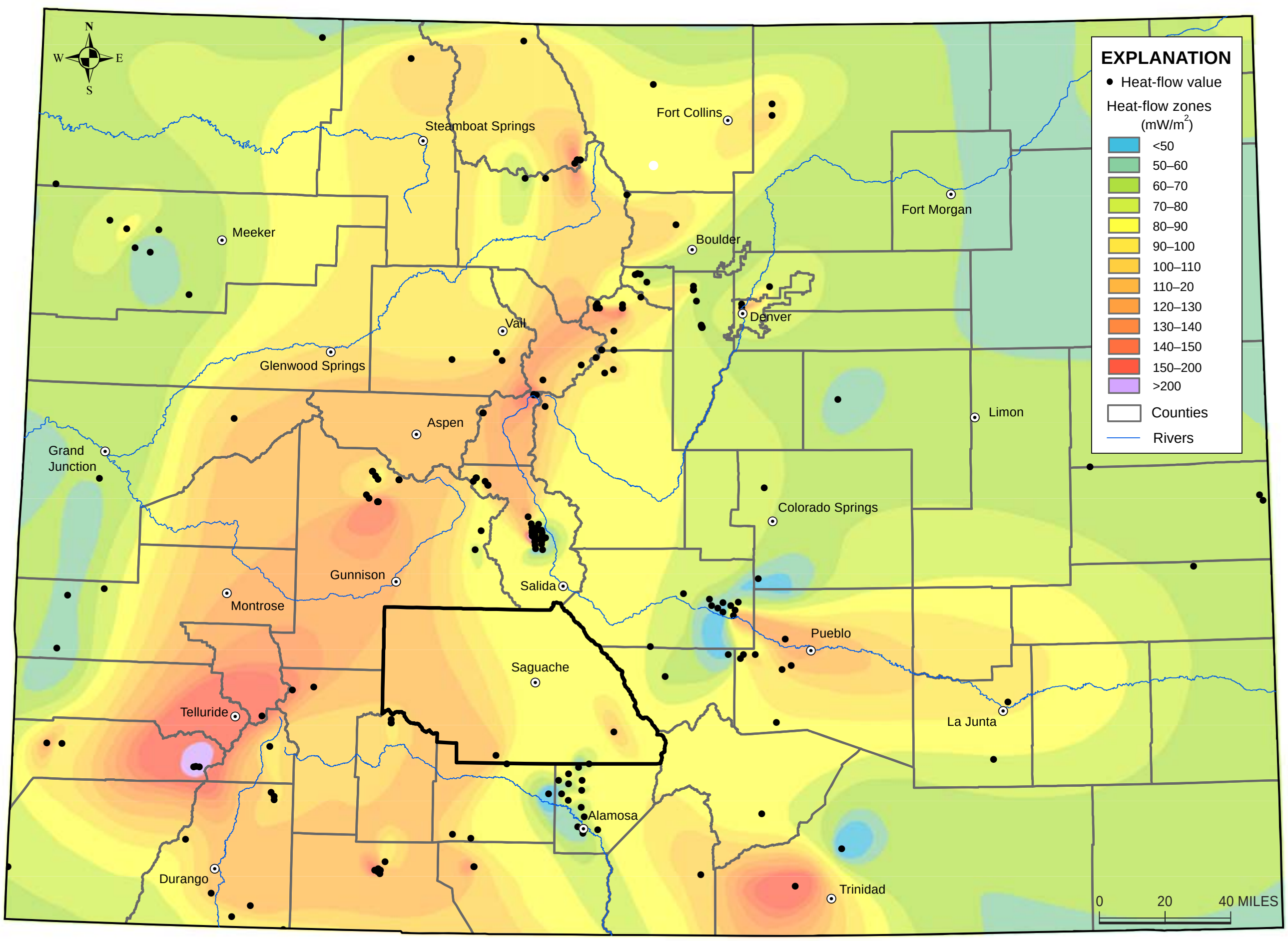


Figure 62. Heat-flow map of Colorado.

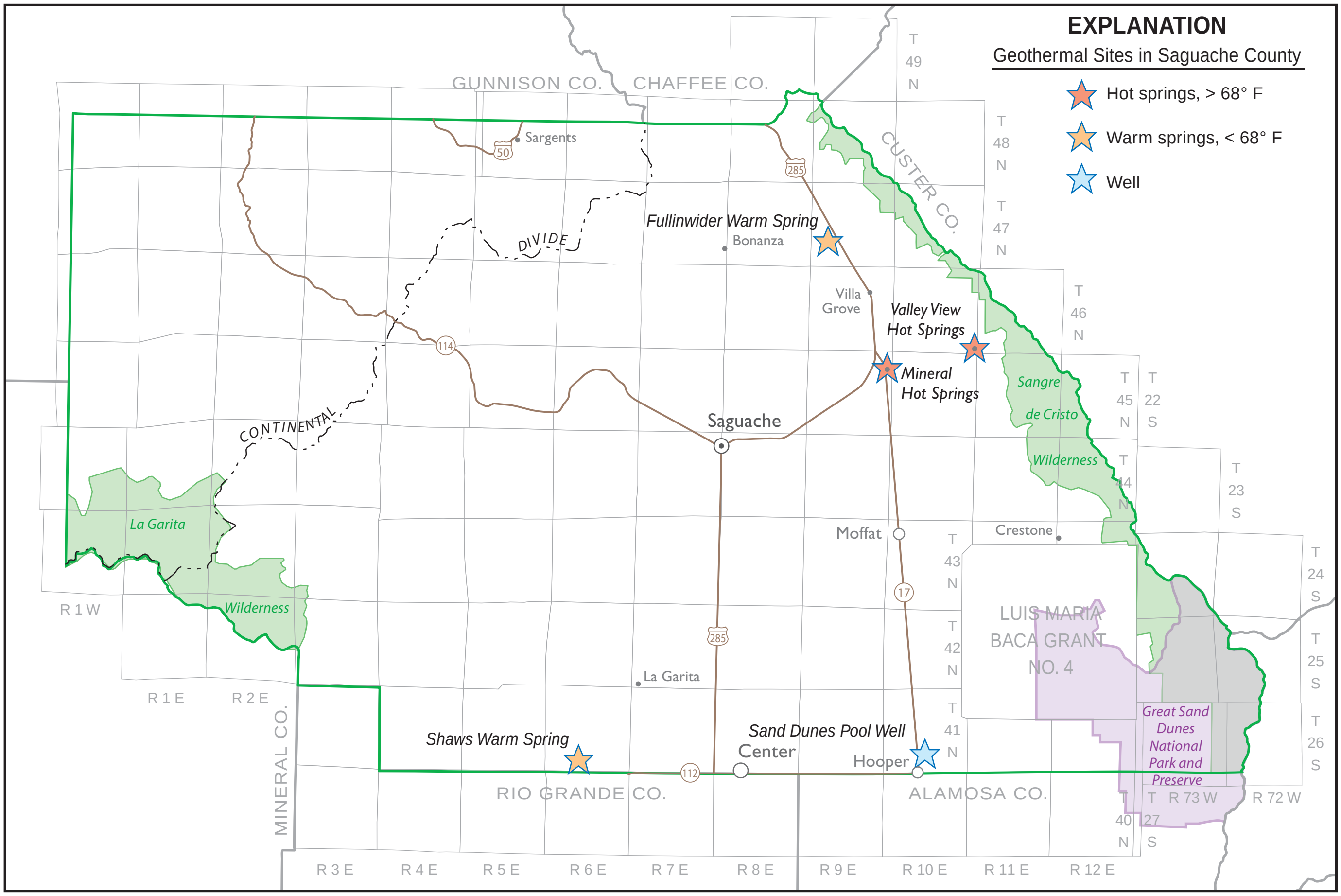


Figure 63. Geothermal sites in Saguache County.

Geochemical data and physical characteristics of the geothermal sites of Saguache County are listed in **table 3**.

In 1979, 16 geothermal-gradient drill holes were completed in the western San Luis Valley just south of the Saguache County line in Rio Grande and Alamosa counties. All drill holes were planned for a total depth of 330 ft. Bottom-hole temperatures and temperatures at 90 ft depth were measured and averaged for each drill hole. The average geothermal gradient of all 16 drill holes is 220° F/mi (Ringrose, 1980).

IIn 1983, the Colorado Geological Survey studied the geothermal resource potential of the Shaws Warm Spring in the western part of the San Luis Valley. The study confirmed earlier estimates of a geothermal resource of small size, 0.6 sq mi, at a temperature of 113° F (Zacharakis and others, 1983). The question remains why high heat flow on the western side of the Rio Grande Rift fails to result in more significant geothermal sites.

Table 3. Chemistry and physical characteristics of low-temperature geothermal wells and springs of Saguache County.

	Type	Temp. (° C)	Flow (L/m)	pH	TDS	$CaCO_3$	HCO_3	PO_4	Ca	Mg	Na	K	Cl	SO_4	F	SiO_2
Fullinwider Warm Spring																
	WS	18	42	6.7	332	95	116	0.08	21	4.2	80	1.6	15	120	4.4	27
Mineral Hot Springs																
A	W	60	380	--	643	275	335	0.12	57.0	14.0	130.0	14.0	39.0	170.0	3.7	48
A	W	60	635	6.5	663	275	335	0.03	60.0	13.0	140.0	14.0	41.0	180.0	3.6	45
A	W	60	266	7.0	658	288	351	ND	57.0	13.0	140.0	15.0	39.0	170.0	3.9	47
A	W	60	361	6.8	639	289	352	0.12	59.0	13.0	140.0	14.0	37.0	150.0	4.6	47
B	HS	51	small	--	--	--	--	--	--	--	--	--	--	--	--	--
C	HS	60	--	--	723	280	341	0.12	60.0	14.0	150.0	14.0	43.0	190.0	4.2	50
D																
D	HS	59	--	--	665	286	349	0.09	55.0	13.0	140.0	14.0	39.0	170.0	3.9	48
D	HS	60	--	6.5	690	290	354	0.03	59.0	13.0	150.0	14.0	40.0	190.0	3.4	45
D	HS	60	19E	6.5	657	289	352	ND	56.0	13.0	140.0	14.0	40.0	170.0	3.8	46
D	HS	60	--	7.3	648	288	351	0.12	58.0	13.0	140.0	14.0	38.0	160.0	4.6	47
Sand Dunes Swimming Pool Well																
	W	44	1,300	8.3	334	144	176	0.18	3.2	0.4	81.0	8.6	4.7	23.0	5.9	120
	W	43	--	8.8	--	--	--	--	--	--	--	--	--	--	--	--
Shaws Warm Spring																
	HS	30	129	9.3	406	214	121	0.12	0.9	0.6	130.0	1.5	7.5	50.0	3.1	83
	HS	30	129	9.3	402	222	114	0.09	0.5	0.3	130.0	1.4	7.2	53.0	2.9	73
	HS	30	198	9.0	424	221	154	0.15	2.7	0.7	130.0	1.5	7.3	46.0	3.0	100
	HS	30	152	8.9	398	219	127	0.12	0.9	0.1	130.0	1.5	7.0	46.0	4.2	76
	HS	28	--	9.5	--	--	--	--	--	--	--	--	--	--	--	--
Valley View Hot Springs																
A	HS	37	--	--	252	98	120	0.03	51.0	15.0	3.5	2.5	0.8	96.0	0.4	21
A	HS	36	228E	6.5	249	102	124	ND	50.0	14.0	3.7	2.6	1.5	95.0	0.4	20
A	HS	35	--	6.8	243	102	124	0.09	50.0	14.0	3.9	2.7	1.1	89.0	0.3	20
A	HS	36	--	7.5	234	103	125	0.03	50.0	14.0	3.3	2.8	0.9	80.0	0.7	20
A	HS	35	190	7.8	--	--	--	--	--	--	--	--	--	--	--	--
B	HS	32	--	--	234	105	128	0.03	46.0	14.0	3.7	2.2	2.6	82.0	0.3	19
B	HS	34	250E	8.2	--	--	--	--	--	--	--	--	--	--	--	--
B	HS	34	456E	6.0	229	100	122	0.12	49.0	12.0	3.2	2.4	1.8	82.0	0.5	17
D	HS	35	285E	6.5	247	102	124	0.17	51.0	13.0	4.3	2.8	2.5	93.0	0.2	18
D	HS	36	285E	7.5	223	103	125	0.15	50.0	13.0	2.6	2.5	0.6	73.0	0.4	18
D	HS	31	380E	7.8	--	--	--	--	--	--	--	--	--	--	--	--

Oil and Gas Resources

Saguache County does not contain any commercial oil and gas resources. A total of 17 oil and gas wells were drilled in the county since the early 1920s, mostly in the San Luis Basin (**fig. 64**). **Table 4** lists the exploration oil and gas wells completed in Saguache County. None of the wells in Saguache County has any recorded production. The closest producing oil well is the Kirby 1 Jynnifer well, which was drilled just south of the Saguache County line in NE¼SE¼ sec. 9, T. 40 N., R. 5 E. This well produced 30 barrels of oil per day from a volcanic sill in the Cretaceous Mancos Shale (Gries, 1985a, p. 174).

In recent years, the most interesting development was the discovery of hydrocarbons in Mesozoic rocks during a gold exploration program along the western front of the Sangre de Cristo Range in the early 1990s by Lexam Explorations Inc. In this area, Proterozoic metamorphic rocks are thrust over a sequence of Mesozoic sedimentary rocks. Gold exploration drill holes encountered live oil in breccia and fractured gneiss below a thrust fault. Two wildcat wells were drilled to test the hydrocarbon potential in 1995. No economic amounts of oil were found. The Mesozoic sedimentary rocks in the well include the Mancos Shale, Dakota Sandstone, and Morrison Formation overlying Proterozoic quartz monzonite. The company is continuing to evaluate these properties (Lexam Explorations Inc., unpublished 2000 Annual Report).

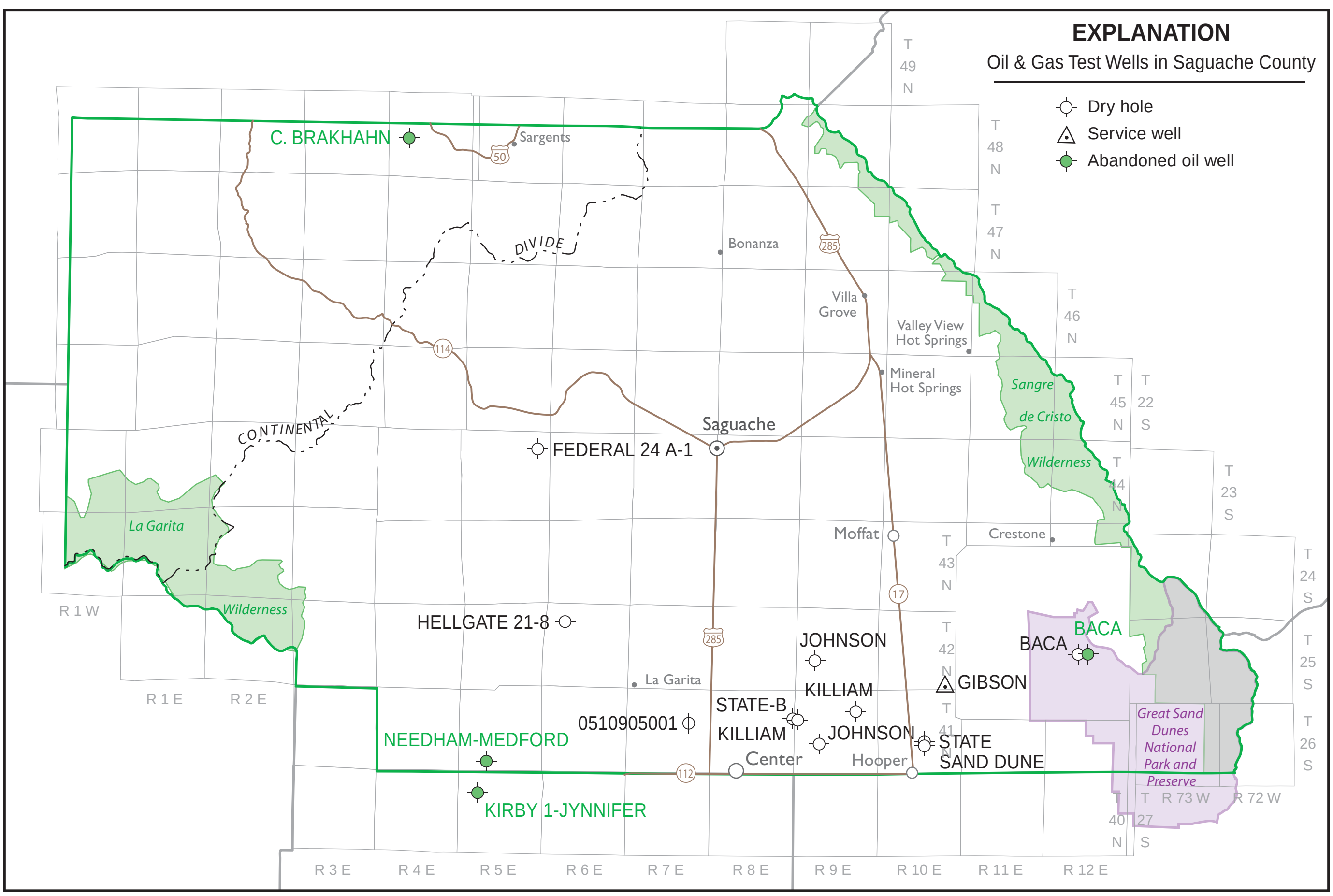


Figure 64. Oil and gas test wells in Saguache County.

Other oil shows of interest have been noted in the western part of Saguache County in the San Juan volcanic field. Oil shows were encountered in two mineral exploration core holes in the Summer Coon volcanic complex, sec. 19, T. 41 N., R. 6 E. Both drill holes intercepted fractured volcanic rock saturated with thick, biodegraded oil at depths of 1,024 ft and 720 ft, respectively (Gries, 1985a, p. 173–174). Gries (1985a) described several oil shows in volcanic rocks of the San Juan volcanic field south of Saguache County.

Table 4. Oil and gas wells drilled in Saguache County.

API number	Company	Lease	No.	Date of completion	Class	Total depth (feet)
50000000	Valley Oil & Gas	Gibson	1	6/22/1923	WF	4,308
50010000	Tenneco Oil Co.	State-B	1	5/5/1959	WF	10,346
50020000	Tucker Orin	Tucker-Thomas	1	12/31/1952	D	8,024
50030000	Snowden	Killiam	1	1/29/1952	WF	1,043
50030001	Snowden	Killiam	1	12/7/1952	D	3,985
50050000	Carr F. William	Kennedy-Williams	1	8/24/1952	D	6,200
50060000	Finnel Ranch	ND		ND	U	ND
50070000	Snowden	Johnson	1	12/31/1952	WF	702
50080000	Majestic Petroleum Corp.	Brackhahn	1	11/6/1955	WF	830
50090000	Majestic Petroleum Corp.	Brackhahn	1	11/6/1955	WF	365
50100000	Snowden Homer	Johnson	1	9/10/1952	WF	700
50110000	San Luis Valley Oil & Gas	State	1	6/29/1924	WF	4,308
50120000	Nelson Bunker Hunt Trust Estate	R.K. Thomas	2	7/13/1956	WF	3,784
60010000	Needham and Medford Exploration	Needham-Medford	1	3/17/1985	WF	8,824
60020000	Champlin Petroleum Co.	Federal 24 a-1	1	12/24/1985	WF	3,260
60030000	Wolverine Exploration Co.	Hellgate 21-8	1	12/17/1988	WF	12,000
60040000	Lexam Explorations Inc.	Baca	1	9/26/1995	WF	4,322
60050000	Lexam Explorations Inc.	Baca	2	10/29/1995	WF	6,932

***The API numbers are all preceded by 051090. Abreviations: D, development well (dry); WF, new field wildcat (dry); U, unclassified, ND, no data.**

References

Armstrong, A.K., Mamet, B.L., and Repetski, J.E., 1992, Stratigraphy of the Mississippian System, south-central Colorado and north-central New Mexico: U.S. Geological Survey Bulletin 1787-EE, 22 p.

Balleweg, K.J., 1990, Geology of the Orient limonite deposit, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 218 p.

Barrett, J.K., and Pearl, R.H., 1976, Hydrogeochemical data of thermal springs and wells in Colorado: Colorado Geological Survey Information Series 6, 124 p.

Barrett, J.K., and Pearl, R.H., 1978, An appraisal of Colorado's geothermal resources: Colorado Geological Survey Bulletin 39, 224 p.

Benson, R.G., 1997, Detachment fault-related mineralization in a rift setting at the San Luis gold deposit and Sangre de Cristo Mountains, Alamosa, Costilla, and Saguache counties, Colorado: Golden, Colo., Colorado School of Mines, Ph.D. thesis, 226 p.

Benson, R.G., and Jones, D.M., 1996, Geology of the San Luis gold deposit, Costilla County, Colorado: An example of low-angle normal fault and rift-related mineralization in the Sangre de Cristo Range of Colorado, in Thompson, R.A., Hudson, M.R., and Pillmore, C.L., eds., Geological excursions to the Rocky Mountains and beyond, Field trip guidebook for the 1996 annual meeting, Geological Society of America, Denver, Colorado, October 28–31: Colorado Geological Survey Special Publication 44, CD-ROM.

Berg, R.R., and Ross, R.J., Jr., 1959, Trilobites from the Peerless and Manitou Formations: Journal of Paleontology, v. 33, no. 1, p. 106–119.

Bickford, M.E., Schuster, R.D., and Boardman, S.J., 1989, U-Pb geochronology of the Proterozoic volcano-plutonic terrane in the Gunnison and Salida areas, Colorado, *in* Grambling, J.A., and Tewksbury, B.J., eds., Proterozoic geology of the Southern Rocky Mountains: Geological Society of America Special Paper 235, p. 33–48.

Bolyard, D.W., 1956, Pennsylvanian and Permian stratigraphy in the Sangre de Cristo Mountains between La Veta Pass and Westcliffe (Custer and Saguache Counties), Colorado: Boulder, University of Colorado, M.S. thesis, 130 p.

Bolyard, D.W., 1959, Pennsylvanian and Permian stratigraphy in Sangre de Cristo Mountains between La Veta Pass and Westcliffe, Colorado: American Association of Petroleum Geologists Bulletin, v. 43, no. 8, p. 1896–1939.

Brainerd, A.E., Baldwin, H.L., Jr., and Keyte, I.A., 1933, Pre-Pennsylvanian stratigraphy of the Front Range in Colorado: American Association of Petroleum Geologists Bulletin, v. 17, no. 4, p. 375–396.

Bridwell, R.J., 1968, Geology of the Kerber Creek area, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 104 p.

Brill, K.G., Jr., 1942, Late Paleozoic stratigraphy of Gore area, Colorado: American Association of Petroleum Geologists Bulletin, v. 26, no. 8, p. 1375–1397.

Brill, K.G., Jr., 1952, Stratigraphy in the Permo–Pennsylvanian zeugogeosyncline of Colorado and northern New Mexico: Geological Society of America Bulletin, v. 63, p. 809–880.

Brister, B.S., and Gries, R.R., 1994, Tertiary stratigraphy and tectonic development of the Alamosa basin (northern San Luis Basin), Rio Grande rift, south-central Colorado, *in* Keller, R.G., and Cather, S.M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 39–58.

Brister, B.S., and McIntosh, W.C., 2004, Identification and correlation of Oligocene ignimbrites in well bores, Alamosa Basin (northern San Luis Basin), Colorado, by single-crystal laser-fusion $^{40}Ar/^{39}Ar$ geochronology of well-cuttings, *in* Cather, S.M., McIntosh, W.C., and Kelley, S.A., eds., Tectonics, geochronology, and volcanism in the Southern Rocky Mountains and Rio Grande rift: New Mexico Bureau of Geology and Mineral Resources Bulletin 160, p. 281–296.

Bruce, R.M., and Johnson, B.R., 1991, Reconnaissance geologic map of parts of the Zapata Ranch and Mosca Pass quadrangles, Alamosa and Huerfano

Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2168, scale 1:24,000.
Bruns, D.L., 1971, Geology of the Lake Mountain Northeast quadrangle, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 79 p.
Burbank, W.S., 1932, Geology and ore deposits of the Bonanza mining district, Colorado, with a section on history and production by Henderson, C.W.: U.S. Geological Survey Professional Paper 169, 166 p.
Cahill, Rick, 1986, Colorado hot springs guide: Boulder, Colo., Pruett Publishing Co., 180 p.
Campbell, J.A., 1972, Lower Paleozoic systems, White River Plateau, *in* De Voto, R.H., ed., Paleozoic stratigraphy and structural evolution of Colorado: Quarterly of the Colorado School of Mines, v. 67, no. 4, p. 37–62.
Cappa, J.A., and Hemborg, H.T., 1995, 1992–1993 low temperature geothermal assessment program, Colorado: Colorado Geological Survey Open-File Report 95-1, 35 p.
Carr, M.S., and Dutton, C.E., 1959, Iron-ore resources of the United States including Alaska and Puerto Rico, 1955: U.S. Geological Survey Bulletin 1082-C, 134 p.
Chapin, C.E., 1971, The Rio Grande rift: Part 1. Modifications and additions, in James, H.L., ed., Guidebook of the San Luis Basin, Colorado: New Mexico Geological Society, Twenty-Second Field Conference, p. 191–201.
Chronic, John, 1958, Pennsylvanian rocks in Colorado, in Symposium on Pennsylvanian rocks of Colorado and adjacent areas: Denver, Colo., Rocky Mountain Association of Geologists, p. 59–63.
Clark, R.F., and Walz, D.M., 1985, Stratigraphic sections, depositional environments, and metal content of the upper part of the middle Pennsylvanian Minturn Formation, northern Sangre de Cristo Range, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1622-D.
Clement, J.F., 1952, The geology of the northeastern Baca Grant area, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 129 p.
Condra, G.E., and Reed, E.C., 1943, The geological section of Nebraska: Nebraska Geological Survey Bulletin 14, 82 p.
Cook, D.R., 1960, Bonanza project, Bear Creek Mining Company: American Institute of Mining, Metallurgy, and Petroleum Engineers Transactions, 1960, v. 217, p. 285–295.
Cross, C.W., and Purington, C.W., 1899, Description of the Telluride quadrangle [Colorado]: U.S. Geological Survey Geologic Atlas of the United States, Folio 57, scale 1:62,500.
Davis, T.L., and Stoughton, D., 1979, Interpretation of seismic reflection data from the San Luis Valley, south-central Colorado, *in* Reicker, R.E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 185–194.
De Voto, R.H., 1972, Pennsylvanian and Permian stratigraphy and tectonism in central Colorado, *in* De Voto, R.H., ed., Paleozoic stratigraphy and structural evolution of Colorado: Quarterly of the Colorado School of Mines, v. 67, no. 4, p. 139–185.
De Voto, R.H., and Peel, F.A., 1972, Pennsylvanian and Permian stratigraphy and structural history, northern Sangre de Cristo Range, Colorado, *in* De Voto, R.H., ed., Paleozoic stratigraphy and structural evolution of Colorado: Quarterly of the Colorado School of Mines, v. 67, no. 4, p. 283–320.
Del Rio, S.M., 1960, Mineral resources of Colorado—First sequel: Denver, Colorado Mineral Resources Board, 764 p., 6 pls.
Drobeck, P.A., 1981, Proterozoic syngenetic massive sulfide deposits in the Gunnison gold belt, Colorado, *in* Epis, R.C., and Callender, J.F., eds., Western Slope, Colorado: New Mexico Geological Society Thirty-Second Field Conference Guidebook, p. 279–286.
Dungan, M.A., Lipman, P.W., Colucci, M., Ferguson, K., and Balsley, S., 1989, Southeastern (Platoro) caldera complex, in New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 305–329.
Eckel, E.B., 1949, Geology and ore deposits of the La Plata district, Colorado: U.S. Geological Survey Professional Paper 219, 179 p.
Eckel, E.B., 1997, Minerals of Colorado (updated and revised by Cobban, R.R., Collins, D.S., Foord, E.E., Kile, D.E., Modreski, P.J., and Murphy, J.A.): Golden, Colo., Fulcrum Publishing Co., 665 p.
Eldridge, G.H., 1894, Anthracite–Crested Butte, Colorado: U.S. Geological Survey Geological Atlas, Folio 9, 10 p., 8 maps.
Eldridge, G.H., 1896, Mesozoic geology, in Geology of the Denver Basin in Colorado: U.S. Geological Survey Monograph 27, p. 51–151.
Ellis, C.E., Hannigan, B.J., and Thompson, J.R., 1983, Mineral investigation of the Sangre de Cristo Wilderness Study Area, Alamosa, Custer, Fremont, Huerfano, and Saguache counties,

Colorado: U.S. Bureau of Mines Open-File Report MLA 65–83, 190 p.

Emmons, S.F., 1882, Geology and mining industry of Leadville, Lake County, Colorado: U.S. Geological Survey Annual Report, no. 2, p. 210–290.

Forkner, R.M., 2001, Origins of cone-forming breccias of the Summer Coon volcano [abs.]: Rocky Mountain (53rd) and South-Central (35th) Sections, Geological Society of America Annual Meeting (April 29–May 2, 2001); available at http://gsa.confex.com/gsa/2001RM/finalprogram/abstract_5888.htm (last accessed 18 July 2006).

Frazier, Deborah, 1996, Colorado's hot springs: Boulder, Colo., Pruett Publishing Co., 162 p.

George, R.D., Curtis, H.A., Lester, O.C., Crook, J.K., Yeo, J.B., and others, 1920, Mineral waters of Colorado: Colorado Geological Survey Bulletin 11, 474 p.

Gerhart, L.C., 1974, Redescription and new nomenclature of the Manitou Formation, Colorado: American Association of Petroleum Geologists Bulletin, v. 58, no. 7, p. 1397–1406.

Gregory, K.M., and McIntosh, W.C., 1996, Paleoclimate and paleoelevation of the Oligocene Pitch-Pinnacle flora, Sawatch Range, Colorado: Geological Society of America Bulletin, v. 108, no. 5, p. 545–561.

Gries, R.R., 1985a, San Juan Sag: Cretaceous rocks in a volcanic covered basin, south central Colorado: The Mountain Geologist, v. 22, no. 4, p. 167–179.

Gries, R.R., 1985b, Seismic lines in the San Luis Valley, south central Colorado, *in* Rice, R.R., and Dyer, R.C., eds., Seismic exploration in the Rocky Mountain region: Denver, Colo., Rocky Mountain Association of Geologists and Denver Geophysical Society, p. 267–274.

Gross, E.B., 1965, A unique occurrence of uranium minerals, Marshall Pass, Saguache County, Colorado: American Mineralogist, v. 50, p. 909–923.

Hansen, W.R., 1968, Geologic map of the Black Ridge quadrangle, Delta and Montrose counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-747.

Harrer, C.M., and Tesch, W.J., Jr., 1959, Reconnaissance of iron occurrences in Colorado: U.S. Bureau of Mines Information Circular 7918, 82 p.

Hayden, F.V., 1869, Preliminary field report of the United States geological survey of Colorado and New Mexico: U.S. Geological and Geographic Survey of the Territories, 1867, 1868, 1869, 175 p.

Hedlund, D.C., and Olson, J.C., 1974, Geologic map of the Iris NW quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1134, scale 1:24,000.

Hedlund, D.C., and Olson, J.C., 1975, Geologic map of the Powderhorn quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1178, scale 1:24,000.

Henderson, C.W., 1926, Mining in Colorado: U.S. Geological Survey Professional Paper 138, 263 p.

Hills, R.C., 1899, Elmoro folio, Colorado: U.S. Geological Survey Geologic Atlas of the United States, Folio 58, scale 1:125,000.

Hon, K., and Lipman, P.W., 1989, Western San Juan caldera complex, in New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 350–380.

Hunsaker, E.L., III, 1988, Geology and gold potential east of the Vulcan Mine, Gunnison and Saguache counties, Colorado: Fort Collins, Colo., Colorado State University, M.S. thesis, 113 p.

IHS Energy Group, 2004 [includes data current as of May 2004], PI/Dwights PLUS on CD U.S. well data: Englewood, Colo., IHS Energy Group (database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112).

Jackson, J.A., ed., 1997, Glossary of geology: Alexandria, Va., American Geological Institute, 769 p.

Johnson, B.R., and Bruce, R.M., 1991, Reconnaissance geologic map of parts of the Twin Peaks and Blanca Peak quadrangles, Alamosa, Costilla, and Huerfano counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2169, scale 1:24,000.

Johnson, B.R., Bruce, R.M., and Lindsey, D.A., 1989, Reconnaissance geologic map of the Medano Pass quadrangle and part of the Liberty quadrangle, Alamosa, Huerfano, and Saguache Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2089, scale 1:24,000.

Johnson, B.R., Lindsey, D.A., Bruce, R.M., and Soulliere, S.J., 1987, Reconnaissance geologic map of the Sangre de Cristo Wilderness Study Area, south-central Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1635-B, scale 1:62,500.

Johnson, R.B., 1969, Geologic map of the Trinidad quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-558, scale 1:250,000.

Karig, D.E., 1964, Structural analysis of the Sangre de Cristo Range, Venable Peak to Crestone Peak, Custer and Saguache counties, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 143 p.

Karig, D.E., 1965, Geophysical evidence of a caldera at Bonanza, Colorado: U.S. Geological Survey Professional Paper 525-B, p. B9–B12.

Kirk, E., 1931, The Devonian of Colorado: American Journal of Science, ser. 5, v. 22, p. 222–240.

Kluth, C.F., and Schaftenaar, C.H., 1994, Depth and geometry of the northern Rio Grande rift in the San Luis basin, south-central Colorado, *in* Keller, R.G., and Cather, S.M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 27–37.

Koch, R.W., 1963, A structural study of the Venable Peak region of the Sangre de Cristo Range, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 131 p.

Kottlowski, F.E., 1953, Tertiary–Quaternary sediments of the Rio Grande valley in southern New Mexico: New Mexico Geological Society Guidebook 4, p. 144–148.

Kouther, M.J.H., 1969, Geology and mineralization of the northwest part of the Bonanza quadrangle, Chaffee and Saguache counties, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 93 p.

Lenz, J., 2004, Acid-sulfate alteration under the scanning electron microscope: Available at http://www.science.smith.edu/departments/SEM/pages/Jen/Webpage.html (last accessed August 2005).

Lindsey, D.A., 1995a, Geologic map of the McCarty Park quadrangle, Costilla and Huerfano counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2282, scale 1:24,000.

Lindsey, D.A., 1995b, Geologic map of the Cuchara quadrangle, Huerfano County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2283, scale 1:24,000.

Lindsey, D.A., 2001, Late Paleozoic sedimentation and Laramide tectonics of the Sangre de Cristo Range, from Westcliffe to Crestone, Colorado (revised online edition): Log for joint SEPM–Colorado Scientific Society Field Trip, September 20–21, 1986, U.S. Geological Survey Open-File Report OFR-01-249, 18 p.

Lindsey, D.A., Andriessen, P.A.M., and Wardlaw, B.R., 1986a, Heating, cooling, and uplift during Tertiary time, northern Sangre de Cristo Range, Colorado: Geological Society of America Bulletin, v. 97, p. 1133–1143.

Lindsey, D.A., and Clark, R.F., 1995, Copper and uranium in Pennsylvanian and Permian sedimentary rocks, northern Sangre de Cristo Range, Colorado: U.S. Geological Survey Bulletin 2116, 23 p.

Lindsey, D.A., Clark, R.F., and Soulliere, S.J., 1985a, Reference section for the Minturn Formation (Middle Pennsylvanian) northern Sangre de Cristo Range, Custer County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1622-C.

Lindsey, D.A., Hassemer, J.R., Abrams, G.A., Taylor, R.B., and Hannigan, B.J., 1985b, Mineral resources of the Black Canyon and South Piney Creek Wilderness Study Areas, Saguache County, Colorado: U.S. Geological Survey Bulletin, 1716-A, 15 p., scale 1:24,000.

Lindsey, D.A., Johnson, B.R., and Andriessen, P.A.M., 1983, Laramide and Neogene structure of the northern Sangre de Cristo Range, south-central Colorado, *in* Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colo., Rocky Mountain Association of Geologists Symposium, p. 219–228.

Lindsey, D.A., Johnson, B.R., Soulliere, S.J., Bruce, R.M., and Hafner, Katrin, 1986b, Geologic map and sections of the Beck Mountain, Crestone Peak, and Crestone quadrangles, Custer, Huerfano, and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1878, scale 1:24,000.

Lindsey, D.A., and Schaefer, R.A., 1984, Principal reference section for the Sangre de Cristo Formation (Pennsylvanian and Permian), northern Sangre de Cristo Range, Saguache County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1622-A.

Lindsey, D.A., Scott, G.R., Soulliere, S.J., and DeAngelis, B.L., 1984, Geologic map of the Horn Peak quadrangle, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1623, scale 1:24,000.

Lindsey, D.A., and Soulliere, S.J., 1987, Geologic map and sections of the Valley View Hot Springs quadrangle, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1942, scale 1:24,000.

Lindsey, D.A., Soulliere, S.J., and Hafner, Katrin, 1985c, Geologic map of the Electric Peak and southwestern part of the Beckwith Mountain quadrangles, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1786, scale 1:24,000.

Lindsey, D.A., Soulliere, S.J., Hafner, Katrin, and Flores, R.J., 1985d, Geologic map of the Rito Alto Peak and northeastern part of the Mirage quadrangles, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1787, scale 1:24,000.

Lipman, P.W., 1968, Geology of the Summer Coon volcanic center, eastern San Juan Mountains, Colorado, *in* Epis, R.C., ed., Cenozoic volcanism in the Southern Rocky Mountains: Quarterly of the Colorado School of Mines, v. 63, no. 3, p. 211–236.

Lipman, P.W., 1975, Volcanic evolution of the Platoro caldera complex and related rocks, southeastern San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 852, 128 p.

Lipman, P.W., 1976, Geologic map of the Del Norte area, eastern San Juan Mountains, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-952.

Lipman, P.W., 1989, Oligocene–Miocene San Juan volcanic field, Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 303–305.

Lipman, P.W., 2000, Central San Juan caldera cluster: Regional framework, in Bethke, P.M., and Hay, R.L., eds., Ancient Lake Creede: Its volcano-tectonic setting, history of sedimentation, and relation to mineralization in the Creede mining district: Geological Society of America Special Paper 346, p. 9–69.

Lipman, P.W., 2003, Southward migration of mid-Tertiary volcanism: Relations in the Cochetopa area, north-central San Juan Mountains, Colorado [abs.]: Geological Society of America, Rocky Mountain Chapter Annual Meeting, Durango, Colo.; available at http://gsa.confex.com/gsa/2003RM/finalprogram/abstract_52568.htm (last accessed December 2005).

Lipman, P.W., 2006, Geologic map of the central San Juan caldera complex, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-2799, scale 1:50,000.

Lipman, P.W., Fisher, F.S., Mehnert, H.H., Naeser, C.W., Luedke, R.G., and Steven, T.A., 1976, Multiple ages of mid-Tertiary mineralization and alteration in the western San Juan Mountains, Colorado: Economic Geology, v. 71, no. 3, p. 571–588.

Lipman, P.W., and Sawyer, D.A., 1988, Preliminary geology of the San Luis Peak quadrangle and adjacent areas, San Juan volcanic field, southwestern Colorado: U.S. Geological Survey Open-File Report 88-359, scale 1:24,000, 32 p.

Lipman, P.W., Sawyer, D.A., and Hon, K., 1989, Central San Juan caldera cluster: New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 330–349.

Lipman, P.W., Steven, T.A., and Mehnert, H.H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by potassium-argon dating: Geological Society of America Bulletin, v. 81, no. 8, p. 2327–2352.

Lisle, R.E., 1974, The geology and geochemistry of the Embargo intrusive center, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 85 p.

Litsey, L.R., 1958, Stratigraphy and structure of the northern Sangre de Cristo Mountains, Colorado: Geological Society of America Bulletin, v. 69, p. 1143–1178.

Madole, R.F., 2004, Quaternary geology and geomorphology of the Indian Spring district and adjoining areas: Mosca, Colorado: Great Sand Dunes National Monument and Preserve, 37 p. (in press; unpublished manuscript submitted to the Colorado State Historic Fund, Project 2001-P1-015, by The Friends of The Dunes, Mosca, Colorado).

Maill, A.D., 1978, Lithofacies types and vertical profile models in braided river deposits—A summary, *in* Maill, A.D., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 597–604.

Malan, R.C., 1959, Geology and uranium deposits of the Marshall Pass district, Gunnison, Saguache and Chaffee counties, Colorado: Denver, Colorado Mining Association, National Western Mining Conference, 20 p.

Malan, R.C., and Ranspot, H.W., 1959, Geology of the uranium deposits in the Cochetopa mining district, Saguache and Gunnison counties, Colorado: Economic Geology, v. 54, p. 1–19.

Marrs, R.W., 1973, Application of remote sensing techniques to the geology of the Bonanza volcanic center: Golden, Colo., Colorado School of Mines, Ph.D. dissertation, 281 p.

Mayhew, J.D., 1969, Geology of the eastern part of the Bonanza volcanic field, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 94 p.

McCalpin, J.P., 1982, Quaternary geology and neotectonics of the west flank of the northern Sangre de Cristo Mountains, Colorado: Colorado School of Mines Quarterly, v. 77, no. 3, 97 p.

McFaul, E.J., Mason, G.T., Jr., Ferguson, W.B., and Lipin, B.R., 2000, U.S. Geological Survey mineral databases—MRDS and MAS/MILS: U.S. Geological Survey Digital Data Series DDS-52, two discs.

McIntosh, W.C., and Chapin, C.E., 2004, Geochronology of the central Colorado volcanic field, *in* Cather, S.M., McIntosh, W.C., and Kelley, S.A., eds., Tectonics, geochronology, and volcanism in the Southern Rocky Mountains and Rio Grande rift: New Mexico Bureau of Geology and Mineral Resources Bulletin 160, p. 205–237.

Meek, F.B., and Hayden, F.V., 1862, Descriptions of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska: Academy of Natural Science of Philadelphia, Pennsylvania, Proceedings 1861, v. 13, p. 415–447.

Melton, F.A., 1925, Correlation of Permo–Carboniferous red beds in southwestern Colorado and northern New Mexico: Journal of Geology, v. 33, p. 807–815.

Mertzman, S.A., Jr., 1971, The Summer Coon volcano, eastern San Juan Mountains, Colorado, *in* James, H.L., ed., Guidebook of the San Luis Basin, Colorado: New Mexico Geological Society Twenty-Second Field Conference, p. 265–272.

Mertzman, S.A., Jr., 1972, The geology and petrology of the Summer Coon volcano, Colorado: Cleveland, Ohio, Case Western Reserve University, Ph.D. dissertation, 253 p.

Molenaar, C.M., and Baird, J.K., 1989, Stratigraphic cross sections of Upper Cretaceous rocks in the northern San Juan basin, southwestern Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2068.

Myrow, P.M., Taylor, J.P., Miller, J.F., Ethington, R.L., Ripperdan, R.L., and Allen, J., 2003, Fallen arches: Dispelling myths concerning Cambrian and Ordovician paleogeography of the Rocky Mountain region: Geological Society of America Bulletin, v. 115, no. 6, p. 695–713.

Nadeau, J.E., 1972, Mississippian stratigraphy of central Colorado, *in* De Voto, R.H., ed., Paleozoic stratigraphy and structural evolution of Colorado: Quarterly of the Colorado School of Mines, v. 67, no. 4, p. 77–101.

Nash, J.T., 1988, Geology and geochemistry of the Pitch uranium mine area, Saguache County, Colorado: U.S. Geological Survey Bulletin 1797, 38 p.

Nelson-Moore, J.L., Collins, D.B., and Hornbaker, A.L., 1978, Radioactive mineral occurrences of Colorado and bibliography: Colorado Geological Survey Bulletin 40, 1054 p.

Olson, J.C., 1974, Geologic map of the Rudolph Hill quadrangle, Gunnison, Hinsdale, and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1177, scale 1:24,000.

Olson, J.C., 1976a, Geologic map of the Iris quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1286, scale 1:24,000.

Olson, J.C., 1976b, Geologic map of the Houston Gulch quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1287, scale 1:24,000.

Olson, J.C., 1983, Geologic and structural maps and sections of the Marshall Pass mining district, Saguache, Gunnison, and Chaffee counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1425, scale 1:24,000.

Olson, J.C., and Hedlund, D.C., 1973, Geologic map of the Gateview quadrangle, Gunnison County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1071, scale 1:24,000.

Olson, J.C., and Steven, T.A., 1976a, Geologic map of the Sawtooth Mountain quadrangle, Saguache County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-733, scale 1:24,000.

Olson, J.C., and Steven, T.A., 1976b, Geologic map of the Razor Creek Dome quadrangle, Saguache County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-748, scale 1:24,000.

Olson, J.C., Steven, T.A., and Hedlund, D.C., 1975, Geologic map of the Spring Hill Creek quadrangle, Saguache County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-713, scale 1:24,000.

Osterwald, E.J., 1977, The Beidell and Sanderson volcanic centers, Saguache County, Colorado: Fort Collins, Colo., Colorado State University, M.S. thesis, 145 p.

O'Sullivan, R.B., 1992, Jurassic Wanakah and Morrison Formations in the Telluride–Ouray–western Black Canyon area of southwestern Colorado: U.S. Geological Survey Bulletin 1927, 24 p.

Pansze, A.J., 1987, Geologic sketch of the Crystal Hill breccia pipe, Saguache County, Colorado, in Gold mineralization of Colorado's Rio Grande rift: Denver, Colo., Denver Region Exploration Geologists Society, Fall Field Guidebook, p. 23–25.

Patton, H.B., 1916, Geology and ore deposits of the Bonanza district, Saguache County, Colorado: Colorado Geological Survey Bulletin 9, 136 p.

Pearl, R.M., 1941, Turquoise deposits of Colorado: Economic Geology, v. 36, p. 335–344.

Peel, F.A., 1971, New interpretations of Pennsylvanian and Permian stratigraphy and structure history, northern Sangre de Cristo Range, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 75 p.

Perry, H.A., 1971, Geology of the northern part of the Bonanza volcanic field, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 72 p.

Peterson, F., and Turner-Peterson, C.E., 1987, The Morrison Formation of the Colorado Plateau—Recent advances in sedimentology, stratigraphy, and paleotectonics: Hunteria, v. 2, no. 1, p. 1–18.

Pettijohn, F.J., 1957, Sedimentary rocks: New York, Harper and Row, 718 p.

Pierce, Walter, 1969, Geology and the Pennsylvanian–Permian stratigraphy of the Howard area, Fremont, County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 129 p.

Reiter, M., Edwards, C.L., Hartman, H., and Weridman, C., 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geological Society of America Bulletin, v. 86, p. 811–818.

Ringrose, C.D., 1980, Temperature-depth profiles in the San Luis Valley and Canon City areas, Colorado: Colorado Geological Survey Open-File Report 80-12, 18 p.

Robinson, T.W., Jr., and Waite, H.A., 1937, Ground water in the San Luis Valley, Colorado: A contribution to the Rio Grande Joint Investigation: Washington, D.C., U.S. Government Printing Office, U.S. Geological Survey, 119 p.

Ross, R.J., Jr., and Tweto, Ogden, 1980, Lower Paleozoic sediments and tectonics in Colorado, *in* Kent, H.C., and Porter, K.W., eds., Symposium on Colorado geology: Denver, Colo., Rocky Mountain Association of Geologists, p. 47–56.

Scott, G.R., Taylor, R.B., Epis, R.C., and Wobus, R.A., 1978, Geologic map of the Pueblo 1° × 2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1022, scale 1:250,000.

Shafer, D.S., 1989, The timing of late Quaternary monsoon precipitation maxima in the southwest United States: Tucson, Ariz., University of Arizona, Ph.D. dissertation, 234 p.

Siebenthal, C.E., 1910, Geology and water resources of the San Luis valley, Colorado: U.S. Geological Survey Water-Supply Paper 240, 128 p.

Smith, R.L., 1960, Ash Flows: Geological Society of America Bulletin, v. 71, p. 795–842

Soulliere, S.J., DeAngelis, B.L., and Lindsey, D.A., 1984, Measured sections and discussion of the main turbidite member, middle Pennsylvanian Minturn Formation, northern Sangre de Cristo Range, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1622-B.

Spencer, M.I., and Goldman, A.C., 1941, Correlation of Cross' La Plata sandstone, southwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 25, no. 9, p. 1745–1767.

Steven, T.A., and Bieniewski, C.L., 1977, Mineral resources of the La Garita Wilderness, San Juan Mountains, Colorado: U.S. Geological Survey Bulletin 1420, 65 p.

Steven, T.A., and Eaton, G.P., 1975, Geologic environment of ore deposition in the Creede district, San Juan Mountains, Colorado: Economic Geology, v. 70, p. 1023–1037.

Steven, T.A., and Hail, W.J., Jr., 1989, Geologic map of the Montrose 30 x 60 minute series quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1939, scale 1:100,000.

Steven, T.A., and Lipman, P.W., 1976, Calderas of the San Juan volcanic field, southwestern Colorado: U.S. Geological Survey Professional Paper 958, 35 p.

Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Leudke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-764, scale 1:250,000.

Steven, T.A., and Ratte, J.C., 1965, Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 487, 90 p.

Stone, J.B., 1934, Limonite deposits at the Orient Mine, Colorado: Economic Geology, v. 29, p. 317–329.

Stoughton, D., 1977, Interpretation of seismic reflection data from the San Luis Valley, south-central Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 100 p.

Sweet, W.C., 1954, Harding and Fremont Formations, Colorado: American Association of Petroleum Geologists Bulletin, v. 38, p. 284–305.

Taylor, R.B., Scott, G.R., Wobus, R.A., and Epis, R.C., 1975, Reconnaissance geologic map of the Cotopaxi 15-minute quadrangle, Fremont and Custer counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-900, scale 1:62,500.

Thompson, T.B., 1992, Geology and mineral deposits of the Bondholder district, Colorado, USA: Society of Economic Geologists Newsletter, January 1992, no. 8, p. 1–16.

Toulmin, P., III, 1953, Petrography and petrology of the Rito Alto stock, Custer and Saguache counties, Colorado: Boulder, Colo., University of Colorado, M.S. thesis, 49 p.

Tweto, Ogden, 1949, Stratigraphy of the Pando area, Eagle County, Colorado: Colorado Scientific Society Proceedings, v. 15, no. 4, p. 149–235.

Tweto, Ogden, 1980, Precambrian geology of Colorado, in Kent, H.C., and Porter, K.W., eds., Colorado geology: Denver, Colo., Rocky Mountain Association of Geologists, p. 37–46.

Tweto, Ogden, 1987, Rock units of the Precambrian basement in Colorado: U.S. Geological Survey Professional Paper 1321-A, 54 p., scale 1:1,000,000.

Tweto, Ogden, and Lovering, T.S., 1977, Geology of the Minturn 15-minute quadrangle, Eagle and Summit counties, Colorado: U.S. Geological Survey Professional Paper 956, 96 p., scale 1:62,500.

Tweto, Ogden, Steven, T.A., Hail, W.J., Jr., and Moench, R.H., 1976, Preliminary geologic map of the Montrose 1° × 2° quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-761, scale 1:250,000.

Van Alstine, R.E., 1974, Geology and mineral deposits of the Poncha Springs SE quadrangle, Chaffee County, Colorado: U.S. Geological Survey Professional Paper 829, 19 p., scale 1:24,000.

Van Alstine, R.E., 1975, Geologic map of the Bonanza NE quadrangle, Chaffee and Saguache counties, Colorado: U.S. Geological Survey Open-File Report 75-53, scale 1:62,500.

Vanderwilt, J.W., 1947, Mineral resources of Colorado: Denver, State of Colorado Mineral Resources Board, 547 p., 34 pls.

Varga, R.J., and Smith, B.M., 1984, Evolution of the early Oligocene Bonanza caldera, northeast San Juan Volcanic Field, Colorado: Journal of Geophysical Research, v. 89, no. B10, p. 8679–8694.

Voynick, S.M., 1994, Colorado rockhounding: Missoula, Mont., Mountain Press Publishing Co., 372 p.

Walcott, C.D., 1892, Preliminary notes on the discovery of a vertebrate fauna in Silurian strata: Geological Society of America Bulletin, v. 3, p. 153.

Wallace, A.R., 1997a, Geologic map of the Russell quadrangle, Costilla County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2312-D, scale 1:24,000.

Wallace, A.R., 1997b, Geologic map of the Fort Garland quadrangle, Costilla County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2312-E, scale 1:24,000.

Wallace, A.R., and Lindsey, D.A., 1996, Geologic map of the Trinchera Peak quadrangle, Costilla, Huerfano, and Las Animas counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2312-A, scale 1:24,000.

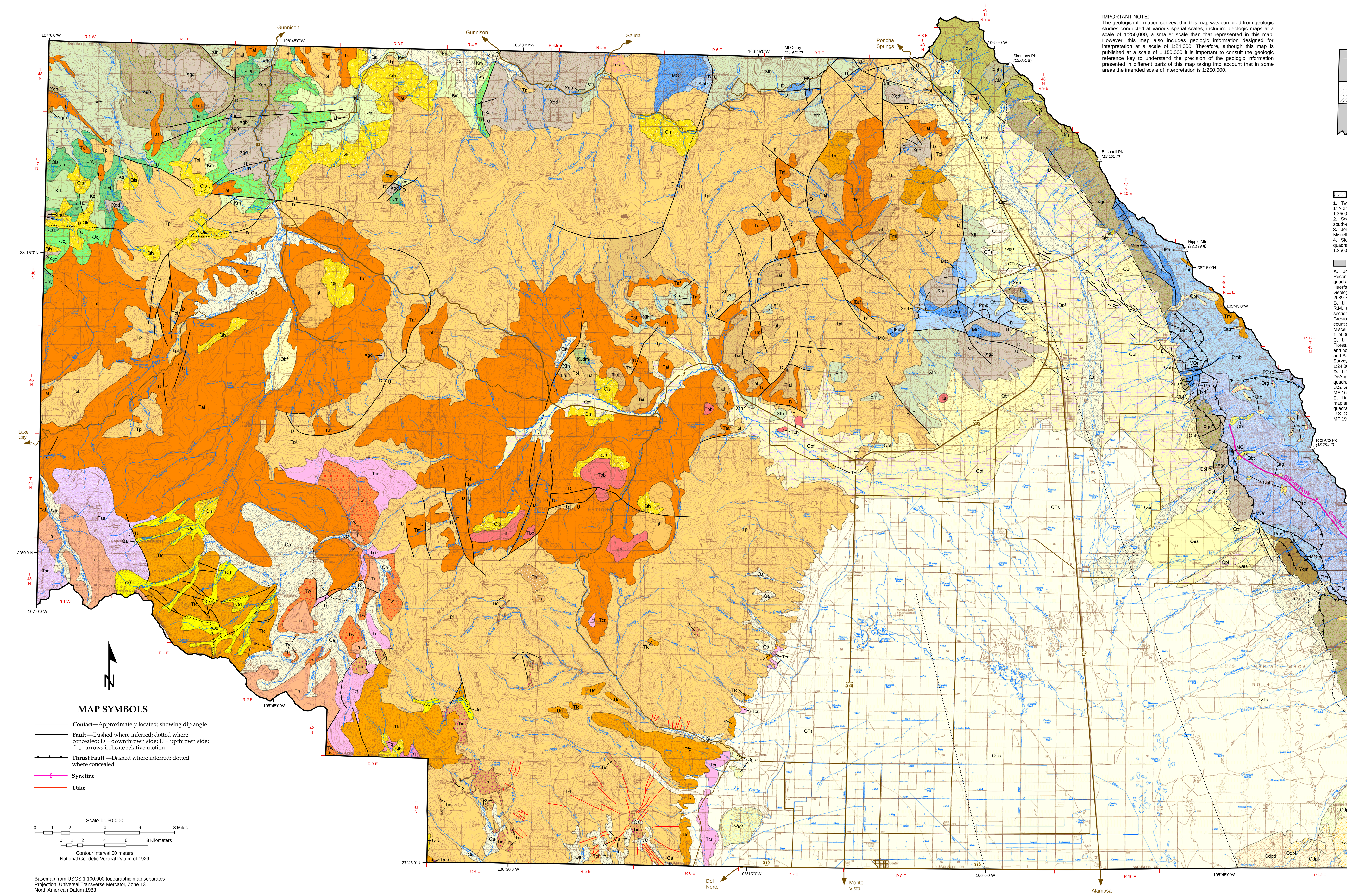
Wallace, A.R., and Soulliere, S.J., 1996, Geologic map of the Omit Peak quadrangle, Costilla County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2312-B, scale 1:24,000.

Wallace, C.A., and Lawson, A.D., 1998, Geological map of the Cameron Mountain quadrangle Chaffee, Park, and Fremont counties, Colorado: Colorado Geological Survey Open-File Report 98-4, scale 1:24,000, 23 p.

Watkins, T.A., 1996, Geology of the northeastern San Luis Basin, Saguache County, Colorado, *in* Thompson, R.A., Hudson, M.R., and Pillmore, C.L., eds., Geological excursions to the Rocky Mountains and beyond, field trip guidebook for the 1996 annual meeting, Geological Society of America, Denver, Colorado, October 28–31: Colorado Geological Survey Special Publication 44, CD-ROM.

Wrucke, C.T., and Dings, M.G., 1979, Geologic map of the Cameron Mountain quadrangle, Colorado: U.S. Geological Survey Open-File Report 79-660, scale 1:62,500.

Zacharakis, T.G., Pearl, R.H., and Ringrose, C.D., 1983, Geothermal resource assessment of the western San Luis Valley, Colorado: Colorado Geological Survey Resource Series 19, 71 p.



IMPORTANT NOTE:
The geologic information conveyed in this map was compiled from geologic studies conducted at various spatial scales, including geologic maps at a scale of 1:250,000, a smaller scale than that represented in this map. However, this map also includes geologic information designed for interpretation at a scale of 1:24,000. Therefore, although this map is published at a scale of 1:150,000 it is important to consult the geologic reference key to understand the precision of the geologic information presented in different parts of this map taking into account that in some areas the intended scale of interpretation is 1:250,000.

MAP SYMBOLS

Contact—Approximately located; showing dip angle

Fault—Dashed where inferred; dotted where concealed; D = downthrown side; U = upthrown side; arrows indicate relative motion

Thrust Fault—Dashed where inferred; dotted where concealed

Syncline

Dike

Scale 1:150,000

0 1 2 4 6 8 Miles

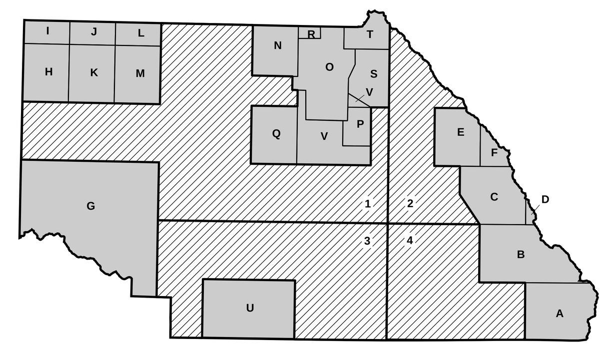
0 1 2 4 6 8 Kilometers

Contour interval 50 meters
National Geodetic Vertical Datum of 1929

Basemap from USGS 1:100,000 topographic map separates
Projection: Universal Transverse Mercator, Zone 13
North American Datum 1983

GIS and cartography by Nicholas Watterson and Karen Morgan

KEY TO GEOLOGIC REFERENCES USED IN MAP COMPILATION



1:250,000-Scale Geologic Maps

1. Tweto, Ogden, Steven, T.A., Hail, W.J., Jr., and Moench, R.H., 1976, Preliminary geologic map of the Montrose 1° × 2° quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-761, scale 1:250,000.
2. Scott, G.R., Taylor, R.B., Epis, R.C., and Wobus, R.A., 1978, Geologic map of the Pueblo 1° × 2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1022, scale 1:250,000.
3. Johnson, R.B., 1969, Geologic map of the Trinidad quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-558, scale 1:250,000.
4. Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Leudke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-764, scale 1:250,000.

Additional Geologic References

A. Johnson, B.R., Bruce, R.M., and Lindsey, D.A., 1989, Reconnaissance geologic map of the Medano Pass quadrangle and part of the Liberty quadrangle, Alamosa, Huerfano, and Saguache Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2089, scale 1:24,000.
B. Lindsey, D.A., Johnson, B.R., Soulliere, S.J., Bruce, R.M., and Hafner, Katrin, 1986, Geologic map and sections of the Beck Mountain, Crestone Peak, and Crestone quadrangles, Custer, Huerfano, and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1878, scale 1:24,000.
C. Lindsey, D.A., Soulliere, S.J., Hafner, Katrin, and Flores, R.J., 1985, Geologic map of the Rito Alto Peak and northeastern part of the Mirage quadrangles, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1787, scale 1:24,000.
D. Lindsey, D.A., Scott, G.R., Soulliere, S.J., and DeAngelis, B.L., 1984, Geologic map of the Horn Peak quadrangle, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1623, scale 1:24,000.
E. Lindsey, D.A., and Soulliere, S.J., 1987, Geologic map and sections of the Valley View Hot Springs quadrangle, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1942, scale 1:24,000.
F. Lindsey, D.A., Soulliere, S.J., and Hafner, Katrin, 1985, Geologic map of the Electric Peak and southwestern part of the Beckwith Mountain quadrangles, Custer and Saguache counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1786, scale 1:24,000.
G. Lipman, P.W., 2006, Geologic map of the central San Juan caldera cluster, southwestern Colorado: U.S. Geological Survey Geological Investigation Series I-2799, scale 1:50,000.
H. Olson, J.C., Steven, T.A., and Hedlund, D.C., 1975, Geologic map of the Spring Hill Creek quadrangle, Saguache County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-713, scale 1:24,000.
I. Hedlund, D.C., and Olson, J.C., 1974, Geologic map of the Iris NW quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1134, scale 1:24,000.
J. Olson, J.C., 1976, Geologic map of the Iris quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1286, scale 1:24,000.
K. Olson, J.C., and Steven, T.A., 1976, Geologic map of the Sawtooth Mountain quadrangle, Saguache County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-733, scale 1:24,000.
L. Olson, J.C., 1976, Geologic map of the Houston Gulch quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1287, scale 1:24,000.
M. Olson, J.C., and Steven, T.A., 1976, Geologic map of the Razor Creek Dome quadrangle, Saguache County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-748, scale 1:24,000.
N. Olson, J.C., 1983, Geologic and structural maps and sections of the Marshall Pass mining district, Saguache, Gunnison, and Chaffee counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1425, scale 1:24,000.
O. Burbank, W.S., 1932, Geology and ore deposits of the Bonanza mining district, Colorado, with a section on history and production by Henderson, C.W.: U.S. Geological Survey Professional Paper 169, 166 p.
P. Bridwell, R.J., 1968, Geology of the Kerber Creek area, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 104 p.
Q. Bruns, D.L., 1971, Geology of the Lake Mountain Northeast quadrangle, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 79 p.
R. Kouther, M.J.H., 1969, Geology and mineralization of the northwest part of the Bonanza quadrangle, Chaffee and Saguache counties, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 93 p.
S. Mayhew, J.D., 1969, Geology of the eastern part of the Bonanza volcanic field, Saguache County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 94 p.
T. Van Alstine, R.E., 1975, Geologic map of the Bonanza NE quadrangle, Chaffee and Saguache counties, Colorado: U.S. Geological Survey Open-File Report 75-53, scale 1:62,500.
U. Lipman, P.W., 1976, Geologic map of the Del Norte area, eastern San Juan Mountains, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-952.
V. Marrs, R.W., 1973, Application of remote sensing techniques to the geology of the Bonanza volcanic center: Golden, Colo., Colorado School of Mines, Ph.D. dissertation, 281 p.

LIST OF MAP UNITS

The complete description of map units and references are in the accompanying booklet

QUATERNARY DEPOSITS

EOLIAN DEPOSITS

Qes — **Eolian Sand (Holocene and Pinedale glaciation of the Pleistocene)** -- Fine- to coarse-grained windblown sand

Qb — **Lag Deposits (Holocene)** -- Pebbles in deflation pits

Qdt — **Transverse Dunes (Holocene)** -- Fine- to medium-grained sand

Qdl — **Older longitudinal dunes (Holocene)** -- Fine- to medium-grained sand

Qdpf — **Parabolic dunes (Holocene)** -- Fine- to medium-grained sand, fixed parabolic dunes of accumulation

Qdpa — **Parabolic Dunes (Holocene)** -- Fine- to medium-grained sand, active parabolic dunes of accumulation

Qdpd — **Parabolic Dunes (Pleistocene)** -- Fine- to medium-grained sand, parabolic dunes of deflation

Qdc — **Climbing Dunes**

ALLUVIAL DEPOSITS

Qa — **Alluvium (Holocene and Pleistocene)** -- Composed of nonconsolidated, stratified and poorly stratified, pebble to boulder gravel, matrix-supported gravel. Matrix composed of sand and silt. Interbedded layers of crossbedded sand and laminated silt and clay occur as laterally discontinuous layers in the gravel. Common in modern streams and rivers in mountainous areas and in the San Luis Valley.

Qc — **Colluvium (Holocene and Pleistocene)** -- nonsorted, nonstratified, coarse-grained slopewash in mountains

LANDSLIDE DEPOSITS

Qls — **Landslide Deposits (Holocene and Pleistocene)** -- Mudflows, cohesive block-slip, and debris flows common in La Garita Mountains where Fish Creek Tuff, Wason Tuff, Rat Creek Tuff, and Nelson Mountain Tuff yielded to down-slope mass movement in La Garita Mountains and Cochetopa Hills

GLACIAL DEPOSITS

Qd — **Bull Lake and Younger Glacial Drift (Pleistocene)** -- Unsorted boulder glacial deposits (till) and associated sand and gravel deposits

Qrg — **Rock Glaciers (Pleistocene)** -- Rock glaciers of undetermined Pleistocene age

Qpt — **Pinedale Till and Rock Glaciers (Pleistocene)** -- Till composed of unsorted, nonstratified to poorly stratified, boulder gravel in a pebbly, sandy, and silty matrix. Composition of till closely related to the lithology of rocks in the glacial valley. Rock glaciers composed of unsorted, angular boulders derived from adjacent rock outcrops. Some rock glaciers are ice-cored, and other rock glaciers contain a sandy, silty, and pebbly matrix. Size of clastic material depends on proximity to glacial front. Pinedale till has prominent lateral and terminal moraines, hummocky topographic surfaces, and high parts of mountain ranges were scoured by alpine glaciers that left U-shaped canyons in the Sangre de Cristo Range and La Garita Mountains. Pinedale glacial event occurred between 35,000 yrs. B.P. and 8,000 yrs. B.P.

Qpf — **Pinedale Lacustrine Deposits, and Outwash (Pleistocene)** -- Lacustrine deposits composed of laminated or massive sand, silt, and clay, and commonly rich in organic material. Glacial outwash stratified boulder and cobble conglomerate in a pebbly, sandy, and silty matrix interbedded with crossbedded sand and laminated silt. Outwash fans formed in a braided stream regime. Size of clastic material depends on slope of outwash fan. Outwash fans extend from mouths of canyons to flats of the San Luis Valley. Pinedale glacial event occurred between 35,000 yrs. B.P. and 8,000 yrs. B.P.

Qbt — **Bull Lake Till and Rock Glaciers, (Pleistocene)** -- Till composed of unsorted, nonstratified to poorly stratified, boulder gravel in a pebbly, sandy, and silty matrix. Composition of till closely related to the lithology of rocks in the glacial valley. Rock glaciers composed of unsorted, angular boulders derived from adjacent rock outcrops. Some rock glaciers are ice-cored, and other rock glaciers contain a sandy, silty, and pebbly matrix. Size of clastic material depends on proximity to glacial front. Bull Lake glacial period occurred between 155,000 yrs. B.P. and 125,000 yrs. B.P. Bull Lake deposits generally located along the fringes of the younger Pinedale glacial event, and the glacial landforms are more subdued than those of the younger event.

Qbf — **Bull Lake Lacustrine Deposits, Fan Alluvium, and Outwash (Pleistocene)** -- Lacustrine deposits composed of laminated or massive sand, silt, and clay, and commonly rich in organic material. Glacial outwash is stratified boulder and cobble conglomerate in a pebbly, sandy, and silty matrix interbedded with crossbedded sand and laminated silt. Outwash fans were formed in a braided stream regime. Size of clastic material depends on proximity to slope of outwash fan. Bull Lake glacial period occurred between 155,000 yrs. B.P. and 125,000 yrs. B.P. Bull Lake deposits generally located along the fringes of the younger Pinedale glacial event, and the glacial landforms more subdued than those of the younger event.

Qgo — **Older Quaternary gravel deposits (Pleistocene)** -- Pre-Bull Lake gravels and alluvial deposits in fans, and till. Composed of pebbly gravel in the Villa Grove area.

QUATERNARY AND TERTIARY ROCKS

QTs — **Santa Fe Group (Quaternary? to Oligocene)** -- Red sand and conglomerate, volcanic-rich conglomerate, and interbedded basaltic andesite flows in lower part.

TERTIARY ROCKS

SEDIMENTARY ROCKS

Td — **Dry Union Formation (upper Pliocene to lower Miocene)** -- Upper part consists primarily of conglomerate composed of Precambrian rock clasts. Lower part consists of clay, silt, sand, and conglomerate composed of volcanic rock clasts. Thickness estimated at more than 5,000 ft near Salida in Chaffee County.

Tos — **Oligocene Sedimentary Deposits (Oligocene)** -- Gravels, water-laid tuffs, sands and silts in various stratigraphic positions within the volcanic sequences

INTRUSIVE ROCKS

Tmi — **Middle Tertiary Intrusive Rocks (Miocene and Oligocene)** -- Granodiorite, quartz monzonite, and granite intrusive rocks in stocks, dikes, sills, laccoliths, and irregular bodies

Tio — **Intrusive Rocks Emplaced during Period of Early Intermediate Eruptions (Oligocene and older)** -- Hypabyssal intrusive rocks including granodiorite, quartz monzonite, and fine–grained rocks of equivalent compositions

VOLCANIC ROCKS

San Juan Volcanic Field - Post-Caldera Volcanic Rocks

Tbb — **Basalt of the Bimodal Suite (Miocene)** -- Dense, black, resistant, lava flows, interbedded tuffs, breccias, and volcanic conglomerates. Up to 5,200 ft thick.

Th — **Hinsdale Formation (Pliocene to Miocene)** -- Trachyandesite, silicic rhyolite, andesite, and basalt assigned to Hinsdale Formation (4.7- to 23.4 Ma). Fine-grained, silicic, alkali-olivine basalt and basaltic andesite, generally containing olivine phenocrysts. Xenocrysts of quartz and feldspar locally abundant.

Tial — **Andesite Lava and Breccia (Oligocene)** -- Fine-grained and porphyritic intermediate lava and breccia from local centers

Undifferentiated ash flow units of the San Juan Volcanic Field

Taf — **Ash Flow Tuff (Oligocene)** -- Includes Masonic Park Tuff, Fish Canyon Tuff, Carpenter Ridge Tuff, Nelson Mountain Tuff, Volcanics of Stewart Peak, syngenetic and post-caldera volcanogenic sediment, Wason Park Tuff. These ash flow units are described in reference to their map symbol in the following section. Cochetopa Park Tuff, and Sapinero Mesa Tuff do not have their own map symbols and are described below:

Cochetopa Park Tuff (Oligocene) -- Light-gray to reddish-brown, densely to moderately welded tuff composed of 20 to 30 percent phenocrysts in the upper part, and 8 to 20 percent phenocrysts in lower part. Tuff is a composite cooling unit. Phenocrysts of sanidine, plagioclase, quartz, and some biotite in an aphanitic eutaxitic matrix that contains shards and small pumice fragments. Contains inclusions of older Tertiary volcanic rocks, lapilli, and minor granite. Locally at base welded tuff is a vitrophyre. Age range of the Cochetopa Park Tuff is 26.4 Ma to 26.7 Ma.

Sapinero Mesa Tuff (Oligocene) -- Reddish-brown to light-brownish-gray, densely welded, and devitrified tuff. Contains 5 to 12 percent phenocrysts composed of calcic oligoclase, sanidine, quartz, and biotite. The matrix is eutaxitic and collapsed pumice is common. Locally a thick black vitrophyre occurs at base. Erupted from Uncompahgre caldera at 28 Ma to 29 Ma in the western San Juan caldera complex.

Tiql — **Quartz Latite Lava and Breccia (Oligocene)** -- Porphyritic quartz latite and minor rhyolite in thick flows and associated breccia

Tq — **Numerous local ash flows at many stratigraphic positions (Oligocene)** -- Varied rhyodacite, quartz latite, and rhyolite flows and breccias; most are finely to coarsely porphyritic

Named volcanic rock units of the San Juan Volcanic Field

Tsa — **Volcanics of Stewart Peak (Oligocene)** -- Andesite and dacite lavas containing 5 to 25 percent phenocrysts composed of plagioclase, and augite or hornblende. Andesitic lavas are dark-gray and dacitic lavas are light gray in color. Volcaniclastic rocks are mainly mudflow deposits and coarse breccias derived from coarsely porphyritic andesite and dacite lava domes, and commonly fill moat areas of caldera. Late-stage volcanic rocks associated with the San Luis caldera are grouped in "volcanics of Stewart Peak", and "rhyolite of Mineral Mountain". Deposits range in age from 26.9 Ma to 25.7 Ma.

Tn — **Nelson Mountain Tuff (Oligocene)** -- Grades upward in composition from rhyolite at base to dacite and silicic dacite (quartz latite) at top. Rhyolite at base is a gray, nonwelded tuff, which is overlain by a light-gray, densely welded, phenocryst-poor, tuff that contains collapsed pumice fragments, and a light-gray to light-reddish-brown welded tuff that contains partly collapsed pumice fragments near the top. Phenocrysts form 3 to 5 percent of the rock and are sanidine, plagioclase, biotite, and rare augite. Silicic dacite (quartz latite) is brownish-gray welded tuff transitional from rhyolite below to dacite above, and contains 10 to 20 percent phenocrysts of plagioclase, sanidine, biotite, and sparse augite and quartz, overlain by dark-gray silicic dacite (quartz latite). Dacite welded tuff composed of 20 to 35 percent phenocrysts of plagioclase, biotite, and augite, and at top is yellow-tan and gray, nonwelded, crystal-rich silicic dacite (quartz latite) composed of phenocrysts of plagioclase, biotite, and augite. The top of the unit is eroded. Nelson Mountain Tuff erupted from the San Luis caldera complex at 26.1 Ma.

Tw — **Wason Park Tuff (Oligocene)** -- Grayish-red rhyolite and silicic dacite (quartz latite) that contains 10 to 30 percent phenocrysts composed of plagioclase, sanidine, biotite, and augite. Densely welded lower part and a less welded upper part. Wason Park Tuff was erupted from the South River caldera at 27.2 Ma.

Tcr — **Carpenter Ridge Tuff (Oligocene)** -- Light-gray, nonwelded to reddish-brown, densely welded rhyolitic ash flow tuff. Contains 2 to 3 percent plagioclase, sanidine, and biotite. Has a conspicuous black vitrophyre at the base and a central lithophysal zone. Erupted from the Bachelor caldera at 27.4 Ma.

Tfc — **Fish Canyon Tuff (Oligocene)** -- Light-gray, nonwelded tuff and tan, moderately welded quartz latite ash flow tuff. Contains 35 to 50 percent phenocrysts of plagioclase, sanidine, biotite, and hornblende, and sparse resorbed quartz. Potassium-argon age of 27.8 Ma. Erupted from La Garita caldera.

Tmp — **Masonic Park Tuff (Oligocene)** -- Gray to yellow-brown, nonwelded to partly welded, ash-flow tuff containing 40 to 50 percent phenocrysts of plagioclase, biotite, augite, and fragments of andesite. Postassium-argon age of 28.4 Ma. Thin layer of tuff extends into southwestern-most corner of Saguache County northeast of South Fork. Erupted from the Mount Hope caldera southwest of county.

Central Colorado Volcanic Field - Bonanza Caldera

Taf — **Ash Flow Tuff (Oligocene)**

Bonanza Tuff and other named volcanic and intrusive rocks -- Brown, brownish-gray, gray, and blackish-gray, densely welded quartz latite (silicic dacite). Contains 20 to 30 percent phenocrysts of plagioclase, sanidine, and biotite. The Bonanza Tuff is 32.9 to 33.1 Ma. Younger volcanic rocks in the area of the Bonanza caldera are Squirrel Gulch Latite, Porphyry Peak Rhyolite, Porphyry Peak Rhyolite, and Hayden Peak Latite. Stratigraphic relations of these younger volcanic rocks to the Bonanza caldera are poorly understood.

Intermediate volcanic rocks of the San Juan and Central Colorado volcanic fields

Tpl — **Pre-Ash Flow Andesite and Latite (Oligocene-Eocene)** -- Early volcanic rocks of intermediate composition assigned to Conejos Formation and composed of: (1) upper lava unit of porphyritic dark andesite and rhyodacite flows and flow breccia; (2) vent facies composed of aphanitic to porphyritic andesite, rhyodacite and quartz latite lava flows and flow breccia; (3) conglomerate, sandstone, and mudflow breccia that accumulated on the flanks of stratovolcanoes; (4) rhyolite lava flows and domes; and (5) intrusive dikes and small plugs of intermediate composition. Rock of similar early andesite and latite flows and breccias occur in northwestern part of county. Includes, Lake Fork, San Juan, and Picayune Formations, Beidell Quartz Latite, Tracy Creek Quartz Latite, Rawley Andesite, and Hayden Peak Latite. In southern La Garita Mountains Summer Coon and Baughman Creek volcanic centers (34.7 Ma and 31.1 Ma) composed of flows and dikes of rhyodacite, quartz latite, porphyritic rhyolite, rhyolite, and andesite. Breccia and local flows are composed of alkali-olivine andesite. Rhyodacite, and quartz latite are youngest eruptive rocks on Summer Coon volcano. Porphyritic rhyolite and rhyolite flows occur locally. Intrusive bodies in the Summer Coon and Baughman Creek volcanic centers are andesite, diorite, and quartz monzonite porphyry.

MESOZOIC ROCKS

Km — **Mancos Shale (Upper Cretaceous)** -- Dark-gray-brown silty shale. Contains lenses of friable dark-gray and gray sandstone scattered through the shale. Contains calcareous concretions. Shale is easily eroded and landslides are common. Overlies Dakota Sandstone on a probable conformable contact. Top of Mancos Shale eroded in the northwestern part of Saguache County where Tertiary volcanic rocks unconformably overlie shale.

Kd — **Dakota Sandstone (Upper and Lower? Cretaceous)** -- Light gray to light brown moderately to well-cemented, medium- to coarse-grained, quartzose sandstone and conglomeratic sandstone near base. Pebbles are gray and black chert. Crossbeds and channels common. In upper part, siltstone and flaggy sandstone beds interspersed with coarse-grained sandstone. Locally carbonaceous and argillaceous. Overlies Morrison Formation on a regional unconformity.

KJdm — **Dakota Sandstone and Morrison Formation undivided**

Morrison Formation (Upper Jurassic) -- Composed of variegated reddish-gray, grayish-green, light-gray, and grayish-purple shale, mudstone, argillaceous siltstone, and minor sandstone. Sandstone beds are lenticular and crossbedded. Rare limestone beds are light gray and medium gray. Sandstone and limestone beds as thick as 3 ft. Overlies Junction Creek Sandstone in northwestern part of Saguache County. Morrison unconformably overlies Paleoproterozoic rocks at some places, and appears conformable on Junction Creek Sandstone.

KJdj — **Dakota Sandstone, Morrison Formation, and Junction Creek Sandstone undivided**

Junction Creek Sandstone (Upper Jurassic) -- White- to light-yellowish-gray, fine- to medium-grained, silica cemented, quartzose sandstone. Locally crossbedded. Overlies different units of Paleoproterozoic metamorphic and igneous rocks on an angular unconformity.

Jmj — **Morrison Formation and Junction Creek Sandstone undivided**

PALEOZOIC ROCKS

PIPsc — **Sangre de Cristo Formation (Middle or Upper Pennsylvanian and Lower Permian)** -- Composed mainly of red, grayish-pink, reddish-gray, and dark-red, arkose conglomerate, sandstone, siltstone, and shale. Top of unit eroded.

Crestone Conglomerate Member -- Composed of coarse conglomerate, conglomerate, conglomeratic sandstone, sandstone, all of which is arkose, and minor siltstone and shale. Conglomerate is unsorted, unstratified, chaotically packed, containing angular to subrounded clasts up to boulder size. Schists are composed of red syenite, pink- to red porphyritic felsite, granite, gneiss, gray quartzite and minor amounts of other igneous and metamorphic rocks. Conglomerate beds have sharp, erosional basal contacts. Chaotic conglomerate beds are better stratified, better sorted, and fine grained near the top. Tops of chaotically packed conglomerate beds have thin sandstone layers at upper boundary. Sequences of fining-upward stratified conglomerate and sandstone alternate with the chaotically packed conglomerate. A sequence of fining-upward conglomerate, sandstone, and shale at the top.

Lower member -- Composed mainly of fining-upward cycles of conglomerate, sandstone, siltstone, and shale. Arkose conglomerate and conglomeratic sandstone fill channels at base of cycles and grade up into sandstone, siltstone, and shale in decreasing bed thickness. Fining-upward cycles are prominently stratified. Arkose sandstone contains planar and trough crossbeds, and upper parts of sandstone beds contain planar lamination, ripple cross lamination, and ripple marks. Uppermost shaly intervals commonly contain calcareous nodules. Limestone beds occur at the top of cycles, and some limestone contains marine invertebrate fossils. In upper part of lower member, coarse, poorly stratified conglomerate interspersed with the upward-fining cycles. Conglomerates are clast- and matrix-supported, pebble to cobble conglomerate, and composed of rounded to angular igneous and metamorphic clasts. Overlies Minturn Formation on a gradational contact.

IPm — **Minturn Formation (Middle Pennsylvanian)** -- Composed mainly of interbedded arkose, conglomerate, siltstone, shale, and limestone; some beds are fossiliferous. Siltstone, sandstone, and conglomerate commonly contain feldspar and lithic fragments. Sandstone beds are coarse- to fine-grained, gray to pink in color, and some beds contain pebbles and are conglomeratic. Sandstone beds commonly lenticular and contain planar and trough crossbeds, ripple cross-lamination, planar lamination, flute casts, normal and reverse grading, and plant remains. Interbedded shale and siltstone composed mainly of gray, black, gray-black, brown-black, gray-green and rarely dark-red, laminated, thinly bedded units; shale and silty shale contain abundant mica on bedding planes. Shale is fissile, and fine-grained beds contain ripple cross-lamination, load casts, trough cross beds, and mud chips. Limestone beds common in upper part of Minturn, and are composed of gray and brown, silty and shaly carbonate. Limestone beds contain wavy laminae and ripple cross-lamination. Crinoids, brachiopods, stromatolites, sponge spicules, bryozoans, fusulinids, and conodonts occur in some limestone beds. Overlies the Sharpsdale Formation on gradational and conformable contact or Minturn Formation overlies Leadville Limestone on disconformable contact.

IPmb — **Sharpsdale Formation, Kerber Formation, and Belden Shale undivided (Middle Pennsylvanian to Lower Pennsylvanian)**

Sharpsdale Formation (Middle Pennsylvanian) -- Grayish-red, purplish-red, and bright-grayish-red, coarse-grained arkose, pebbly arkose, boulder conglomerate, and medium-and fine-grained arkose interbedded with grayish-red, purplish-red, and bright-grayish-red siltstone and shale. Composite bedding units generally between 20-in. to 50-ft thick. Channeled bases of composite bedding units overlie fine-grained upper parts of fining upward sequences. Moderate-gray, fossiliferous limestone beds as thick as 30 ft. Interbedded fine-grained intervals are olive drab, grayish-green, dark-gray, and moderate-gray fine-grained sandstone, siltstone, and shale; generally fine-grained intervals less than 3-ft thick. Sharpsdale overlies the Kerber Formation on a contact that appears gradational and conformable.

Kerber Formation (Lower to Middle Pennsylvanian) -- Grayish-green, olive-drab, greenish-brown, and olive-brown, coarse-grained arkose and conglomeratic arkose, medium- and fine-grained arkose, siltstone, and shale. Black shale, black siltstone, moderate-gray limestone, discontinuous coal beds, and rare dolostone as interbeds in olive drab and grayish-green rocks. Coarse-grained zones separated by zones of medium- and fine-grained arkose, siltstone, or shale commonly 9- to 30-ft thick. Coarse-grained rocks most abundant near the base, and finer grained rocks, mostly olive-drab shale and siltstone, and black shale, more common upward. Moderate-gray, fossiliferous limestone interbeds common near top and range between 3- and 30-ft thick. Conglomeratic and sandy units are coarse-grained at base becoming finer grained upward. Overlies Leadville Limestone on a disconformable contact.

Sharpsdale Formation, Kerber Formation, and Belden Shale undivided
(CONTINUED FROM PREVIOUS COLUMN)

Belden Shale (Lower Pennsylvanian) -- Dark-gray carbonaceous shale, shaly siltstone, and coarse- to fine-grained sandstone in thin beds. (1) The lower unit is composed of red or brown, fine-grained sandstone and shale interbedded with 3- to 10-ft thick layers of carbonaceous black shale or mudstone and local red or yellowish shale. (2) The middle unit is composed of layers of blue-gray limestone, partly fossiliferous, interbedded with gray to purplish-red shale, siltstone, and fine sandstone. Limestone beds range between a few inches thick to 100 ft thick. This unit is 100- to 400-ft thick. (3) Buff or drab-colored medium- to coarse-grained sandstone, interbedded siltstone, and gray shale, and minor conglomeratic sandstone. This member has a minimum thickness of about 660 ft.

MOr — **Leadville Limestone, Chaffee Group, Fremont Dolomite, Harding Quartzite, Manitou Formation and isolated patches of Sawatch Quartzite undivided-- (Lower Mississippian to Upper Cambrian)**

Leadville Limestone (Lower Mississippian) -- Interbedded zones of dark-gray and moderate-gray, finely-crystalline, thin- to thick-bedded, limestone and dolomitic limestone, with lenticular interbeds of biomicrite, and oolitic limestone. Stromatolitic limestone and conglomeratic limestone occur locally. Limestone and dolomitic limestone are mottled light-gray and moderate-gray, and nodules of black chert are common at some levels. Base is marked by lenticular beds of sandy limestone and limestone conglomerate; sandy limestone is composed of medium-grained orthoquartzite and calcite cement. In Cochetopa Hills Leadville is massive, blue-gray and brownish-gray dolostone and subordinate limestone. A thinly bedded blue-gray sandy limestone occurs at the base. Overlies the Dyer Dolomite Member of the Chaffee Formation on a disconformable contact. Thickness variation results from post-lithification solution of limestone and from volume reduction that resulted from solution and silicification of limestone.

Chaffee Group (Lower Mississippian? To Upper Devonian)

Dyer Dolomite Member (Lower Mississippian? to Upper Devonian) -- Yellowish-gray, light-gray, and pale-yellowish-gray, laminated and microlaminated, finely-crystalline dolostone that contains some interbeds of light-grayish-green and light-greenish-gray shale. Rare chert layers are interbedded with dolostone and are from 0.25- to 2-in. thick.

Parting Quartzite Member (Upper Devonian) -- Light-gray, pale-brownish-gray, and grayish-pink, fine-grained, silica-cemented orthoquartzite. Rare interbeds of dolostone and shale 2- to 8-in. thick, and some pebbly and granular sandstone interbeds occur. Quartzite beds generally 2- to 9-in. thick, and planar lamination and rare planar crossbeds occur. At some places this member is not densely cemented and the quartzite is friable.

Fremont Dolomite (Upper and Middle Ordovician) -- Light-gray, moderate-gray and dark-gray, massive-weathering, crystalline, fetid dolostone that contains echinoid debris in a fine-grained dolostone matrix, and trilobite and brachiopod fragments occur on some bedding planes. Dolostone is mottled light-gray and moderate-gray, and rare black chert nodules are irregularly distributed through the unit. Beds generally 2-in. to 3-ft. thick and bedding poorly developed. Resistant-weathering dolostone has rough and uneven weathering surface that has sharp ridges. Overlies the Harding Quartzite on a disconformable contact.

Harding Quartzite (Middle Ordovician) -- Dark-reddish-gray, dark-grayish-orange, dark-grayish-red, light-gray, and rusty-orange, silica-cemented, mottled, orthoquartzite. Quartzite is completely cemented by silica and has the conchoidal fracture of a quartzite. Locally a pebble conglomerate in lower 3 ft of the unit. Quartzite beds range from 1-in. thick to about 8-in. thick, and contain planar lamination and planar crossbeds. Phosphatic bony plates of primitive fish occur at some places. In westernmost exposures a sulfide-bearing black shale, 2- to 6-in. thick, occurs in upper part. Overlies the Manitou Limestone on a disconformable contact or Proterozoic rocks in Sangre de Cristo Range.

Manitou Formation (Lower Ordovician) -- Moderate-gray, light-gray, and dark-gray cherty dolomitic limestone, thinly bedded and laminated. Characteristic black and very-light-grayish- white chert nodules and interbeds in the dolomitic limestone. Chert is internally laminated and parallel to bedding. Silicified breccia is absent in the Sangre de Cristo Range. Overlies Proterozoic rocks at most places in county.

Sawatch Quartzite (Upper Cambrian) -- Grayish-white, light-gray, and white, quartz-cemented, medium- to coarse-grained, conglomeratic orthoquartzite and feldspathic quartzite. Pebbles and sand grains are rounded to well rounded, and conglomeratic beds generally occur at the base of the unit. Cross-bedding and shallow channels are the main primary bedding structures. Overlies Proterozoic metamorphic and igneous rocks in isolated patches in parts of Saguache County.

PRECAMBRIAN ROCKS

MESOPROTEROZOIC ROCKS

Yqm — **Granitic stock and dikes** -- Leucogranite and quartz monzonite in northwestern part of county is light-pinkish-gray, medium- to fine-grained, or aplitic composed of perthitic microcline, albite-oligoclase, quartz, and rare biotite, muscovite, apatite, iron oxides, and chlorite. Locally granitic unit is sheared and sericitic. Quartz monzonite stock in Sangre de Cristo Range is gray to pink, medium-grained, non-foliated rock composed of 35 percent plagioclase, 30 percent microcline, 30 percent quartz, and 2 to 5 percent biotite. Extensively altered to chlorite, epidote, and muscovite. This unit correlates with 1,400 Ma Silver Plume Granite.

PALEOPROTEROZOIC ROCKS

Xgb — **Metagabbro and gabbro stocks, sills, and dikes** -- Scattered through the northern part of Saguache County. Dark-greenish gray and greenish-black, foliated or massive, metagabbro and gabbro composed of hornblende, plagioclase, and olivine or augite. Hornblende commonly altered to chlorite. Accessory minerals are epidote, clinozoisite, biotite, sphene, apatite, calcite, and magnetite. Sills in metamorphic rocks may have been basaltic or andesitic flows or pyroclastic rocks.

Xgd — **Granitic and granodioritic stocks** -- Isolated quartz monzonite, granodiorite, and granite intrusions in northern part of Saguache County. Quartz monzonite of Cochetopa Creek composed of pink and reddish-gray, medium-grained, non-foliated rocks composed of 35-40 percent microcline, 25 percent oligoclase, 20 to 30 percent quartz, and 3 to 10 percent biotite. Quartz monzonite of Gold Basin is light-pinkish-gray, medium-grained, and composed of 65 percent oligoclase, 2 to 5 percent microcline, and 27 percent quartz, and 7 percent biotite. Isolated granite stocks in northwestern part of county are light-pinkish-gray, light-gray, and grayish-pink, fine- to medium-grained, and composed of 30 to 65 percent oligoclase, 20 to 35 percent quartz, 2 to 47 percent microcline, and 2 to 11 percent biotite. Hornblende, epidote, sphene, garnet, and apatite are common accessory minerals.

Xqm — **Quartz monzonite of Music Pass** -- Gray to pink, coarse-grained, foliated porphyry composed of 25 to 45 percent microcline phenocrysts in a groundmass composed of 60 percent plagioclase, 20 percent quartz, and 20 percent biotite.

Xvs — **Metasedimentary and metavolcanic rocks** -- Mainly muscovite-feldspar gneiss, biotite-plagioclase metarhyolite tuff, metabasalt, phyllite, slate, siltite, argillite, muscovite schist, spotted schist, and metamorphosed sedimentary breccia and tuff. Occurs in the Sangre de Cristo Range and in the Poncha Pass areas. Regionally, metamorphic grade of these rocks varies from amphibolite to greenschist facies. Most rocks muscovite rich. Sillimanite rarely present. Rocks little deformed at some places and original rock textures, such as graded bedding and cross-laminae are preserved despite locally high metamorphic grades. Regionally, these rocks are more metamorphosed toward the south and west, and less metamorphosed toward the north. These rocks grade into mafic and felsic gneiss (Xgn).

Xfh — **Felsic and hornblendic gneiss** -- Interlayered hornblende schist and quartzofeldspathic gneiss. Hornblende schist is a dark-greenish-black, fine-grained, moderately foliated rock that contains mostly hornblende and andesine, plus accessory biotite, calcite, chlorite, and iron oxides. Hornblende is commonly altered to chlorite. Locally, amygdules, breccia, and local pillow structures preserve the volcanic origin of this unit. Quartzofeldspathic gneiss is light- to medium-gray, fine-grained gneiss composed of large crystals of albite-oligoclase in a finer-grained granoblastic or microcrystalline groundmass of quartz, microcline, and oligoclase. Accessory minerals are muscovite, epidote, biotite, and iron oxides. Felsite and felsite porphyry are less metamorphosed equivalents of the quartzofeldspathic gneiss. Felsites are light-gray to yellowish-gray, fine-grained, metamorphosed rhyolite, quartz latite, and tuffaceous sedimentary rocks composed of phenocrysts of albite-oligoclase and quartz in a microcrystalline groundmass of quartz, feldspar, biotite, muscovite, chlorite, epidote, and iron oxide minerals.

Xgn — **Mafic and felsic gneiss** -- Interlayered, well-foliated mafic and felsic gneiss in pink, gray, and black colors. Locally migmatitic and intruded by pegmatite and mafic dikes. Mafic gneiss consists of quartz, plagioclase, orthoclase, biotite, and accessory magnetite and sphene. Felsic interlayers in the gneiss are rich in quartz and feldspar. The protolith may have been sedimentary and volcanic rocks. Leucocratic gneiss is white to medium-gray gneiss of granitic and granodioritic composition. Locally migmatitic. Leucocratic layers composed of 35 percent plagioclase, 30 percent quartz, 30 percent microcline, and 4 percent biotite, and a trace of muscovite and hornblende. Cataclastic textures are pervasive. Mafic layers account for about 20 percent of the rock and consist of 40 percent plagioclase, 25 percent quartz, 20 percent microcline, and 15 percent biotite and hornblende. The protolith may have been volcanic rocks of rhyolite to dacite. Includes leucocratic gneiss (Xlgn) of Lindsey Johnson, Soulliere, Bruce, and Hafner (1986).

GEOLOGIC MAP OF SAGUACHE COUNTY

Compiled by James A. Cappa
2007

Bill Ritter Jr., Governor
State of Colorado

Harris D. Sherman, Executive Director
Department of Natural Resources

Vincent Matthews
State Geologist and Division Director
Colorado Geological Survey

Basemap from USGS 1:100,000 topographic map DRGs
Projection: Universal Transverse Mercator, Zone 13
North American Datum 1983

GIS and cartography by Nicholas Watterson

MINERAL OCCURRENCES AND DISTRICTS OF SAGUACHE COUNTY

By James A. Cappa
2007

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APPENDIX 1

Excerpts from the Ore Deposits and the Mines and Prospects sections (pages 63-163) of U.S Geological Survey Professional Paper 169, Geology and ore deposits of the Bonanza Mining District, Colorado, by W.S. Burbank, 1932. Includes all the plates and figures from the full report.

Minerals of the ore deposits

The following brief descriptions, which are arranged in mineral groups according to Dana's system, are confined to those minerals that are closely associated with the ore deposits or that occur in altered rocks. In the subjoined alphabetic list a question mark indicates that the mineral is probably present in the district but that its identity has not been definitely established.

Adularia	Diaspore	Petzite
Altaite	Dolomite	Proustite (?)
Alunite	Embolite (?)	Psilomelane
Anatase	Empressite	Pyrargyrite
Anglesita	Enargite	Pyrite
Apatite	Epidote	Pyrolusite
Argentite	Fluorite	Quartz
Azurite	Galena	Rhodochrosite
Barite	Gold (native)	Rhodonite
Bornite	"Gray copper"	Rickardite
Bromyrite (?)	Gypsum	Rutile
Calcite	Hematite	Sericite
Cerargyrite	Hessite	Siderite
Cerusite	Jarosite	Silver (native)
Chalcedony	Kaolin	Sphalerite
Chalcocite	Limonite	Stromeyerite
Chalcopyrite	Malachite	Sylvanite
Chlorite	Manganite	Tellurium (native)
Chrysocolla	Manganosiderite	Tennantite
Clay	Muscovite	Tetrahedrite
Copper (native)	Orthoclase	Wad
Covellite	Pearceite (?)	Zunyite

NATIVE ELEMENTS

Copper – Native copper is probably widely distributed in small amounts adjacent to copper ore and within a short distance of the surface. It is found in small masses and in the form of thin sheets along joint cracks in the upper levels of the Rawley vein but is probably mostly within 50 feet of the outcrop of the vein.

Gold – Native gold was mined from a small vein on Little Kerber Creek, several miles southeast of the district. It is said to occur there in visible amounts in vein quartz. Native gold is not visible in any of the ores of the district high in gold, such as some mined from the St. Louis vein, on Copper Gulch. It may, however, be present in these ores or may occur as "mustard gold" from the oxidation of gold-bearing tellurides.

Silver – Native silver has been found in the upper levels of the Eagle mine (p. 155), where it is unquestionably of secondary origin (supergene). It occurs in the form of wire silver. Native silver is said to have been found within 20 to 40 feet of the surface impregnating parts of the walls of the Antoro vein, and it probably occurs under conditions favorable to enrichment in the uppermost parts of many veins. Except in the Eagle vein, it is not known to have been found in quantities sufficient to be of economic importance.

Tellurium – Native tellurium occurs in the Empress Josephine vein in small masses of tin-white color, but its relation to the other tellurides is not known. A small amount of rickardite was associated with it in one specimen examined.

SULPHIDES

Galena (PbS) – Galena (sulphur, 13.4 percent; lead, 86.6 percent) is the only valuable ore of lead in the district, as the oxidized lead minerals are negligible. The most common crystal form of the galena seen is the simple cube, or cleavable masses in which the cubic cleavage is very prominent. Where the galena has crystallized in vugs or open spaces it commonly has the form of cubo-octahedrons, and rarely the cubical faces may be entirely lost of very subordinate to the octahedral faces. Very beautiful crystals of this character are found in parts of the Joe Wheeler vein, on Alder Creek. Galena in large quantity was deposited in the open spaces of the fissures. Locally it may have replaced gouge and the fine matrix of breccia material to some extent, and polished sections show that it has replaced other sulphides, notably sphalerite and pyrite.

Peculiar intergrowths of galena and quartz found at the Queen City prospect, in Copper Gulch, seem to indicate a contemporaneous intergrowth of galena and the gangue. This gives the specimens an appearance like that of steel galena, although a study of the polished ore shows that many of the small irregular galena areas are continuous in crystallographic orientation with neighboring ones. This is the only locality where this peculiar type of intergrowth was seen. The silver in the ores of the district is probably only to a very slight extent associated with the lead. The richest silver-bearing ores of the Rawley vein are those in which copper minerals are predominant. An assay of galena published by Patton[36] shows only 51.8 ounces of silver and 0.02 ounces of gold to the ton.

Argentite (Ag_2S) – A mineral appearing pale brownish gray in reflected light under the microscope occurs in minute amounts in some of the ores richer in silver. It is not common but where seen was associated with covellite and stromeyerite, apparently as an alteration product of stromeyerite. Argentite of supergene origin is reported by Wuensch[37] as occurring in the Eagle vein (See pp. 159-160.)

[36] Patton, H.B., op. cit., p. 83.
[37] Wuensch, C.E., Secondary enrichment at Eagle mine, Bonanza, Colo.: Am. Inst. Min. and Met. Eng. Trans., vol. 69, p. 99, 1923.

Chalcocite (Cu_2S) – Chalcocite is found in small amounts both as a primary and a secondary (supergene) mineral in the veins. It occurs in graphic intergrowths with bornite on several levels of the Rawley vein. In ore from the 900-foot level it forms irregular areas in bornite, which suggest a primary origin. It is also found in minute cracks in practically all the sulphides, where it is associated with late chalcopyrite or is partly altered to covellite. These cracks possibly represent small capillary openings in the ore, and their sulphide filling may have been deposited by surface waters percolating downward along the vein. They are of negligible importance, however, with regard to the total volume of the sulphide ores. Sphalerite contains coatings of bluish-black sooty chalcocite and covellite in partly oxidized ore near the surface. This occurrence is undoubtedly the result of interaction with surface waters containing copper in solution.

Stromeyerite ($(Ag.Cu)_2S$) – Stromeyerite was first identified as a constituent of the Rawley ore by M.N. Short, who reported as follows concerning one of a suite of specimens examined by him:

*"Bornite contains rounded blebs of a soft gray mineral which has the appearance and gives the etching tests of argentite according to the tables of Davy and Farnham. It is slightly brittle, however; argentite is sectile. It gives strong anisotropism, which is characteristic of stromeyerite rather than argentite, which is isotropic or shows feeble anomalous anisotropism. It gives a good microchemical test for silver, but it could not be tested for copper, as some bornite was mixed in sample. *** However, its universal association with bornite suggests that the mineral also contains copper and is stromeyerite rather than argentite."*

A large number of polished sections from different parts of the district, including many from the Rawley vein, have since been examined by the writer, and stromeyerite was recognized in ore from the Cocomongo and Joe Wheeler veins and less definitely in ore from the Rico, Liberty, and Express veins. In ore from the 400 north level of the Rawley mine it was possible to find small areas of stromeyerite relatively free of impurities, and tests for both copper and silver were obtained. Etching tests of the mineral gave somewhat variable results but agree essentially with the tests given by Davy and Farnham[38] for either stromeyerite or argentite. The reaction with ferric chloride was rather quickly brown to iridescent, rubbing to a bluish iridescent surface in most specimens. The mineral was found to be associated with bornite, tennantite, galena, and chalcopyrite in all the occurrences and is a primary mineral of the veins. It occurs in the 400 north level of the Rawley vein intergrown with tennantite in such a manner as to indicate contemporaneous deposition, and both of these minerals are replacing bornite. Stromeyerite also appears to be the result of a late stage of primary (hypogene) silver enrichment, and as yet no evidence has been found to prove that it was deposited by descending surface waters. Photomicrographs showing the relation of this mineral are given in Plate 18.

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[38] Davy, W.M., and Farnham, C.M., Microscopic examinations of the ore minerals, p. 67, New York, 1920.

Stromeyerite is probably an important source of silver in many of the veins of the district, and its universal association with primary copper minerals shows it to be related to the deposition of copper in the veins or to have been derived from the breaking down of silver-bearing copper minerals.

Sphalerite (zinc blende) (ZnS) – Sphalerite (sulphur, 33 percent; zinc, 67 percent) commonly exceeds galena in quantity as a constituent of the veins in the district, the ratio being somewhat less than 2 to 1. The quantity of sphalerite does not appear to decrease so markedly with increasing depth as that of galena in the higher-grade lead ores in the district. In the Rawley vein the quantity of zinc is fairly constant, near 2 or 3 percent, throughout the explored part of the vein, although it may be somewhat less abundant in the higher-grade lead ores of the southern part. During the operation of the Cocomongo mill in 1926 (p. 95) the mill heads showed that zinc exceeded lead in the ratio of 1½ to 1. This is also about the ratio of zinc to lead in the ore blocked out in the Cocomongo mine as shown by mine samples.

Sphalerite occurs both in the veins and to a very minor degree in replaced wall rock. Skeletal crystals of sphalerite are seen in some of the siliceous replacement deposits associated with pyrite, but the amount is so small as to indicate that the solutions depositing zinc did not have nearly the penetrating power of those that formed pyrite in the wall rock. Large bodies of sphalerite occupy positions in veins which indicate that like galena it was deposited mainly in relatively open spaces in the veins or in breccias. It is not unusual, however, for small breccia fragments within the vein walls to show considerable replacement by the common sulphides, particularly by pyrite and sphalerite.

The sphalerite found in the district ranges from yellowish resinous varieties to nearly black varieties containing iron.

Polished sections of ore containing sphalerite show that some of it contains blebs of chalcopyrite where it is associated with copper minerals. Although its crystallization is in places contemporaneous with the other original (hypogene) sulphide minerals, much of the sphalerite has been subjected to replacement by chalcopyrite, bornite, galena, and to a lesser extend by silver minerals. Sphalerite rarely replaces pyrite.

In ore that has been subjected to the action of surface waters containing copper sulphates the sphalerite is coated with a bluish-black film composed largely of covellite; such sphalerite resembles blackjack unless the surface is broken to show the nature of the black coating.

Covellite (CuS) – Covellite, like chalcocite, is probably of both primary and secondary (supergene) origin in this district, but is also present only in very small amount. It occurs in graphic intergrowth with galena in primary ore. Covellite also occurs is small capillary cracks and replaces late chalcopyrite and chalcocite. Associated with anglesite and cerusite, it replaces massive galena peripherally, an occurrence that is undoubtedly of supergene origin. Covellite forms a thin coating on sphalerite that has been subjected to the action of waters containing copper sulphate in the lower part of the zone of oxidation or just below.

Bornite (Cu_5FeS_4) – The only ores in which bornite (sulphur, 28.1 percent; copper, 55.5 percent; iron, 16.4 percent) has been recognized, so far as is know to the writer, are those of the Rawley, Joe Wheeler, and St. Louis veins, although it is very probably present in many other veins in small amounts. It commonly occurs in massive form associated with chalcopyrite and pyrite. In the Rawley vein it is found in noticeable quantities only on and below the 300-foot level and was especially abundant on the 700-foot level. Where it has crystallized in openings the crystals are commonly rounded with imperfect curved faces and occur together with crystals of chalcopyrite and tennantite. It is not as abundant as chalcopyrite as a constituent of the veins in which it is found but is much more common than enargite in the Rawley vein. It always appears as a primary mineral of comparatively early formation.

Chalcopyrite (copper pyrites) ($CuFeS_2$) – Chalcopyrite (sulphur, 35 percent; copper 34.5 percent; iron 30.5 percent) is one of the abundant copper minerals of the district and is present in small amounts at least in practically every vein containing sulphides. It occurs in massive form intimately intergrown with granular pyrite and other sulphides and as small crystals in open cavities in the ores. In the Rawley vein the massive copper ore which is found on the lower levels consist mainly of intimate mixtures of pyrite, chalcopyrite, and bornite, probably in order of abundance as named. The abundance of chalcopyrite would not be suspected in some of the massive pyretic ores, as the intergrowths are on a microscopic scale. (See pl. 15)

Chalcopyrite is found less commonly as small crystals in cavities of some of the ores. Good examples of this are seen in the Joe Wheeler vein, in the Alder Creek region. The form of the chalcopyrite is tetrahedral. Patton[39] reports plus and minus tetrahedrons.

Chalcopyrite replaces pyrite, sphalerite, and bornite extensively and evidently has a wide range of deposition compared to some of the other sulphides. It both preceded and followed galena and also was formed at a very late stage in small cracks in other sulphides where it may be wholly or supergene nature.

Patton[40] reports chalcopyrite to contain 0.05 ounce of gold and 35.35 ounces of silver to the ton, but the silver content may be due largely or at least partly to an intergrowth with silver-bearing tennantite, as this mineral is in many places intimately associated with chalcopyrite. (See pl. 16, *B*.)

Pyrite (FeS_2) – Pyrite (sulphur, 53.4 percent; iron, 46.6 percent) is in many of the veins the most abundant sulphide mineral. The iron content of many of the heavier sulphide ores ranges from about 5 to 35 percent, and in many veins the iron is

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[39] Patton, H.B., op. cit., p. 79.
[40] Idem, p. 83.

contained mostly in pyrite and to a minor extent in chalcopyrite or bornite.

Pyrite has several modes of occurrence in association with ore deposits, as it is found both in the silicified wall rocks and in the massive sulphide ores. As a general thing it is much better crystallized where it occurs in jaspers than in well-formed crystals as much as a quarter of an inch in diameter embedded in rhodochrosite or other gangue minerals of an early stage of crystallization. In Plate 11, *A*, is shown a typical occurrence of pyrite in hematite-bearing jasper from the Rawley tunnel. The most usual habit is that of the 12-sided pyritohedron or pentagonal dodecahedron. Cubical crystals are found in the jaspers but are less common. The crystals are very evenly distributed through the silicified wall rocks. The latter mode of occurrence is presumably of different origin from that of pyrite found in and near pyretic veins and represents the later stages of fumarolic or solfataric activity.

In the veins pyrite occurs either as a rather massive form associated with quartz, or intergrown irregularly with other gangue minerals, and as small crystals in vugs of the veins. The pyrite when examined microscopically proves to be an aggregate of small irregular microscopic grains, 0.0025 to 0.50 millimeter in diameter, as seen in a number of polished sections from the Rawley and Cocomongo veins. (See pls. 15 and 17, *A*.) Very commonly the coarser-grained pyrite of typical crystal outline was the earlier form to crystallize and was embedded in the vein quartz, whereas the granular pyrite occupies spaces interstitial to quartz prisms. Both of these modes of occurrence are likely to be represented in the same specimen. The differences in crystal form and in time of formation are probably to be explained by changes in the chemical nature or concentration of the solutions. The change from one mode of occurrence to the other is in places gradual and exhibits intermediate textural relations. The later granular pyrite may be intimately intergrown and probably in part contemporaneous in formation with sphalerite, chalcopyrite, and bornite. Granular pyrite may also be extensively replaced, especially by chalcopyrite and bornite and rarely by sphalerite. (See pl. 15.)

Pyrite exhibiting a colloform concentric structure is seen rarely. It was probably formed in connection with the colloidal deposition of silica, with which it is associated. It appears to be an early form of this mineral.

An assay of the gold and silver content of pyrite was made under the direction of Patton[41] during his study of the Bonanza district. This was made by Messrs. Ho and Wang and showed 0.04 ounce of gold and 7.16 ounces of silver to the ton. No statement was given regarding the purity of the sample, and as no microscopic examination of polished surfaces is mentioned the possibility of the intergrowth of pyrite with silver-bearing minerals is not eliminated. Growths of tennantite and other silver-bearing minerals interstitially to pyrite occur in places on a minute scale, visible only on polished surfaces under the microscope.

[41] Patton, H.B., op. cit., p. 83.

TELLURIDES

Sylvanite or krennerite ($(Au, Ag)Te_2$) – A telluride containing both gold and silver, with gold predominating, is found associated with other tellurium minerals in ore from the Empress Josephine vein. Under the microscope on polished surfaces this mineral has a pinkish or creamy-white color and gives the following etching reactions: HNO_3, effervesces after sometime and turns brown; HCl, negative or turns faintly brown; KCN, negative; $FeCl_3$, negative; $HgCl_2$, stains brown. These reactions do not check exactly with those given by Davy and Farnham for sylvanite or krennerite but are closer to these than to the reactions given for other gold-bearing tellurides. Microchemical tests indicate that gold is greatly in excess of silver, but the proportion of tellurium could not be judged. It was not found in sufficient quantity to reach definite conclusions, but the various tests indicate that the mineral is probably sylvanite.

Sylvanite is listed by Patton[42] as one of the minerals having been found in the Empress Josephine vein, but no details are given as to its identification.

Empressite (AgTe) – Empressite was first recognized as a new mineral species by Dr. R. D. George, in telluride ore from the Empress Josephine mine. It was not analyzed except qualitatively at the time of its discovery but has since been quantitatively analyzed by Bradley[43] and Dittus,[44] and its identity as a mineral species has been established. As the mineral does not appear in current editions of American mineralogies, these analyses are repeated for reference in the table below. It is, however, listed by Doelter[45] as a mineral species and its properties and constitution discussed. Doelter[46] calls attention to the fact that the pure silver monotelluride, empressite, in contrast to the silver gold telluride, muthmannite, (Ag, Au) Te, possesses no cleavage. He also records that the only natural occurrence of the mineral yet known is that in the Empress Josephine mine. Bradley discusses the chemical and blowpipe reactions of the mineral and gives its hardness as 3 to 3.5 and its specific gravity as 7.510.

In polished sections under the microscope the mineral appears pale bluish gray beside altaite or hessite but is more brownish than galena. Etching tests based on an examination by M.N. Short and repeated on tests of additional specimens by the writer are given below. The paragenetic relations of the mineral are discussed in the description of the Empress Josephine mine on page 140.

Empressite was found only in small pockets in the Empress Josephine vein, and very few specimens are now preserved. The writer is indebted to Dr. R.D. George,

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[42] Patton, H.B., op. cit., p. 108.
[43] Bradley, W.M., Empressite, a new silver-tellurium mineral from Colorado: Am. Jour. Sci., 4th ser., vol. 38. pp. 163-165, 1914.
[44] Dittus, E.J., in Patton, H.B., op. cit., p. 110.
[45] Doelter, C., and Leitmeier, H., Handbuch der Mineralchemie, Band 4, erste Hälfte, pp. 873, 874, Dresden and Leipzig, 1926.
[46] Idem, p. 875.

of the University of Colorado, and to Mr. Frank Leavitt, of Bonanza, Colo., for the loan of specimens for study.

Analyses of empressite from the Empress Josephine mine

	1	2	3	4
Specific Gravity ……..	7.510		-----	-----
Ag …………………….	45.16	45.17	43.71	43.68
Fe ……………………..	.30	.15	2.17	2.16
Te ……………………..	54.62	54.89	53.86	53.81
Insoluble matter ……..	.38	.39	.32	.34
	100.16	100.60	100.06	99.99

1,2. Bradley, W.M., analyst. Am. Jour. Sci., 4th ser., vol. 38, pp. 163-165, 1914.
3,4. Dittus, E.J., analyst, in Patton, H.B., op. cit., p. 110.

Microscopic tests on polished surfaces gave the following results: Bluish gray, soft, anisotropic; HNO_3 forms iridescent stains, or its fumes produce a slight tarnish; HCl quickly stains differentially iridescent or some specimens almost negative; KCN, negative; $FeCl_3$ instantly stains differentially iridescent and brings out structure; KOH, negative; $HgCl_2$ instantly stains iridescent.

Hessite (Ag_2Te) – Hessite has been recognized only in ore from the Empress Josephine mine, although it may also occur in other veins in this vicinity in which unidentified tellurides are know to be present. In the specimens examined it was associated with empressite and altaite, together with the more common sulphides sphalerite, galena, and chalcopyrite. A mineral that is probably hessite was identified by M.N. Short in two specimens, lent by Dr. R.D. George, and the same mineral was identified by the writer in one specimen supplied by Mr. Frank Leavitt, of Bonanza.

The appearance of the mineral in polished sections is described by Short as follows: *"It has a brownish tinge in places and varies in color in different grains, probably owing to different orientations. It is strongly anisotropic and gives the following etch tests: HNO_3 stains brown, developing scratches; HCl, negative; KCN, negative; $FeCl_3$ slowly stains brown to iridescent, action slower than with empressite; KOH, negative; $HgCl_2$ slowly stains brown, action slower than with empressite."*

Petzite ($(Ag.Au)_2Te$) – Petzite is listed by Patton[47] as one of the minerals found in the Empress Josephine vein, but it was not identified in any of the specimens of telluride ore examined during the present investigation.

Rickardite (Cu_4Te_3) – Rickardite in very small amounts associated with native tellurium was identified by M.N. Short in one specimen from the Empress Josephine vein. It is also listed by Patton as having been found in this vein. No other occurrence is known in the district.

[47] Patton, H.B., op. cit., p. 108.

Altaite (PbTe) – The lead telluride, altaite, is found in ore from the Empress Josephine and usually is closely associated with galena, about which it forms a shell in contact with other tellurides. (See pl. 19, *C*, *D*.) No other occurrence of the mineral is known in the district.

SULPHOSALTS

Tennantite ($Cu_8As_2S_7$) – Tennantite is very widely distributed in the district and appears to be an important source of the silver in all veins. It is commonly referred to as "gray copper," but it is not the more common antimonial variety, tetrahedrite, as shown by the chemical analysis (p. 8). This analysis is in agreement with much "gray copper" found in Colorado.

Tennantite usually occurs in solid masses or in intimate mixtures with the other sulphides but is also found in crystal form in vugs associated wit the chalcopyrite and galena. Patton[48] reports having observed crystals in cavities of the ore, where it occurs either in simple tetrahedrons or in tetrahedrons slightly modified by other forms. The crystal form is usually imperfect, however, and not easily determinable.

As seen in polished sections of the ores tennantite has a distinct greenish-gray color, in contrast with the usual brownish gray of tetrahedrite. Although it does not give a microchemical test for silver by the ammonium chromate method, which yields results with freibergite, a pure sample of tennantite carefully separated by M.N. Short, and assayed by E.T. Erickson, of the United States Geological Survey, ran 385.4 ounces of silver to the ton. The gold was visible but not weighable, and Erickson estimates it at less than 0.1 ounce to the ton. This sample came from the Rico prospect, on the north side of Round Mountain. Patton[49] cites an assay of a sample of tennantite from the Rawley vein, which ran 0.08 ounce of gold and 105.52 ounces of silver to the ton. A commercial assay of picked tennantite-bearing ore from the Cocomongo vein showed copper, 16.1 percent; lead, trace; zinc, 5.9 percent; iron, 3.7 percent; silver, 374 ounces to the ton. The percentages of copper, zinc, and iron show that this sample was not pure tennantite, although the silver assay is unusually high. Stromeyerite is associated with some of the tennantite in this vein, and very likely this high silver value is due partly to its presence. (See pl. 18, *A*.)

All the tennantite is probably of primary (hypogene) origin and not in any way connected with deposition by surface waters, as it is intimately associated with chalcopyrite, bornite, and enargite in the Rawley ore and with chalcopyrite and galena in the Cocomongo ore. In some places tennantite appears to have been deposited almost contemporaneously with chalcopyrite and galena, but it also replaces pyrite, sphalerite, chalcopyrite, and galena.

The following analysis was made by the Fahlerz method:

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[48] Idem, p. 80.
[49] Idem, p. 83.

Analysis of tennantite from the Cocomongo mine, Bonanza, Colo.
[E.P. Henderson, analyst]

Antimony (Sb) ……….	12.85	Zinc (Zn) ……………	5.29
Arsenic (As) …………	18.62	Lead (Pb) …………...	Trace
Copper (Cu) …………	35.49	Silver (Ag) …………..	Present
Iron (Fe) ……………...	5.93		

Pyrargyrite ($3Ag_2S.Sb_2S_3$) – Pyrargyrite is found in the silver-bearing shoots of the manganese veins of the southern part of the district. It appears to be the main source of the silver in some of these veins. It forms delicate deep-red crystals in cavities in the ore, where the bases of the crystals are intergrown with rhodochrosite and galena. Small specks also occur entirely within galena, and the mode of occurrence of the mineral is such as to suggest that it is of primary (hypogene) origin. Its common occurrence within small, comparatively isolated shoots of sulphides in large bodies of barren gangue, as in the Eagle vein, also suggests that it is not the result of supergene enrichment. It is found in the Eagle vein to a depth of about 640 feet. It is a late mineral of the sequence and commonly has replaced galena. (See pl. 22.)

Proustite ($3Ag_2S.As_2S_3$) – Although proustite has been reported as occurring in the Eagle vein, all the specimens of ruby silver obtained by the writer, on being tested microchemically by M.N. Short, proved to be pyrargyrite.

Pearceite (Ag_2AsS_6) – A microscopic greenish-gray mineral having chemical and physical properties that appear like those of pearceite was found intergrown with galena in the ore from the 600-foot level of the Eagle mine, and also with galena from the 400-foot level of the Rawley mine. The amount of the mineral was too small to be isolated and clearly identified. Both occurrences seen appear to be clearly primary. If the mineral of the Eagle vein is pearceite, then pearceite is of earlier formation in this vein than pyrargyrite, but it is not nearly as common.

Enargite (Cu_3AsS_4) - Enargite (sulphur, 32.6 percent; arsenic, 19.1 percent; copper, 48.3 percent) was recognized only in the ore from the Rawley and Express veins and usually can be identified only by examination of polished sections under the microscope. It is a very minor constituent of the sulphides, and during the present study of the Rawley ores was found only in the ore from the 700 and 800 north levels, but it is undoubtedly present at higher levels, because Patton,[50] at a time before the 700 level was driven, reported its occurrence in the vein. The enargite in the Rawley vein occurs in intricate intergrowth with bornite and tennantite and associated with pyretic ore. It possesses a decided pink color as seen under the microscope in polished sections and gives a microchemical test for antimony as well as arsenic, although the arsenic appears to be in excess, so that it is doubtless "rose

[50] Patton, H.B., op. cit., p. 81.

enargite" rather than famatinite. It usually appears to be a somewhat later mineral than bornite and to have been replaced by tennantite. Together with bornite it is undoubtedly primary.

Enargite is commonly seen by microscopic examination to have partly broken down and altered to tennantite. (See pl. 16, *C*.) As most of the enargite seen was largely altered to tennantite, it appears that enargite was very unstable during the later stages of vein formation.

HALOIDS

Chlorides and bromides of silver – The term "chlorides and bromides" used by many prospectors and miners throughout the West, is commonly applied to vein material stained green or blue by carbonates of copper in or near the outcrop. Some of this stained material contains little or no silver, but some is rich in silver, and although the mineral containing the silver has not been determined it is probably cerargyrite (AgCl) or embolite (Ag(BrCl)), both of which may have a light-green color. Highly oxidized ores of this character are not of great economic importance in the Bonanza district, although they may have yielded returns to individual prospectors in the early days. A body of horn silver (cerargyrite) is said to have occurred at the outcrop of the Eagle vein in Eagle Gulch. (See p. 156.)

Fluorite (CaF_2) – Fluorite (fluorine, 48.9 percent; calcium, 51.1 percent) is a fairly common gangue mineral in the veins of the southern part of the district, including some of the veins of the Express mine, the Eagle vein, and the Oregon vein, and is seen on dumps from several other inaccessible veins. In these veins most of the fluorite is green, though both green and purple varieties are associated in vein material from the dump of the Eagle mine. Some fluorite is reported to have been found in the Bonanza vein of the northern part of the district, but it is a very rare mineral north of the vicinity of Eagle Gulch. A small fissure containing fluorite was seen in the Rawley drainage tunnel.

OXIDES

Quartz and chalcedony (SiO_2) – Quartz is a conspicuous constituent of the gangue in most of the veins in the district and is the most abundant gangue mineral in the ordinary lead-zinc-copper-silver veins, where it exhibits several modes of occurrence.

An abundant form of the earliest quartz is that commonly called "jasper," which has replaced the wall rock of the veins. Siliceous replacement of this kind was very widespread in the district but did not occur everywhere and was confined largely to the country rock adjacent to fissures (pp. 20-27). In places, however, sulphide ore is intimately associated with broken or brecciated jaspers. The siliceous material of this origin that contains no ferric oxide or hematite is white, gray, or greenish gray of different shades, but where hematite or some other form of disseminated iron oxide is present, the color is brown, reddish brown, or brick-red, as in true jaspers. Microscopic examination shows that the silica is present largely as cryptocrystalline quartz and partly as chalcedony. The quartz is apparently in part metacolloidal, however, as it shows smoothly curved or banded structures due to various proportions of impurities or differences in crystallization, and in many places the structure of the replaced rock is perfectly preserved. (See pl. 12, *A*.) Where recrystallization has been more complete, the quartz may be more granular, and the original texture of the rock may be completely destroyed. The accessory minerals commonly present in small amounts in siliceous replacement deposits of this kind are pyrite, hematite, and rutile; less common are barite, sphalerite, sericite, and minerals allied to kaolinite. In many of the reddish jaspers disseminated pyrite crystals are present, forming a rock of striking appearance. (See pl. 9, *B*.) Red jasper containing pyrite is common in parts of the Rawley drainage tunnel and adjacent to the veins along Copper Gulch but is also found at many other places. Strongly silicified wall rock occurs on some of the lower levels of the Cocomongo mine, where the slightly reddish stained jaspers appear to have replaced andesitic wall rock, and the gray or white quartz has commonly replaced the Bonanza latite. Although the texture of the rocks is in some places partly preserved, the recrystallization has been so complete in other places adjacent to the Bonanza vein that it is exceedingly difficult or impossible to determine what the original wall rock was. Some photomicrographs of thin sections of typical siliceous replacement deposits are shown in Plates 9-12.

Within the ore bodies the quartz occurs as a fine-grained mineral replacing rock that has undergone brecciation, as relatively fine to irregularly grained aggregates which probably represent replacement and crystallization in soft breccia or gouge material, and as typical drusy quartz and small, clear terminated quartz crystals formed largely by crystallization in open spaces. Isolated and doubly terminated quartz crystals as much as half an inch long are found in heavy gouges. Very coarse drusy quartz is uncommon, as the larger crystals are in general not more than half an inch to an inch in length and a quarter of an inch in diameter. White milky quartz and chalcedonic quartz are rare in association with sulphide ores in the district but are found in places, mostly outside of the intensely mineralized areas. Chalcedony banded and mottled in red, white or gray is found along some fault planes in association with coarser crystalline quartz, but such occurrences are usually barren of sulphides.

Some kinds of veins contain comparatively little quartz, particularly certain gouge-filled fissures containing tennantite or gray copper as the principal ore mineral. As the silver-bearing tennantite represents a rather late stage of the sulphide mineralization it may be taken as an indication that the greater part of the quartz in the Bonanza ores was deposited in the earlier stages. Tennantite is found commonly in association with quartz, but it usually appears to be a later mineral that has filled cavities within the quartz mass.

Quartz occurs in some veins as platy pseudomorphic growths that may in part be determined as having replaced barite and as intergrowths with barite from which the barite has later been removed by some process not understood. Negative pseudomorphs of quartz after carbonates are also found. They are present in the ore of the Eagle mine and in many prospects in other parts of the district.

Specularite (hematite) and other forms of ferric oxide – Specular hematite (Fe_2O_3) and less definitely crystallized aggregates of ferric oxide are commonly present in the siliceous deposits that have replaced the wall rock and give the jaspers a reddish or brownish color. Small veins consisting mostly of dark specular hematite occur in some of the jaspers and in places are sufficiently abundant to give the jaspers a nearly black color. The occurrences of ferric oxide may be associated with ore in some veins, because of the fact that the products of the earliest stages of alteration with which the ferric oxide is associated may be preserved in some of the fault breccias in which the sulphide ore was deposited. Intense pyritization and recrystallization of red jaspers may have resulted in the destruction of some of the earlier hematite, and rarely during this process it was replaced by pyrite pseudomorphically.

Some of the red coloring matter in the jaspers may consist of hydrated forms of ferric oxide, such as turgite ($2Fe_2O_3H_2O$) or göthite ($Fe_2O_3H_2O$).

Rutile (TiO_2) – Rutile is present in many of the sericitic gouges of the veins and also usually in small amounts in some of the vein quartz and siliceous replacement deposits. It occurs as small yellowish or yellowish-brown crystals of the usual prismatic habit, which are visible only under the microscope. In the jasperoids or siliceous deposits replacing the wall rock rutile is almost invariably present and occurs in two forms – ordinary prismatic crystals, which are very clear and of pale color, and irregular trains or fine aggregates, which are nearly opaque and dark yellowish brown or yellow. The larger irregular grains are generally crackled.

Anatase (octahedrite) (TiO_2) – Anatase is recognized very rarely in the gouge clays in the district. Microscopic flattened octahedral and tabular crystals of a light to deep bluish color were seen in gouge clays from the Cocomongo and Rawley veins. Their association was similar to that of rutile, but they are distinguished from rutile by their optically negative character and tabular mode of crystallization. This mineral was suspected of being present in other gouge clays, but its identity could not be definitely established, because of the small size of the grains.

Diaspore ($Al_2O_3H_2O$) – So far as is known, diaspore (alumina, 85 percent; water, 15 percent) is not found as a vein mineral in the district, but it occurs in some intensely silicified rocks. It is associated with kaolinite, sericite, and zunyite.

Pyrolusite (MnO_2) – Pyrolusite is found in quantities of economic importance only in the oxidized zone of manganese carbonate and silicate veins in the southern part of the district. The Headlight or Pershing vein (pp. 168-170), in the upper part of Manganese Gulch, contains pyrolusite associated with psilomelane, siliceous material, and minor amounts of iron oxides. It occurs in radial prismatic aggregates, in granular crusts, and in distinct prismatic striated crystals which are probably pseudomorphic after manganite.

Manganite ($Mn_2O_3.H_2O$) – The hydrated manganese oxide, manganite, had not been definitely identified in the ore of the Pershing vein at the time of investigation, but in all probability was originally present in the vein. The prismatic striated crystals of pyrolusite, which line drusy cavities in the ore, are probably pseudomorphic replacement deposits due to dehydration of manganite. Manganite is probably present in the veins in small amounts but has been so largely dehydrated to pyrolusite that it is difficult to recognize in the mixtures. Several polished surfaces of the mixed manganese oxides fail to disclose its presence.

Psilomelane (H_4MnO_5?) – Psilomelane is present in the mixed oxides in hard, compact masses which are generally intergrown with limonite. It is distinguished from pyrolusite by its hardness, lack of crystal form, and on polished surfaces by these properties and its reaction with hydrogen peroxide. It appears to be very subordinate to pyrolusite in the Pershing vein.

The paragenetic relations of the different manganese minerals are very complex, but their original source is undoubtedly in large part rhodochrosite and to a lesser extent rhodonite of the primary veins. (See pp. 47 and 170.)

Wad – Some indistinct mixtures of oxides of manganese and iron associated with the manganese ores form what is commonly called wad.

Limonite ($2Fe_2O_3.3H_2O$) – Mixtures of hydrated iron oxides generally referred to as limonite occur in the oxidized zones of all the veins. Most of the iron has resulted from the oxidation of pyrite but part of it from other iron-bearing minerals. Limonite occurs mixed in different proportions with the manganese oxides and is a minor constituent of the oxidized manganese veins, such as the Pershing vein (p. 169). Complete oxidation to mixtures of limonite, pyrolusite, psilomelane, and wad may extend to depths of several hundred feet in veins of the southern part of the district, as in the Eagle and Oregon veins. In the northern part of the district limonite is not usually found in appreciable amounts at such depths except along local watercourses.

PHOSPHATES

Apatite (or dahllite) ($(CaF)Ca_4(PO_3)_3$) – Some mineral probably of the apatite group occurs in a few places so intimately associated with quartz, carbonates, and sulphides as to make it definitely a gangue mineral; it was seen only in a few sections, but these came from widely separated veins. The mineral occurs as colorless hexagonal or rectangular grains, 0.5 millimeter or less in diameter, of very sharp crystal outline, characterized in some of the larger grains by anomalies of birefringence and of optical orientation. The index of refraction varies in different occurrences, but its range and the birefringence and optical character of the mineral correspond to those of the apatite group. The mineral is possibly dahllite or podolite, carbonated apatites in which the calcium fluoride is replaced by calcium carbonate, as it is everywhere associated with carbonates, and its optical properties are too variable to correspond with ordinary apatite. This mineral was identified in gangue from the Cocomongo and Little Jennie veins.

Ordinary apatite occurs sparingly in some of the altered and silicified wall rocks, where it has evidently been recrystallized and locally concentrated during the vein-forming processes.

SILICATES

Adularia ($KAlSi_3O_3$) – Adularia (vein orthoclase) is founding some of the low-temperature quartz rhodochrosite-fluorite veins of the southern part of the district. It is particularly common associated with quartz in vein material from the Chloride mine, in Chloride Gulch. It also occurs in small veinlets cutting altered country rock close to the veins in other parts of the district. It was noted especially in altered latite wall rock from the Cocomongo mine, where the relatively high potash content of the latite may have assisted in its precipitation.

Epidote ($HCa_2(Al, Fe)_3Si_3O_{13}$) – Ordinary epidote is fairly common as an alteration product of the country rock. It occurs in altered Eagle Gulch latite and was found in the hanging-wall latite of the Cocomongo vein associated with sericite, quartz, and carbonate (p. 33).

Small veinlets in altered andesite on Alder Creek (Manitou-Sunlight, pl. 1) contain radial growths of an acicular prismatic epidote which has the following optical properties: Optically+; 2V=70º±; dispersion strong, $\rho > v$, birefringence moderate, 0.025 to 0.30; refractive index, β is about 1.75; pleochroism, *Y* dark smoky brown, *X* and *Z* are pale pinkish brown or yellowish; axial plane perpendicular to elongation of fibers. This mineral was identified by W.T. Schaller, of the United States Geological Survey, as ordinary epidote, although its color and optical properties are somewhat unusual. It is associated with chlorite, calcite, pyrite, and chalcopyrite. This mineral is quantitatively insignificant, but its occurrence and associations indicate a comparatively high temperature of formation for these small veins.

Sericite ($H_2KAl_3(SiO_4)_3$) – Sericite, a finely divided form of muscovite, is a common alteration product of the country rock adjoining veins, and some of the vein gouges may be largely sericite, though including possibly some of the minerals of the clay group. Sericite and kaolin are associated in some of the altered rocks of the southern part of the district. In places sericite is intergrown in small amounts with vein quartz and is a constituent of some silicified wall rocks.

Chlorite – Chlorite, a hydrated silicate of aluminum, iron, and magnesium of variable composition, is a very common constituent in the country rock adjoining mineralized fissures but is rare as a vein mineral. Small amounts of it are associated with quartz and jaspers. Some chlorite was seen as a constituent of small veins in altered andesite on Alder Creek. It is associated with quartz, pyrite, calcite, chalcopyrite and epidote.

Kaolin minerals – A mineral corresponding in optical and crystallographic properties to one of the kaolin minerals that occur in the Red Mountain region of Silverton, Colo., is found as an alteration product associated with the silicified rocks in the Bonanza district. This mineral occurs in microscopic platy crystals that occasionally show pseudohexagonal outlines but more commonly are intergrown and of irregular shape, having a size near 0.01 millimeter. Extinction angles of 15º or more were obtained on the small plates in some individuals that were large enough to permit study of the optical properties. The birefringence is low, and the indices of refraction all lie between 1.56 and 1.57. By comparison with some of the kaolin minerals from the Red Mountain region[51] to which the writer had access it is clear that the kaolin of the two areas is identical. The kaolin of the Bonanza district occurs as a by-product of the silicification of the volcanic rocks and so is of hydrothermal origin. It is commonly associated with quartz, barite, sericite, and other fine-grained fibrous clay minerals of doubtful identity. In the southern part of the Bonanza district it commonly fills small pockets in the silicified rocks or has replaced the feldspar phenocrysts. It appears in some occurrences to have either replaced quartz or filled small cavities that have been formed by solution of the quartz. Its association with the silicified rock is similar to that of alunite, diaspore, and zunyite (see p. 25), but as compared to these minerals, it is probably of lower acidity.

Other claylike minerals of doubtful identity are commonly associated with sericite and quartz. One of these minerals occurs with sericite in the silicified rock from the altered area between Chloride and Greenback Gulches. (See analysis 8, p. 31.) The mineral is in small fibrous or scaly aggregates with a somewhat lower index of refraction and lower birefringence than sericite, but it has a higher birefringence than typical kaolinite. It may be a potash-bearing clay. Its relation to sericite is obscure because of intimate intergrowth, but both it and the sericite are later than the quartz.

Some minerals of the clay group are present in and near the veins. Wuensch[52] describes a claylike alteration product in the Eagle vein (now inaccessible) associated with rhodochrosite in which the mineral is yellowish white and tends to form claylike earthy masses. From a commercial analysis made of this mineral, Wuensch determined it to be nontronite, but as the analysis was made on an impure mixture containing and excess of carbonates of manganese and calcium containing iron, and as no optical data were given, the identification is open to doubt. Microscopic examination of a nearly white clay mineral collected by the writer from the Eagle dump shows its indices of refraction and optical properties to correspond

[51] Silver Belle and National Bell mines; collected by F.L. Ransome in 1899. See U.S. Geol. Survey Bull. 182, pp. 73-74, 124-131, 234, 1901.
[52] Wuensch, C.E., Secondary enrichment at the Eagle mine, Bonanza, Colo.: Am. Inst. Min. and Met. Eng. Trans., vol. 69, pp. 104-108, 1923.

to kaolinite[53] or some closely allied mineral, and it does not possess the properties of the minerals that have been listed as nontronite by Larsen.[53]

The gouge "clays" of at least the northern part of the district consist mainly of sericite, but it is likely that a more comprehensive study of gouge clays, particularly of unmineralized fissures, would reveal the presence of other minerals of the clay group. In ore containing supergene covellite from the Paragon mine a yellowish claylike mineral filling cavities was found to have moderate birefringence and the higher indices of refraction near 1.57. As it gave a negative test for sulphate, it is probably one of the clay minerals such as beidellite.

Rhodonite ($MnSiO_3$) – The silicate of manganese, rhodonite, occurs in very intimate intergrowth with rhodochrosite and quartz in veins of practically all parts of the district but is an uncommon gangue mineral. It is usually found in very hard fine-grained pink or rose-red material from the vein containing small amounts of sulphide. It cannot usually be recognized in the hand specimen but is easily recognized in thin sections under the microscope. In most of the sections examined both rhodonite and quartz have been partly replaced by the later rhodochrosite, the rhodonite showing greater susceptibility to replacement. Rhodonite is also probably present in the Eagle vein. Where its relations can be seen clearly rhodonite is an early mineral in the vein paragenesis, crystallizing before any sulphides except possibly the two earliest, pyrite and sphalerite.

Zunyite ($8Al_2O_3.6SiO_2.9H_2O(O,F_2,Cl_2)$) – Zunyite, a basic orthosilicate of aluminum, is an isotropic colorless mineral (index 1.59) with prominent octahedral cleavage and was found in microscopic grains in a silicified dike rock from the southern part of the district, associated with diaspore and later sericite as an alteration product of the feldspars of the rock. (See pl. 10.) It was not present in sufficient quantity to permit chemical tests, but its distinctive optical properties and cleavage are identical with those of the mineral found at the Zuñi mine, in the San Juan region, which is also associated with diaspore, and its identity as zunyite is therefore beyond reasonable doubt.

CARBONATES

Calcite and "manganocalcite" – Calcite ($CaCO_3$) occurs sporadically as a gangue mineral, generally as a filling in more open parts of the vein, and in many places contains small amounts of manganese and iron and traces of magnesium. Some of it contains sufficient manganese to give it a pale pink color and to warrant its classification as a manganocalcite. The chemical properties of even the pink varieties, however, indicate a content of only a small percentage of the manganese carbonate molecule. Although pure calcite is not an abundant constituent of the ore deposits, it is found in many places as an alteration product in the lavas at some

[53] Larsen, E.S., Microscopic determination of the nonopaque minerals: U.S. Geol. Survey Bull. 679, pp. 217, 249, 251, 259, 1921.

distance from the fissures. (See pp. 32-34.)

Dolomite ((Ca,Mg)CO_3) – Dolomite was identified as a vein mineral in the E.D. vein, in the extreme southern part of the district, near the Villa Grove road, opposite the E.D. ranch. It is associated with calcite and siderite. As this part of the district is very probably underlain by the Paleozoic limestones, the magnesium may have been derived largely from these beds at depths of 500 to 1,000 feet below the outcrop of the vein. Magnesium does not appear to have been commonly precipitated from the vein solutions of the district, as chemical tests by the writer show only traces of magnesium in the common carbonates as manganocalcite, manganosiderite, and rhodochrosite.

Siderite ($FeCO_3$) – Siderite was identified in the Rawley and Clark veins and in some pyretic veins in the southern part of the district. It occurs as small brown rhombohedral crystals of the usual habit, which were found as drusy coatings in small cavities and were deposited upon calcite or manganocalcite. The siderite in the Clark vein contains some manganese and probably is allied to manganosiderite. In the southern part of the district in a small vein near the Villa Grove road, opposite the E.D. ranch, siderite occurs as a late carbonate on calcite and dolomite crystals. The iron carbonate was followed here by a still later pyrite.

Rhodochrosite ($MnCO_3$) – Rhodochrosite is distributed throughout the district as a subordinate gangue mineral, and is found in abundance only in some of the veins in the southern part of the district. In both the Eagle vein and the "rhodochrosite vein" of the Express mine, rhodochrosite in association with fluorite is an abundant constituent of the gangue. It is nearly pure manganese carbonate, though rough checks on the chemical composition show small amounts of iron and calcium but only traces of magnesium. The index of refraction (ω) is somewhat greater than 1.80. Where the mineral is abundant it occurs in slightly warped rhombohedrons of deep-pink or rose-red color. The veins in the northern part of the district contain in places some pale pinkish carbonate in which manganese is present, but this rarely proves to be pure rhodochrosite. Its optical and chemical properties indicate that it is mainly a manganiferous calcite containing 10 percent or less of $MnCO_3$, small amounts of iron, and traces of magnesium. Pinkish carbonate of this nature is found in both the Cocomongo and Rawley veins. In the Clark vein of the Rawley tunnel nearly pure rhodochrosite occurs associated with manganocalcite and manganosiderite. A pink carbonate high in manganese ($\omega = 1.78\pm$) and associated with rhodonite occurs in the Little Jennie vein.

Thus while carbonates high in manganese are found in nearly all parts of the district, veins with a large percentage of true rhodochrosite are limited to the southern part of the district, in the so-called "manganese belt."

Cerusite ($PbCO_3$) – Cerusite occurs in small amounts throughout the district and is in places found practically at the outcrops of lead ores, indicating the weakness of oxidation in the district. In partly oxidized ore from some position in the two upper levels of the Bonanza vein cerusite and anglesite are associated with covellite, forming a shell on massive galena. Their relations clearly show that the covellite and anglesite were formed first and were followed by the cerusite.

Malachite and other copper minerals – Malachite ($CuCO_3.Cu(OH)_2$) occurs as a superficial coating and in tufts near the outcrops of copper-bearing veins. Other oxidized minerals of copper such as azurite ($2CuCO_3.Cu(OH)_2$) and chrysocolla ($CuSiO_3.2H_2O$) probably occur under similar conditions but are of no importance other than as indications of the presence of copper.

Smithsonite ($ZnCO_3$) – The zinc carbonate, smithsonite, is reported to have been found in very small amounts associated with cerusite in oxidized zones in the Bonanza vein. It is only of mineralogic interest as an indication of the extent of local oxidation.

BASIC HYDROUS PHOSPHATES

In ore from the Liberty and Empress Josephine mines of Copper Gulch some small vugs are partly or completely filled with soft white minerals resembling kaolin. Chemical and optical tests show, however, that the white mineral is a hydrous aluminum phosphate. Its exact identity could not be determined without chemical analysis, for which there was insufficient material. Under the microscope it is seen to be composed of rounded particles of radial or concentric growth, possessing very low birefringence, and an index of refraction of about 1.58.

In this same ore in partly oxidized state there also occurred some orange-yellow crusts of a resinous mineral having an index of refraction of about 1.62 (isotropic). Chemical tests showed the presence of ferric iron, phosphate, and sulphate.

There may be many other minerals of this kind, but they are of little importance. They are compounds of the group of which hinsdalite ($2PbO.3Al_2O_3.P_2O_5.2SO_3.6H_2O$) is an example.

SULPHATES

Barite ($BaSO_4$) – The distribution of barite in the veins is very irregular, and it is entirely subordinate to quartz as a gangue mineral. However, in some parts of the Joe Wheeler vein, in the Alder Creek region, barite is the principal gangue mineral in association with ore rich in chalcopyrite and bornite, but this is the only occurrence of this kind seen, and even there the presence of barite to the exclusion of quartz is not typical of the greater part of the vein. Some veins apparently do not contain barite, but in many of the veins it is present at least in small amounts. It was not seen, however, in the ore of a number of the larger veins, including the Eagle, Express, and Oregon veins, in the southern part of the district. Quartz-barite veins were seen in the country adjacent to Greenback Gulch, although they contain only small amounts of sulphides.

The barite occurs in its characteristic white or less commonly gray platy crystals and is usually one of the earliest minerals to have crystallized. It is found in small amounts in some of the jaspers or siliceous replacement deposits in minute irregular crystals, visible only under the microscope. Microscopic examination of some quartz gangue material shows barite in different stages of replacement by quartz or in bladed crystals between which the other minerals have crystallized (See pl. 14.) It is rarely found associated with manganiferous calcite of a late post sulphide stage.

Gypsum ($CaSO_4.2H_2O$) – Gypsum was not recognized as a gangue mineral in the ordinary sulphide veins but occurs in altered andesite as veinlets filling joint cracks. Its relation to the ordinary mineralization was not determined, and it may have been deposited by sulphate-bearing ground waters.

Alunite ($K_2O.3Al_2O_3.4SO_3.6H_2O$) – Alunite is found associated with silicified rocks. Its most abundant occurrence is on the top of the broad flat-topped mountain south of Porphyry Peak, where the rhyolites are completely altered into tough jaspery masses of light color composed of quartz, alunite, and minor amounts of other minerals such as rutile. Alunite was not found in any of the silicified wall rocks of the veins, but a small amount of it is present in the area of solfataric alteration near Greenback Gulch.

Jarosite ($K_2O.3Fe_2O_3.4SO_3.6H_2O$) – Jarosite forms microscopic veinlets in a silicified rock near the Chloride mine in the southern part of the district. It apparently is not a common mineral in the district but may be widespread in very small amounts. Most of the yellowish-brown coatings on oxidized ores that were chemically tested proved to be basic phosphates and sulphates of iron and aluminum.

HYDROTHERMAL METAMORPHISM OF THE WALL ROCKS

During the period of mineralization certain constituents of the mineralizing solutions penetrated the country rocks adjoining fissures and altered them to different degrees. Some kinds of alteration appear closely related to ore deposition; others, so far as the available evidence shows, are much less definitely related. Three principal kinds may be distinguished, based upon the intensity of the alteration and upon the principal residual products of rock decomposition – silicification, sericitization, and propylitization. The characteristic results of these kinds are described below, and an attempt is made to show the probable character of the solutions causing them and to coordinate their periods with that of ore deposition.

SILICIFICATION

Silicification is one of the most prominent and characteristic effects of hydrothermal alteration in the district. Although found in the walls of many veins in the district, it is by no means confined to rocks near ore bodies but is of very widespread distribution. It is, however, clearly related to fault fissures or other fractures in the volcanic rocks and belongs to an earlier part of the same volcanic period of hydrothermal activity as that which produced the ores.

In its simplest and most intense form this type of alteration is characterized by the substitution of silica for the greater part of the original mineral constituents of the volcanic rocks. Silicification of limestone is a common process in many mining districts, as illustrated at Leadville.[54] This, however, is a comparatively simple process compared to the silicification of the difficultly soluble aluminous rocks that are found in the Bonanza district. In silicate rocks silicification may consist of two separate actions – (1) an increase in the free silica content of the rock by the breaking down of primary silicates and (2) a direct addition of free silica from the solutions causing the decomposition. As will be seen from the analyses of the altered rocks (p. 31), direct addition of free silica has taken place in many of the silicified rocks of the Bonanza district. The breaking down of silicates with the formation of free quartz is a common result of other types of hydrothermal alteration, but the process of silicification described here consists mainly of a direct addition of silica above that set free from silicates.

The replacement appears to have been at least in part of a colloidal nature, and the present texture of the rocks is a result of later gradual or perhaps nearly immediate crystallization. Plate 12 shows a photomicrograph of a typical example of silicified volcanic rock. In most of the sections examined quartz is the more common form of silica or is present to the exclusion of chalcedony. The hydrothermal solutions that accomplished the silicification were sufficiently corrosive to dissolve and carry away many of the constituents of the silicate rocks. They were, however, saturated with silica, either derived from the solution of other rocks at depth or occurring as a primary constituent of the solutions themselves. Certain less soluble constituents of the rocks, such as the alumina and ferric iron, were taken into solution but apparently were not carried great distances. There are consequently associated with the silicified rocks certain products of decomposition of the original rock which have been deposited in cavities in the rocks or in cracks and larger fissures. The mineral form assumed by these decomposition products depended apparently on the local chemical and physical conditions under which the alteration took place. The depth from the surface and the influence of changing composition of the solutions in the fissures are possible factors that have not been entirely evaluated. For example, it is not understood why the alumina precipitated in the cavities of silicified rocks at one time combined only with water to form diaspore, at another time combined with silica and water to form kaolin, and at still other times combined into more complex molecules of alunite, zunyite, or sericite. As the chemistry of such hydrothermal processes is not yet sufficiently understood, the silicified rocks are differentiated and described here according to their appearance and to the nature of the by-products contain in them, and the discussion of the theoretical matters relating to their genesis will be left to following pages.

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[54] Emmons, S.F., Irving, J.D., and Loughlin, G.F., Geology and ore deposits of the Leadville mining district, Colo.: U.S. Geol. Survey Prof. Paper 148, pp. 217, 218, 1927.

KINDS OF SILICIFIED ROCKS

The amount and nature of the other insoluble products of decomposition found in the silicified rocks permit the distinction of five more or less gradational kinds – (1) white or grayish silicified rocks in which quartz or chalcedony or both are the major constituents; (2) reddish, brownish, or less commonly black silicified rocks or "jaspers," in which quartz and chalcedony are the major constituents with some ferric and ferrous oxides, the ferric oxide either in some hydrous form, as finely divided hematite (specularite); (3) white or gray rocks that consist largely of quartz and alunite; (4) white, grayish-white, or slightly iron-stained rocks in which quartz is the principal constituent with some kaolin[55]; and (5) white or grayish-white rocks that consist of a mixture in various proportions of quartz, kaolin minerals, [55] and sericite. An accessory mineral common to nearly all these rocks is rutile, and barite is fairly common in very small amounts, but zircon is apparently rare. Diaspore and zunyite are constituents of some of the silicified rocks. The number of specimens studied from some parts of the district was insufficient to determine the extent of the distribution of such minerals as alunite and diaspore. But all these minerals are considered to be common by-products of the process of silicification. Some of these products may be deposited locally in small aggregates or bodies in which free silica is subordinate, but they have evidently been transported and deposited from solutions that have previously effected the decomposition of some more or less distant body of rock. Where silicification has occurred in rocks adjacent to ore bodies or in some areas where silicification is particularly strong the rocks are likely to contain pyrite.

PETROGRAPHIC FEATURES AND DISTRIBUTION

In the north-central and northeastern parts of the district the first two of the five kinds of silicification enumerated above are those which have been most commonly recognized. These are represented by analyses 4, 5, and 7 on page 31. The white or gray silicified rocks consist almost entirely of quartz or chalcedony or mixtures of these, with minor amounts of rutile or other accessory minerals. They are very hard and flinty and break with a conchoidal or splintery fracture. Microscopic examination shows them to consist of cryptocrystalline quartz or less commonly of chalcedony. The quartz occurs in extremely small interlocking grains, which in one specimen studied ranged from 0.005 to 0.025 millimeter in diameter, but the grain size may differ greatly in different specimens or even in the same one. The chalcedony forms fibrous aggregates characteristic of this mineral. In some silicified rocks both quartz and chalcedony are present. The texture of the original rock may be partly preserved, but where recrystallization is of a coarser nature it may be more or less obliterated. Barite where present occurs in very small scattered grains. (See pl. 12.)

Red or brown "jaspers" are very common in the northern part of the district and are

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[55] The term "kaolin" is used here in a general sense to include several of the minerals of hydrothermal origin related to kaolinite, some of which may contain potash. (See p. 16.)

usually the product of replacement of andesitic rocks. (See analysis 4.) The color of these rocks is caused by the presence of ferric iron, which occurs either as metacolloidal and possibly hydrous oxides or as very finely divided crystals or hematite. Hematite crystals large enough to be recognized can usually be seen only on a polished surface that is examined with the higher powers of the reflecting microscope. (See pl. 9.) Both quartz and chalcedony are usually present. In none of the rocks was any opal or other amorphous form of silica recognized.

In the northern part of the district the rocks of these two kinds are found either in the walls adjoining veins or at considerable distances from any known ore bodies. It is clear that they are not directly related to the deposition of ore. Those found adjacent to ore bodies represent a mode of alteration which preceded the sulphide mineralization. The red jaspers are at some places brecciated and veined or cemented with later quartz, sulphides, and sericite, or they may form one or both of the walls of a vein. (See pls. 11 and 12 and fig. 14.) The white or gray silicified wall rock may grade imperceptibly into the later quartz that forms the vein material, and because of lack of contrast in color their age relations are not everywhere evident in the field. Microscopic examination shows, however, that a silicification of wall rock almost invariably preceded the formation of sericite, which took place mostly during the earliest stage of vein filling. Veinlets of sericite cutting a silicified andesite are shown in Plate 12.

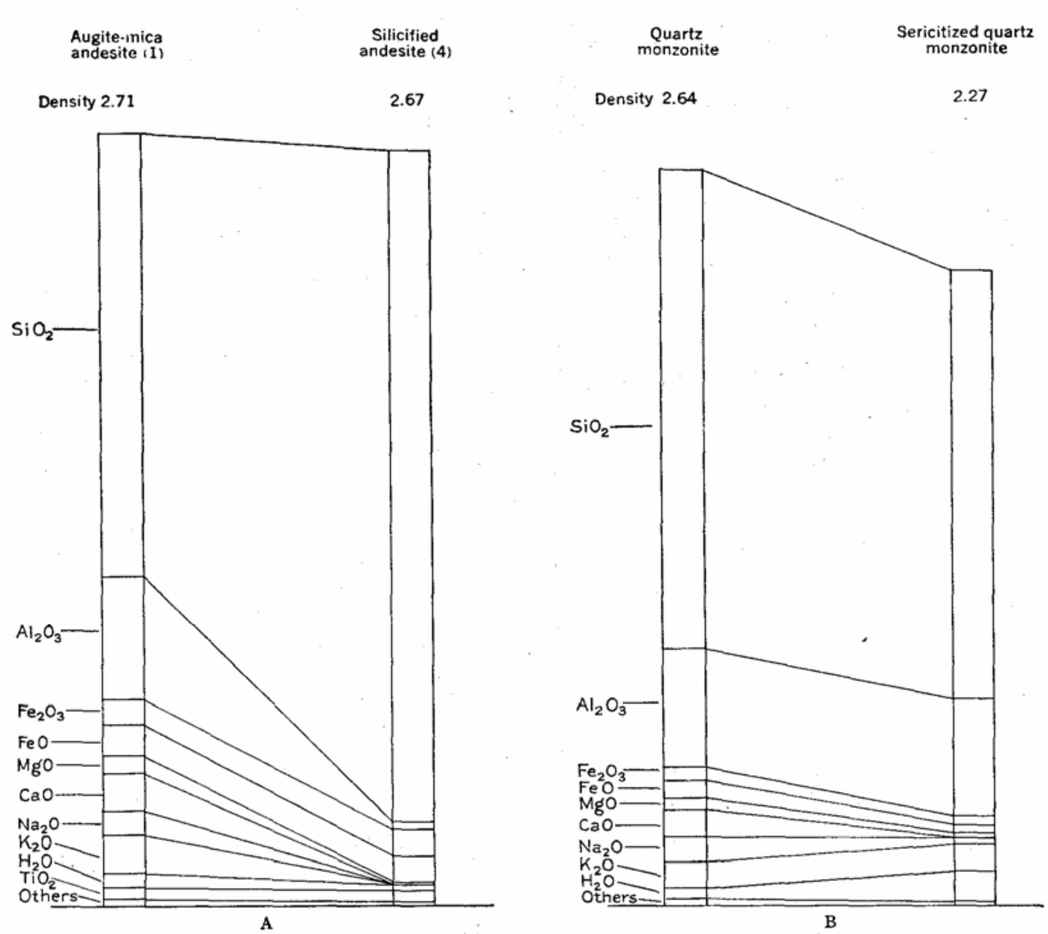

Figure 14. – Gain or loss, in grams, of principal constituents in 100 cubic centimeters of wall rock adjacent to fissures (A) during silicification in the bonanza district, with the formation of red jasper; (B) during ordinary sericitization in the Beaver Lake district, Utah (Butler, B.S., The ore deposits of Utah: U.S. Geol. Survey Prof. Paper 111, p. 164, 1920). Figures in parentheses indicate numbers of analyses in table on page 31.

The red or brown "jaspers" that contain disseminated crystals of pyrite are illustrated by Plate 9, B, and their composition is shown by analysis 6. They are most abundant at the surface in and adjoining the Copper Gulch region, but are also found at other places. The Rawley drainage tunnel penetrated large bodies of pyritized jasper. Intense alteration next to veins may have been accompanied by the introduction of other sulphides, as sphalerite, and by the formation of sericite. Such rocks are partly bleached and may have lost most of their original red or brown color.

Silicified rocks of the third kind, containing alunite, have been found only on the large flat-topped mountain south of Porphyry Peak, in the extreme northwestern part of the district. Part of this area of silicification is indicated on the geologic map. No chemical analysis of rock of this type has been made. Large bodies of rhyolitic rock have been affected by this alteration, particularly on the west slope of the mountain along the Silver Creek and Mears road. (See pl. 1.) The alteration products are quartz and alunite, with minor amounts of titanium minerals, of which the species could not be determined. The alunite is subordinate to the quartz in two specimens that were studied microscopically. The textures of the original rhyolitic rocks are partly preserved. Pyrite is found in them only along some of the sericitized fault zones.

In the southern part of the district both reddish and grayish-white siliceous rocks of the first two kinds are found. These rocks are free from sericite, kaolin, and alunite or at least contain these minerals only in very small amounts. There occur in addition, however, siliceous rocks containing a notable proportion of either kaolin or sericite (see analysis 9), or both, and rarely small amounts of diaspore and zunyite. The largest area of such rocks is the volcanic complex near Greenback Gulch, east of Kerber Creek between Manganese and Chloride Gulches. Within this area the original character of the volcanic rocks has been so largely destroyed that geologic mapping is seriously hindered. Here and there small bodies or inclusions of the outlying andesitic country rock can be identified in the central part of the altered area. The altered zone embraces a small volcanic vent, through which molten rock, gases, and solutions escaped during and subsequent to the main period of faulting. A number of prospected veins lie in and near this zone, including the Express, Chloride, Whitney group, Crown Point, Hayden Mountain, and Schoville claims, but as yet there has been little production from them. Consequently, the claims are developed only to a small extent, and the more extensive workings are inaccessible. Therefore it is not known to what depth this alteration extended. It is apparent, however, from such examination as could be made near the surface and from shallow mine workings, that silicification and kaolinization were the earlier stages of alteration, a condition partly parallel to that in the northern part of the district, just described. The kaolinite has either replaced feldspars in partly silicified rocks in association with potash-bearing clays and sericite or occurs as irregular veinlets or nests in the silicified groundmass. Microscopic sections examined have not revealed any clearly decipherable age relation between the kaolin minerals and associated sericite. Field evidence indicates that intense sericitization is characteristic of altered rocks in the vicinity of the fault fissures and ore-bearing veins in all parts of the area and is clearly later in age than general silicification. As the formation of kaolin was a more widely distributed process and closely associated and contemporaneous with silicification, the deduction would be that the development of that sericite found in the walls of veins followed the formation of hydrothermal kaolin.

The typical mode of alteration of the rocks in the Greenback Gulch area consisted of a complete replacement of the groundmass of porphyritic rocks by fine granular quartz or chalcedony, while the feldspar phenocrysts were replaced by kaolin and quartz, in some places together with barite, or by a mixture of kaolin and sericite. In one example, illustrated in Plate 10, the feldspars were first replaced by an intergrowth of quartz, diaspore, and zunyite. These minerals, including parts of the silicified groundmass, were all partly replaced by later sericite. In volcanic breccias the textural relations are much more complex. Close to the surface the softer products of alteration, consisting of kaolin and sericite, have been more or less completely removed from the silicified rocks, leaving cavities in place of the original feldspar crystals or in place of the fragments in breccias. The result is a very porous rock having in extreme examples somewhat the character of a clinker. These alteration products usually remain in place in bedrock immediately below the surface.

The outcrops of certain fissures in the area affected by this alteration are characterized by dikelike masses and knobs of the silicified rocks, consisting largely of quartz. At intersections of fissures large irregular bodies of the rocks are so altered. Outcrops known locally as quartzite dikes adjoin Chloride and Greenback Gulches, and a heavy siliceous outcrop crowns the hill known as Little Platoro, between these gulches. (See pl. 6, *A*, *B*.) Rocks in which abundant kaolin and sericite are associated with the quartz are much less resistant to disintegration and crop out less prominently.

Some of the siliceous rocks are said to contain gold but not in economically valuable quantities. They are generally free from sulphides, except locally where they are impregnated with minute pyrite crystals.

Silicification of the general character above described is not uncommon in mineralized volcanic areas and is found in other parts of the San Juan region. Very similar alteration in the Red Mountain district of the Silverton quadrangle has been described by Ransome.[56] Here it likewise occurred close to bodies of intrusive porphyry, and the andesite breccia, porphyries, and rhyolites have all be affected by it. It is known to extend to a depth of at least 500 feet. Ransome[57] says regarding the occurrence of kaolinite, one of the abundant products of the decomposition of the lavas: *It was not possible to investigate the occurrence of kaolinite in any of the deeper workings of the Red Mountain mines, but from what could be seen it appears to have accompanied the ores to the greatest depths there attained – about 1,300 feet. It was evidently derived from the country rock adjacent to the ore bodies as a product of its alteration by thermal waters*.

Another area in the San Juan region in which widespread alteration of this same general character has occurred lies in the Platoro-Summitville district. The alteration has been described by Patton,[58] who states that the most intensely altered rocks lie in a large triangular area between Elephant Mountain, Sheep's Head Mountain, and Gilmore, in which the sides of the triangle measure about 12,000, 14,000, and 18,000 feet. To judge from Patton's description the modes of alteration are very similar, except that alunite is probably more abundant in the altered rocks in the Platoro-Summitville area. In that area the products of rock decomposition are quartz, kaolin, sericite, and alunite. With regard to the relation between sericite and

[56] Ransome, F.L., Economic geology of the Silverton quadrangle: U.S. Geol. Survey Bull. 182, pp. 114-131, 1901. See also Cross, Whitman, Howe, Ernest, and Ransome, F.L., U.S. Geol. Survey Geol. Atlas, Silverton folio (No. 120), p. 33, 1905.
[57] Op. cit. (Bull. 182), p. 73.
[58] Patton, H.G., Geology and ore deposits of the Platoro-Summitville mining district, Colo.: Colorado Geol. Survey Bull. 13, pp. 46-53, 1917.

kaolinite Patton[59] says:

So far one may be justified in drawing conclusions from these few cases, the proximity of ore veins has been favorable to the development of sericite rather than kaolinite. On the other hand, all the altered rocks in which kaolinite has been developed are remote from ore veins. We are not, however, to infer that sericite is confined to rocks in proximity to ore veins, as it occurs in two other cases associated with kaolinite, and as it is a very common secondary mineral in all the rocks of the district outside of this are of intense decomposition.

CHEMICAL FEATURES OF SILICIFICATION

The details of the chemical changes involved in the silicification of the lavas of the Bonanza district are illustrated in the accompanying tables (p. 31) and in Figures 14-16. Three analyses of fresh or slightly altered andesites and six analyses of the different kinds of silicified rocks are given. The first three analyses, one of which was taken from the report of the State geological survey, may be considered representative of the extreme variation in the composition of the andesites of the Rawley formation. The two new analyses (nos. 1 and 2) show a relatively high potassium and sodium content as compared with calcium. The lava of No. 2 approaches a quartz latite in composition, although it possesses and andesitic habit and is closely associated with the andesite flows of the Rawley formation. Because of the widespread alteration in the district fresh lava corresponding to each type of altered rock could not be found. The chemical changes that took place during silicification were so pronounced, however, that it matters little which of analyses 1 to 3 is used in comparing the altered and unaltered lavas. In the table showing gain and loss of constituents in 100 cubic centimeters of fresh and altered lava, analysis 1 has been used as probably typical of the fresh andesites, though it records a small amount of calcite. In computing the gains and losses it was assumed that essentially no change in volume occurred during silicification. This assumption is very probably true for the greater part of the silicified rocks, as in many examples the original texture of the rock is perfectly preserved. As the fresh and altered rocks were not collected from adjoining positions a calculation of the change in porosity during silicification cannot be used to verify this assumption.

[59] Patton, H.B., op. cit., p. 48.

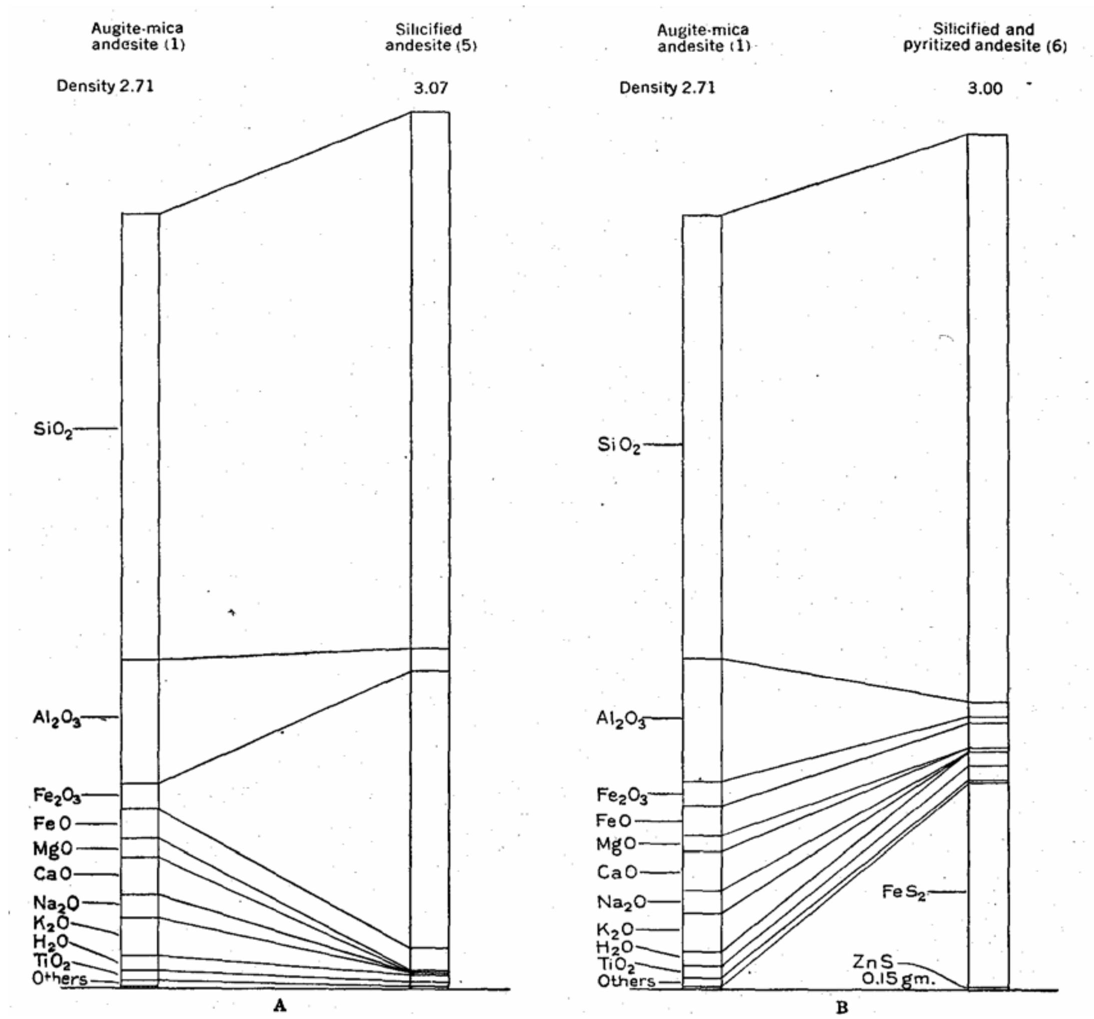

Figure 15. – Gain or loss, in grams, of principal constituents in 100 cubic centimeters of wall rock adjacent to fissures during silicification in the Bonanza district, (A) with the formation of black jasper containing hematite; (B) with the formation of red jasper containing pyrite crystals and a small amount of sphalerite. Figures in parentheses indicate numbers of analyses in table on page 31.

In samples 8 and 9 the increase in porosity is appreciable, suggesting that the interchange was not molecular but that some material has been carried away in solution without a corresponding deposition of quartz or other material to take its place. That small cavities were actually formed in some of the lavas during silicification is also indicated by the structure of alteration products representing original feldspar crystals. The crystals appear to have been attacked vigorously and their constituents carried away, leaving empty cavities. Some of these cavities were later filled with quartz and kaolinite, as shown by the fact that the quartz within and bordering the cavities shows minute prismatic terminations similar to those of vein quartz that has crystallized in an open space. The groundmass in the same rock, however, contains no terminated quartz, but is composed of closely packed and irregular quartz grains, formed evidently by a simultaneous exchange of constituents between the solution and the rock. In other examples angular inclusions within a breccia subjected to silicification show similar differential solution probably with the formation of cavities. Where such rocks have been subjected to weathering close to the surface the softer minerals such as kaolin and sericite have been dissolved or washed out, the result being a very porous rock composed mostly of silica.

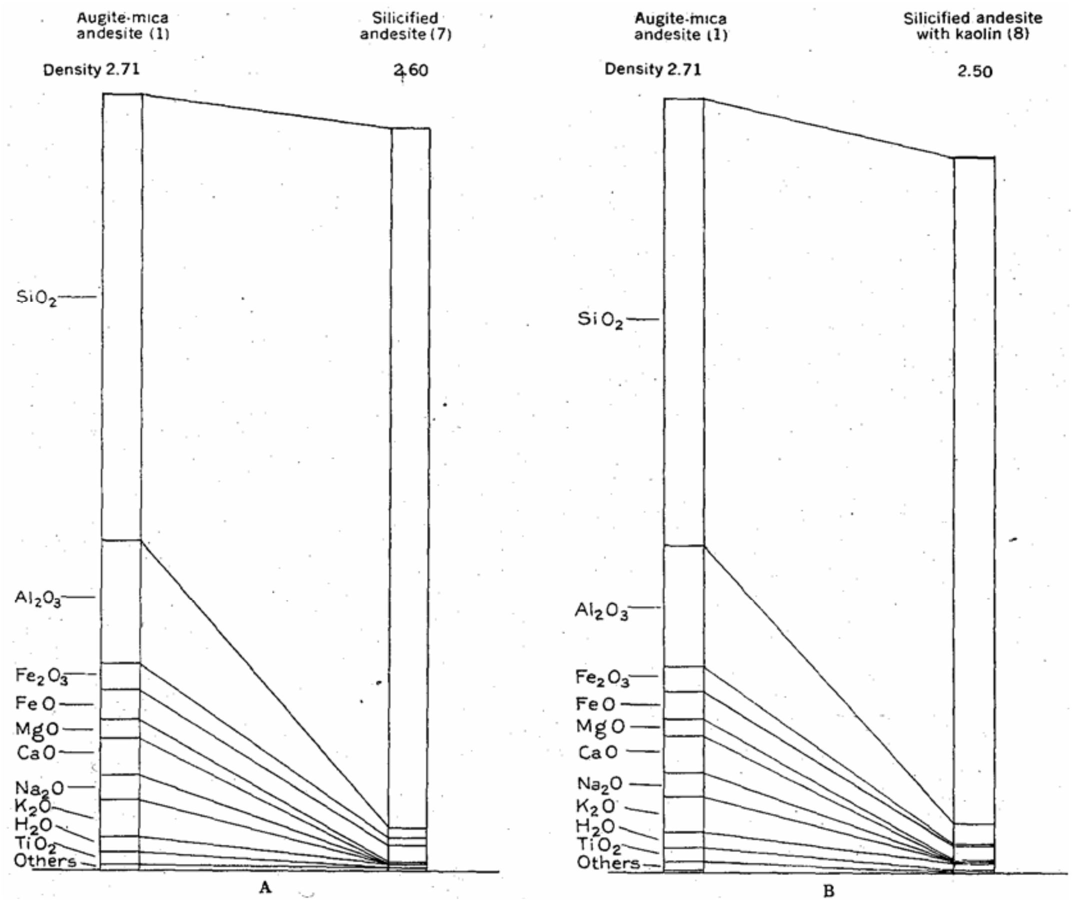

Figure 16. – Gain or loss, in grams, of principal constituents in 100 cubic centimeters of wall rock adjacent to fissures during silicification in the Bonanza district, caused by simple solfataric action, (A) with the formation of extremely siliceous type of altered rock, common in all parts of the district; (B) with the formation of siliceous rock containing a small amount of kaolinite. Figures in parentheses indicate numbers of analyses in table on page 31.

In the altered jaspery rocks represented by analyses 4, 5, 6, 7, and 8 the potassium, sodium, calcium, and magnesium have been so completely leached that no significant difference is shown by the several analyses. Calcium is fixed in the altered rocks to a very slight extent, presumably as apatite. The 0.27 percent of potassium in sample 6 occurs probably as sericite, traces of which were recognized microscopically in the rock. In the very siliceous rocks from which sericite and kaolin minerals are absent there has been a marked dehydration of the lavas (Nos. 4, 5, and 7).

The six analyses of altered rocks represent somewhat different kinds of silicified rocks found in the district. Analyses 4 and 7 represent extremely siliceous types containing, so far as can be detected microscopically, quartz with some iron and titanium oxides and traces of pyrite and some other indeterminable minerals: No. 4 is a red jasper colored by ferric oxide; No. 7 is a nearly white siliceous rock with only traces of recognizable ferric oxide. Ferric iron is comparatively high in No. 4 compared to No. 7, and to it may be ascribed the dark-red color. The form in which most of the ferrous iron occurs in these rocks is not known, though a little pyrite is present in No. 4 and possibly a little magnetite and siderite in No. 7. The quartz usually contains many minute specks of indeterminable minerals, and some iron-rich chlorite may be present. The iron oxides have remained essentially constant in No. 4 compared to the unaltered lavas, but both have been appreciably leached in No. 7. Only small amounts of alumina remain fixed in these altered rocks, possibly as kaolin, diaspore, or more complex aluminum-bearing silicates. No aluminum minerals were detected microscopically in the two samples. Titanium has remained essentially constant, but phosphorus appears to have been partly leached.

Analysis 6 represents a dark-red jasper similar to No. 4 except that it contains many scattered crystals of pyrite. (See pl. 9, *B*.) The bulk of the rock is granular or microcrystalline quartz, with hematite, amorphous ferric oxide, rutile, and traces of barite, sericite, sphalerite, and apatite or possibly other phosphates. Pyrite as shown by the analysis makes up about 25 percent of the rock. The formation of the pyrite was not accompanied by any appreciable development of sericite, nor was the ferric oxide noticeably reduced. The relatively large percentage of ferrous oxide is unaccounted for in the mineral analysis unless it is present in combination with alumina and silica, as in chlorite. Chlorite was not definitely identified by microscopic examination, although there are some minute almost submicroscopic mineral grains present in the quartz. Films of siderite were identified in some rocks along joint cracks.

Analysis 8 represents a silicified andesitic or latitic rock in which the feldspar phenocrysts are mostly represented by aggregates of kaolin containing a few grains of barite and quartz crystals. The groundmass of the original porphyritic rock is composed of microcrystalline quartz, with a little rutile, chlorite, and ferric oxide. The ferrous iron may be largely in iron-rich chlorite or siderite, though microscopic evidence hardly indicates sufficient of these minerals to account for nearly 2 percent of ferrous iron. Some magnetite may be present.

An altered siliceous rock from the southern part of the Bonanza district containing an abundance of kaolin and sericite is represented by analysis 9. This rock was collected comparatively near the surface, because of the inaccessibility and lack of deeper explorations in this part of the region. The rock is very porous and soft, so that satisfactory determinations of specific gravity could not be obtained. The most abundant additions during the alteration appear to be silica, water, and traces of the sulphate radicle. All the other constituents have been appreciably leached, although alumina to a very much less extent than in the more siliceous types of alteration. The alumina in the altered rock is probably in large part combined in kaolin minerals and sericite, although there may be small amounts of alunite. The presence of sericite and the fixation of both potash and alumina indicate that the alteration occurred in part under conditions different from those which existed during the formation of the more highly silicified rocks. In contrast to the other siliceous types of alteration a distinct hydration is noticeable.

Analyses showing siliceous alterations of lavas adjacent to fissures, Bonanza district

	1	2	3	4	5	6	7	8	9
SiO_2	57.62	59.66	54.23	88.73	61.28	66.48	95.18	93.17	82.57
Al_2O_3	15.84	16.09	18.82	.97	2.42	1.64	1.20	2.52	11.44
Fe_2O_3	3.05	2.57	1.69	3.50	31.49	.64	.77	.19	.16
FeO	3.90	3.53	4.06	3.56	2.49	2.74	2.27	1.92	.65
MgO	2.14	2.29	2.25	.05	.05	Tr.	Not det.	.03	Tr.?
CaO …………………………	4.81	4.48	6.62	.24	.28	.20	Not det.	.05	.00
Na_2O …………………………	3.07	3.08	3.91	Not det.	Tr.	Tr.	Tr.	Tr.?	Tr.?
K_2O	4.95	4.92	3.08	Not det.	.19	.27	Tr.	.15	1.89
H_2O-	.24	.25	.08	.02	.05	Tr.	.00	.09	.43
H_2O+	1.39	1.84	1.51	.69	.58	1.64	.40	1.03	2.98
TiO_2 …………………………..	1.30	1.00	1.43	1.50	.50	1.45	.25	.63	.35
CO_2 …………………………..	1.06	.10	2.13	Not det.	.00	Not det.	Not det.	---	---
P_2O_5 …………………………	.44	.35	.16	.20	.20	.43	.06	.10	.09
SO_3 …………………………...	.05	---	Tr.	Not det.	.28	.00	Tr.	.20	.12
Cl ……………………………..	Not det.	---	Tr.	Not det.	Tr.	.09	Not det.	---	---
F ……………………………...	Not det.	---	---	Not det.	.00	.00	Not det.	.00	.00
S ……………………………...	Not det.	---	Tr.	Not det.	.06	Present	Not det.	---	---
MnO …………………………	.15	---	.17	Not det.	Not det.	Not det.	Not det.	---	---
BaO …………………………	.04	---	---	.00	.30	Tr.?	.00	.07	.06
ZrO_2 …………………………..	Not det.	---	Tr.	---	---	---	---	---	---
FeS_2 …………………………	Not det.	---	---	---	Tr.	24.96	---	---	---
ZnS …………………………..	Not det.	---	---	---	.00	.05	---	---	---
	100.05	100.16	100.14	99.46	100.17	100.59	100.13	100.15	100.74
Specific gravity:									
Particles ………………	2.732	2.723	---	2.786	3.227	3.106	2.688	2.704	---
Lump …………………..	2.713	2.686	---	2.667	3.072	2.998	2.598	2.497	---
Weight of sample (grams) …	75	60	200	96	30	90	---	---	---

1. Fresh black augite-mica andesite, with a little secondary calcite and chlorite. From Rawley andesite. Rawley Gulch above Superior mine. J.G. Fairchild, analyst.
2. Fresh gray quartz latite of andesite habit. Superior member of Rawley andesite, Rawley Gulch near Superior mine. J.G. Fairchild, analyst.
3. Augite andesite, with secondary calcite, chlorite, and sericite. From Rawley andesite. Patton, H.B., Geology and ore deposits of the Bonanza district, Saguache County, Colo.: Colorado Geol. Survey Bull 9, p. 54, 1916. George Rohwer and E.Y. Titus, analysts.
4. Altered andesite, red jasper type of alteration. Rawley drainage tunnel, about 4,070 feet from portal. J.G. Fairchild, analyst.
5. Altered andesite, black jasper containing hematite. Rawley drainage tunnel about 4,450 feet from portal. J.G. Fairchild, analyst.
6. Altered andesite, red jasper containing pyrite crystals. Rawley drainage tunnel, about 2,600 feet from portal. J.G. Fairchild, analyst.
7. Silicified andesite, ridge north of Express Gulch. J.G. Fairchild, analyst.
8. Silicified volcanic rock with sericite and kaolin minerals, from hill slope between Chloride and Greenback Gulches about 1,500 feet northeast of Kerber Creek.
9. Silicified volcanic rock with kaolin minerals, from Greenback Gulch about 3,000 feet northeast of Kerber Creek.

Weight, in grams, of constituents in 100 cubic centimeters of fresh and altered lavas adjacent to fissures, Bonanza district, showing grain or loss during alteration, as based on an assumption of no change in volume

	1	2	3[a]	4	5	6	7	8	Increase (+) or decrease (-) from No. 1				
									4	5	6	7	8
SiO_2	156.3	160.3	148.1	236.6	188.3	199.3	247.3	232.6	+80.3	+32.0	+43.0	+91.0	+76.3
Al_2O_3	43.0	43.2	51.4	2.6	7.4	4.9	3.1	6.3	-40.4	-35.6	-38.1	-39.9	-36.7
Fe_2O_3	8.3	6.9	4.6	9.3	96.7	1.9	2.0	.48	+1.0	+88.4	-6.4	-6.3	-7.8
FeO	10.6	9.5	11.1	9.5	7.7	8.2	5.8	4.8	-1.1	-2.9	-2.4	-4.8	-5.8
MgO	5.8	6.2	6.2	.1	.15	Tr	---	.08	-5.7	-5.6	-5.8	-5.8	-5.7
CaO	13.1	12.0	18.1	.6	.9	.6	---	.12	-12.5	-12.2	-12.5	-13	-13.0
Na_2O	8.3	8.3	10.7	---	Tr	Tr	Tr	Tr	-8	-8.3	-8.3	-8.3	-8.3
K_2O	13.4	13.2	8.4	---	.6	.81	Tr	.37	-13	-12.8	-12.6	-13.4	-13.0
H_2O-	.7	.7	.2	.05	.15	Tr	.0	.23	-.65	-.55	-.7	-.7	-.5
H_2O+	3.8	4.9	4.1	1.8	1.8	4.9	1.04	2.58	-2.0	-2.0	+.1	-2.8	-1.2
TiO_2	3.5	2.7	3.9	4	1.5	4.3	.65	1.57	+.5	-2.0	+.8	-2.8	-1.9
CO_2	2.9	.3	5.8	---	.0	---	---	---	-2.9	-2.9	-2.9	-2.9	-2.9
P_2O_5 ………..	1.2	.9	.4	.5	.6	1.3	.16	.25	-.7	-.6	+.1	-1.0	-.7
SO_3 …………	.1	---	---	---	.86	.0	Tr	.50	---	+.76	-.1	-.1	+.4
Cl …………..	---	---	---	---	---	.27	---	---	---	---	+.27	---	---

S ……………	---	---	---	---	.18	---	---	---	---	+.2	---	---	---
BaO ………..	.1	---	---	---	.92	---	.0	.17	---	+.8	---	-.1	-.07
FeS_2 ………..	None	---	---	---	---	74.8	---	---	---	---	+74.8	---	---
ZnS ………..	None	---	---	---	---	.15	---	---	---	---	+.15	---	---
	---	---	---	---	---	---	---	---	-5.2	+36.7	+29.3	---	---

[a] Based upon an assumed specific gravity of 2.73.

SERICITIZATION

Alteration in which fine-grained white mica, or sericite, was formed has affected all the different kinds of volcanic rocks in the district, and its products are invariably found in the wall rocks or the gouges of mineralized veins.

All the vein gouges that were examined microscopically proved to be made up largely of sericite, with which were mixed some pyrite, quartz, carbonate, and titanium oxide, either rutile or anatase. The pyrite in several specimens occurred as small cubes. Apatite also appears to be present in many of them. None of the kaolin minerals were identified in any of the vein gouges, and the common presence of sericite in gouges is therefore considered to be evidence of the premineral age of the faulting. Sericitization was not as pronounced where the wall rocks of veins had been previously replaced by silica. Microscopic examination of silicified wall rock adjacent to ore bodies, however, shows that the quartz has been partly replaced or veined by sericite. (See pl. 12.)

Near veins sericite in the altered wall rock is accompanied by pyrite and carbonates, but in some places these minerals may be present only in minor amounts. In a few places, as in some small veins containing calcite and chlorite along the upper part of Alder Creek, sulphides such as pyrite and chalcopyrite occur in fractures in chloritized rocks, where sericite is absent. The alteration that produced this result was apparently characterized by the introduction of magnesium or by the breaking down of minerals containing magnesium, but it was uncommon or at least of minor importance.

Sericitization may be considered indicative of conditions favorable to the formation of sulphides, which it almost always accompanies, but on the other hand most of the sericitized fissure zones are not known to contain a commercial concentration of metals. It is fairly certain that sericite was introduced into the altered rocks during the early part of the period of vein formation. This is indicated by the fact that it accompanies pyrite and other sulphides that were introduced along fractures in silicified rocks. It appears to be later than the pyrite crystals formed in the jaspers described on page 24.

Sericitization and the formation of secondary carbonates has resulted in a pronounced bleaching of the dark-colored volcanic rocks along fissures and faults in all parts of the district. The width of the bleached zones ranges from a foot or less to several hundred feet. Very wide zones or areas in which the formations have been bleached are probably the result of circulation of the altering solutions through zones of complex fracturing in the faulted rocks. Scarcely a fault of any size is free from such alteration, so that sericitization as a process of rock alteration was widely distributed but has not affected so large a volume of rock as silicification.

Alteration along fault zones has not only caused a bleaching of the formations but has softened them and reduced their resistance to weathering. The softening effect produced by the formation of sericite and carbonate in the lavas is in contrast to the results of silicification previously described. The outcrop of a fissure may thus be marked either by a depression or by a ridge, depending upon which of the two processes of alteration has locally predominated.

PROPYLITIZATION

Alteration of the propylitic type has very commonly attacked the volcanic rocks in the district. Its results are particularly noticeable in the andesitic lavas, scarcely any piece of which is entirely unaffected by it, although the rock may appear perfectly fresh to the unaided eye. The mineralogic changes are usually recognizable only by comparison of fresh and altered rocks under the microscope and consisted in the formation of secondary chlorite, calcite, quartz, epidote, sericite, and rutile. Sulphides and sericite are commonly absent except close to mineralized fissures. The degree of alteration varied, and certain phases of it appear to have graded into more intense sericitic alteration adjacent to fissures. On the other hand, alteration of a weak propylitic character is exhibited especially by certain kinds of rocks. For example, sericite and epidote are widely distributed as alteration products in the Eagle Gulch latite but do not appear as commonly in some of the other volcanic rocks.

The origin of propylitic alteration is a question over which there has been difference of opinion.[60] Some ascribe it entirely to solutions charged with carbon dioxide that invaded the rocks during the period of ore deposition. Others have considered that it occurred when the lavas were erupted, as a result of the escape of steam and carbon dioxide from the cooling lava flow. Ransome,[61] on the other hand, believes that at Breckenridge, Colo., the relation of the propylitically-altered rock to the surface indicates the action of meteoric solutions working downward, although he recognizes the probability that other agencies were effective in different districts.

In the Bonanza district there is no apparent evidence of any relation between this type of alteration and the surface, as rocks at depths of 1,000 feet or more in the Rawley drainage tunnel are altered similarly to those broken from outcrops. There is evidence, however, which at different places may support either an origin related to mineralizing solutions or an origin related to the consolidation of the molten rock. Some of the andesitic lavas of the district are characterized by a constant association of certain secondary minerals, such as chlorite, calcite, quartz, and hematite. The original biotite or augite is nearly everywhere altered to chlorite,

[60] Lindgren, Waldemar, Mineral deposits, 3d ed., pp. 530-535, New York, 1928.
[61] Ransome, F.L., Geology and ore deposits of the Breckenridge district, Colo.: U.S. Geol. Survey Prof. Paper 75, pp. 101-102, 1911.

quartz, calcite, and titanium minerals such as rutile. In certain flows these alteration products have the same characteristic mode of occurrence, even though the outcrops examined may be separated a mile or more. It is very likely that this weak alteration is in part related to the consolidation of the lava. The formation of epidote and sericite in the Eagle Gulch latite, which is probably an intrusive porphyry, also appears to be a phenomenon related to its consolidation.

Near some veins the formation of chlorite and calcite, usually with sericite, was definitely related to the mineralization. This alteration is well illustrated in the hanging wall of the Cocomongo fault in the Cocomongo mine, beyond the northern edge of the main ore shoot. The Bonanza latite, which forms the wall rock, even within a few feet of the unproductive part of the fissure, is of a greenish color and very soft. The feldspars are altered to masses of sericite, and the groundmass contains scattered chlorite and calcite with only a very little pyrite. The original biotite is altered to white mica and rutile. Closer to the ore shoot the latite is more bleached and the altered groundmass contains more abundant calcite and pyrite with irregular areas of secondary quartz, calcite, and apatite. The biotite and feldspars are sericitized. Immediately adjacent to the ore shoot the latite wall consists of a mass of quartz and sericite in which sphalerite and small amounts of other sulphides may be present in addition to pyrite. The texture of the rock may still be partly preserved. There appears to be a gradation outward from the veins into altered rock in which quartz and sericite predominate, and then into rock in which secondary carbonates and chlorite are abundant with smaller amounts of sericite and quartz. It is not apparent, however, whether this alteration graded outward into the still weaker propylitic type in which sericite and pyrite were generally not formed.

NATURE OF THE MINERALIZING SOLUTIONS

SOLUTIONS PRODUCING SILICIFICATION

The earliest stage of hydrothermal alteration was characterized by the formation of silica, with minor amounts of ferric oxide, titanium oxide, and compounds of alumina as the final products of rock alteration. The amount and kind of matter carried away in solution varied from place to place, but large amounts of alumina, alkalies, and alkaline earths have been removed from the original rocks; the principal additions were silica and minor amounts of sulphur. For the purpose of considering the nature of the solutions that caused the early silicification of the rocks the products of this process may be divided into four major types – (1) those consisting of nearly pure quartz with minor amounts of iron and titanium oxides, represented by analysis 7 (p. 31); (2) those of red color consisting of quartz or chalcedony with ferric and ferrous oxides and other minor constituents, represented by analysis 4; (3) those containing in addition to the silica some minerals in which alumina with or without potash is present – kaolinite or sericite, or both (see analysis 9), and less commonly diaspore and alunite; and (4) those containing disseminated pyrite in appreciable quantity.

Rock alteration in which the principal products were silica and kaolinite, with or without the formation of diaspore, has been generally attributed to the solfataric action of acid waters. Examples of altered rock of this type are found at Rosita Hills and Red Mountain, Colo.; Goldfield, Nev.; De Lamar, Idaho, and other places. Where alunite has been an abundant product of the decomposition it has led to the conclusion that the acidity of the waters was due to the presence of free sulphuric acid. At Goldfield[62] there are silicified masses of dacite known as "ledges," which appear to be similar to those found in parts of the Bonanza district. The characteristic alteration products at Goldfield are silica, kaolinite, alunite, and pyrite. The ores are of somewhat later origin, occurring in shattered parts of the silicified rocks. Ransome considered that sulphuric acid was generated near the surface by the oxidation of hydrogen sulphide and that the oxidized solutions carried the sulphuric acid downward, where it intermingled with the rising alkaline solutions. In the Engineer Mountain and Red Mountain districts of Colorado, described by Ransome,[63] the products of alteration of the volcanic rocks consist, at the Polar Star lode, of quartz, kaolinite, pyrite, diaspore, and sericite. At Red Mountain the addition of silica and the formation of kaolinite, usually without sericite, constituted the characteristic alteration. The alteration was not limited to the vicinity of ore bodies, although many of the ore bodies crop out in siliceous knobs.

Recent work by Day and Allen[64] on the hot springs at Lassen Peak and The Geysers, Calif., throws considerable light on the different conditions under which alunite and kaolinite may form as products of rock decomposition by waters containing sulphuric acid. It is shown by them that at both these localities, the final residue of rock decomposition was silica in the form of opal, accompanied by minor amounts of other oxides. They state in referring to the chemical decomposition of the lavas at Lassen Peak:

The active agents are hydrogen sulphide and especially sulphuric acid. When sulphuric acid decomposes a silicate the final products are free silica and sulphates of the metals contained in the silicate, and these products are found in all of the springs.

They state that the sediments in the springs constitute the products of decomposition that have been precipitated from the waters and consist in this region of two types – (1) silica and kaolin, and (2) silica and alunite. Whether the product shall be kaolin or alunite in conjunction with silica in any given spring they considered to be dependent upon the relative concentration of sulphuric acid in the waters, as kaolinite is decomposed by strong sulphuric acid into silica and aluminum sulphate. This assumption is supported by the conditions of acidity at the different springs.

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[62] Ransome, F.L., The geology and ore deposits of Goldfield, Nev.: U.S. Geol. Survey Prof. Paper 66, pp. 150-157, 1909.

[63] Cross, Whitman, Howe, Ernest, and Ransome, F.L., U.S. Geol. Survey Geol. Atlas, Silverton folio (No. 120), p. 33, 1905.

[64] Day, A.L., and Allen, E.T., The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. Washington Pub. 360, pp. 113, 140-145, 1925. Allen, E.T., and Day, A.L., Steam wells and other thermal activity at "The Geysers," California: Carnegie Inst. Washington Pub. 378, pp. 45-50, 1927.

In contrast, however, to the conditions at Lassen Peak the sediments in the springs at The Geysers contained no product which could be identified with kaolinite or other clay minerals, and the major constituent of the sediments was opal. In consideration of the cause of this difference they say:

A more plausible hypothesis in explanation of the absence of kaolin from the springs at The Geysers – at least from the acid springs – is that its formation is prevented by the relatively high acid concentration which is found here.

Both at Lassen Peak and at The Geysers the sole cause of the acidity of the springs is sulphuric acid, as only traces of the halogen acids are present. At Lassen Peak the acid waters contained from 19 to 436 milligrams of H_2SO_4 per liter, at The Geysers the concentration was much greater. The temperature of the hotter springs at these localities ranged from 80º to nearly 100º C. It would appear, then, that the action of hot solutions containing different concentrations of free sulphuric acid could account for the range in the character of the silicification at different places in the Bonanza district. The siliceous rocks that are free from kaolinite and contain only minor amounts of other oxides such as iron and titanium presumably indicate the action of waters of relatively high acidity or were produced by the long-continued action of solutions saturated with silica. The presence of ferric oxide and hematite in many of the silicified rocks is compatible with their formation by acid waters. The fixation of ferric iron could reasonably be accounted for by conditions favoring the hydrolysis of ferric sulphate. In addition such solutions containing free sulphuric acid would be capable of transporting alumina. As kaolinite and other aluminum minerals are usually absent from the red or brown jaspers, either the acidity or the temperature of the waters that deposited them was presumably fairly high. Silicified rocks containing associated kaolin and sericite probably indicate a lowering acidity during the formation of kaolin, for sericite is considered to form only from alkaline solutions. The presence of both minerals indicates a fluctuating or changing condition. As having a possible bearing on the relation between the periods of acidic and alkaline alteration, the replacement of diaspore, zunyite, and quartz by sericite, as shown by the specimen illustrated in Plate 10, is of particular interest. This specimen, coming from Greenback Gulch, near the center of the area of strongest solfataric alteration, indicates at this position a change from acid to alkaline solutions during the period of rock alteration. This same sequence is also invariably shown in the northern part of the district, where the silicified wall rock of veins or the red jaspers have been replaced by pyrite and sericite or brecciated and cemented by sulphides. (See pl. 13, *A*.)

During periods of active oxidation some secondary deposition of kaolin may have taken place adjacent to oxidizing sulphide bodies (p. 161). This process represents the commonly described kaolinization produced by meteoric waters near ore bodies and is here definitely differentiated from the hydrothermal kaolinization described above.

SOLUTIONS CAUSING PYRITIZATION OF THE SILICIFIED ROCKS

Pyrite is commonly disseminated through the silicified rocks, usually in positions adjacent to mineralized fissures or ore bodies, though in places pyrite is found in jaspers hundreds of feet from any known ore bodies. The characteristic feature of the pyrite in such occurrences is its well-developed crystal form, usually the pyritohedron, but the sizes of the crystals differ. (See pls. 9 and 11.) In the red iron-bearing jaspers of the northern part of the district much of the pyrite is strikingly well crystallized, some of the larger crystals ranging from 3 to 5 millimeters in diameter. An analysis of such a rock is given as No. 6 on page 31. In the southern part of the district in the silicified area adjoining Greenback Gulch pyrite is present in parts of the quarts-kaolin-sericite rock, but much of it is in crystals so minute that it is easily overlooked unless the rock is examined with a hand lens.

Pyrite occurs in the spring deposits at Lassen Peak, Calif., associated with opal and kaolin under conditions of rock alteration similar to those at Bonanza. Day and Allen[65] attribute its formation to the coexistence of ferrous salt, hydrogen sulphide, and sulphur in the spring waters. The significant feature of its occurrence at Lassen Peak and at The Geysers is that distinctly crystallized pyrite was confined to the acid springs, while all the minerals referred to pyrite found in the alkaline waters were of a cryptocrystalline or amorphous nature.[66] Marcasite did not occur in the acid springs associated with the crystalline pyrite. By analogy, then, some of the pyrite in the silicified rocks at Bonanza may have formed from acid waters containing hydrogen sulphide.

Pyritization particularly near ore bodies, where the rocks have been brecciated and veined with pyrite and other sulphides, was usually accompanied by sericitization and was probably a later process than that described above. A partial or nearly complete loss of the red color of silicified rocks has resulted. The bleaching of red rocks and the replacement of hematite by pyrite may have marked the transition between early acid and later alkaline conditions that continued naturally through the later period of normal vein formation.

The transition stage may be explained by an increase in the concentration of hydrogen sulphide, which would cause the precipitation of pyrite, even in solutions of slight acidity. The bleaching of some of the red rocks near veins agrees with the natural antipathy between ferric oxide and sulphide compounds that has often been recognized. This was first emphasized by Butler[67] and has been discussed in more recent papers.[68] Hematite usually appears only in deposits relatively low in sulphur, and where associated with later sulphides it is as a rule partly destroyed or exhibits

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[65] Day, A.L., and Allen, E.T., op. cit. (Lassen Peak), pp. 137-138.
[66] Idem, pp. 121-122; Allen, E.T., and Day, A.L., op. cit. (The Geysers), p. 48.
[67] Butler, B.S., Suggested explanation of the high ferric oxide content of limestone contact zones: Econ. Geology, vol. 18, pp. 398-404, 1923.
[68] Gilbert, Geoffrey, The significance of hematite in certain ore deposits: Econ. Geology, vol. 21, pp. 560-577, 1926. Butler, B.S., and Burbank, W.S., Relation of the electrode potentials of some elements to the formation of hypogene mineral deposits: Am. Inst. Min. and Met. Eng. Yearbook, 1929, pp. 341-353.

evidence of instability. However, at variance with this normal relation some of the red jaspers of the Bonanza district contain pyrite crystals thickly embedded in them and yet show little evidence of the destruction or instability of the ferric oxide. This suggests that ferric oxide may be stable under certain conditions when pyrite is being formed. In this example the condition may have been one of acidity caused by the presence of free sulphuric acid or other acid in the altering solutions.

SOLUTIONS FORMING THE VEINS

The sulphide ores of the veins are similar to those of many other vein deposits of the low or intermediate temperature zone and were deposited presumably from alkaline solutions. In addition to the valuable metals that were deposited in the veins these solutions must have carried silica, iron, manganese, calcium, barium, potassium, probably sodium, sulphur, phosphorus, fluorine, and carbon dioxide. In the higher-temperature veins of the northern part of the district the solutions were apparently relatively high in potassium and silica, as shown by the intense sericitization and the high silica content of the ores. Magnesium was apparently present only in relatively small quantities, as the vein carbonates rarely contain but little of this element. In the southern part of the district dolomite was deposited together with pyrite and other carbonates, notably in the E.D. vein, near the Kerber Creek road. The presence of dolomite is rather unusual, and its magnesium may have been derived from the dolomitic Paleozoic limestones which presumably underlie the volcanic rocks in this area, probably at a depth of at least 800 feet.

Some alumina must have been carried in the vein solutions of the southern part of the district, as adularia is associated in some places with the vein quartz, though only in small amounts.

ORIGIN OF THE MINERALIZING SOLUTIONS

There are no outcrops of large intrusive masses in the district that could have been the source of the ore-depositing solutions. However, the occurrence of small bodies of intrusive granite porphyry in the vicinity of Alder Creek and of latite, rhyolite, or monzonite dikes in considerable abundance in all parts of the region point to the existence of some molten body of rock beneath the surface immediately before the faulting and mineralization. The depth of this body can not be estimated, but it probably lay at a not very great depth below the present surface, as in some parts of the district scarcely a fault is free from some intrusive material. The solutions that deposited the ores were probably not derived from the same parts of the intrusive body as the small dikes, as all the dikes except those of monzonite were greatly altered by the mineralizing solutions. As no dikes are known to cut ore bodies, it is likely that the upper parts of the intrusive body had become solidified before ore deposition began. The acid solutions which appear to have caused the earliest period of alteration may have come entirely from the underlying intrusive mass during an early stage of its crystallization, or they may have had some other source, as will be considered farther on.

In regions of recent volcanic activity some of the constituents of hot springs are believed to represent primary emanations from crystallizing and cooling bodies of lava below the surface. Both acid and alkaline springs are found, but as to the cause of the acidity or alkalinity and the relations between them opinions in the literature differ and some of the evidence on record is conflicting. Day and Allen[69] in summarizing their own views on this problem, say:

The problem is one that calls for detailed observation in many localities, but at present the weight of the evidence clearly inclines the student of the subject to the conclusion that the acid hot springs constitute a stage of volcanism, logically following the acid fumaroles, and that the alkaline springs develop subsequently as a necessary result of the process of rock decomposition.

Speaking generally, all volcanic hot springs in the lapse of time should become alkaline as a result of the gradual decline in the amount of sulphur gases and halogen acids in the volcanic emanations as the temperature of the batholith falls. (This statement supposes that the chemically active gases disappear before the steam. It is supported by a considerable body of evidence.) A uniform decline would not, however, explain the coexistence of acid and alkaline springs in the same area.

The evidence offered by wall-rock alteration and ore deposition at Bonanza appears to accord with a gradual decline in acidity of the active solutions and may be considered as supporting the contention of Day and Allen regarding the decrease in acidity of batholithic emanations during the period of solidification and cooling.

As against this theory it might be contended that the acid solutions which resulted in the early silicification and kaolinization were derived, as was postulated by Ransome[70] for the conditions at Goldfield, by the oxidation of alkaline hydrogen sulphide solutions as these reached the surface of the ground. After the hydrogen sulphide became oxidized by the atmosphere to sulphuric acid, the solutions would carry the sulphuric acid downward to intermingle with the rising alkaline solutions. It is known that the hydrogen sulphide gas may react with air, forming as a direct product sulphuric acid, and small amounts of acid might thus be produced in porous ground adjacent to fumaroles or springs. Sulphuric acid can also be formed by interaction of hydrogen sulphide with solutions of ferric salts. These were the reactions to which Day and Allen attributed the formation of sulphuric acid at Lassen Peak[71] and at The Geysers. However, the small amounts of sulphuric acid which are known to result from such processes hardly seem sufficient to account for extensive alteration to depths of several thousand feet below the surface. The acidity of such solutions would be lost rapidly as they descended by interaction with

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[69] Day, A.L., and Allen, E.T., op. cit. (Lassen Peak), p. 169.
[70] Ransome, F.L., The geology and ore deposits of Goldfield, Nev.: U.S. Geol. Survey Prof. Paper 66, pp. 193-195, 1909.
[71] Day, A.L., and Allen, E.T., op. cit. (Lassen Peak), pp. 138-140.

the rocks, in addition to their neutralization by the rising alkaline solutions.

Alteration characteristic of low acidity would be expected at depth, yet in the Bonanza district red jaspers and silicified rocks free from kaolin are found in the deepest mine workings associated with deposits of intermediate temperature. The rocks showing alteration of low acidity type found in the southern part of the district are associated with deposits probably formed nearer the surface. It is also difficult to conceive under these conditions why such oxidizing processes suddenly ceased and failed to recur after the beginning of sulphide deposition, inasmuch as the sulphides were surely deposited from solutions containing hydrogen sulphide. The sulphides in the veins show no effect of interaction with later acid solutions except within a very shallow oxidized zone that is clearly related to the present topography and hence caused by meteoric waters. It might conceivably happen that in a few springs oxidation for some fortuitous reason suddenly stopped and thereafter only alkaline solutions circulated in the feeding fissures underground. The fact that this appears to have happened in nearly every fissure in the district, however, necessitates some other explanation than mere chance. It is evidently necessary to postulate either some significant change in the character or amount of solutions coming from the magmatic source or a change in conditions at the surface whereby further oxidation of the rising solutions was prevented. The second alternative can be dismissed as improbable, because conditions like those at Bonanza are commonly found in other mineralized districts in volcanic regions. It is also unlikely that a sudden increase in volume of the magmatic emanations took place, because most regions or fumarolic or hot spring activity are characterized by a gradual decrease in activity. Furthermore, in the Bonanza district the wider distribution and greater volume of rock affected by silicification as compared with alteration attributable to ore-forming solutions indicate a greater volume of the earlier emanations. The only plausible explanation, therefore, appears to be some change in composition of the primary or hypogene solutions, and the simplest interpretation is that the solutions became more alkaline. This conclusion is in accordance with the hypothesis of Allen and Day with regard to the gradual decrease in primary acid constituents. It remains to be considered, however, whether the decrease in acidity occurring at the surface was entirely the result of some primary change at the source of the solutions or whether this primary change was only a directing influence.

According to Day and Allen, both at Lassen Peak and at The Geysers the alkaline waters have resulted from chemical change of waters that are acid nearer their source. They further state:[72]

Thus we find logical grounds for the conception that volcanic hot springs may be originally alkaline, or highly acid changing later to alkaline, but no basis for the conclusions that volcanic springs originally alkaline may become acid by later development.

Although they admit that sulphates may conceivably arise from the oxidation of

[72] Day, A.L., and Allen, E.T., op. cit. (Lassen Peak), pp. 170.

sulphide or thiosulphate they say, "There appears to be no convincing evidence that either of these reactions has ever been observed in alkaline solutions through the agency of air alone.[73] Their conclusions, therefore, seem opposed to the hypothesis that sulphuric acid may have been generated by original alkaline springs.

Even if it is assumed that the primary "solutions" or "emanations" at Bonanza were acid in the early stages, this does not exclude the possibility that at least some or all of the sulphuric acid may have been generated at or close to the surface by oxidation of hydrogen sulphide in acid solutions. Under these condition the primary acidity would necessarily have been largely due to halogen acids. Chlorine has been found in the zunyite molecule, but this is the only mineral associated with silicification in which chlorine might have become fixed. Primary sulphates, however, are know to occur in some hypogene deposits under conditions where the assumption of surface oxidation seems hardly justified.[74]

The effects of the early emanations on the rocks and analogy with the recent hot springs and fumaroles would suggest the general conclusions that these emanations were acid originally and under saturated with many of the common rock constituents. Whether this primary acidity was produced mainly by halogen acids or by sulphuric acid is not apparent, but presumably the oxidation of sulphur would be favored by the presence of other acids, whether or not this action occurred at the surface or at great depths. The emanations vigorously attacked the rocks and must either have originally carried silica or soon became saturated with it, for the earliest effect observed is silicification. Locally or at later stages the solutions were also saturated with alumina.

PARAGENESIS OF THE PRIMARY ORES

The sequence and character of the mineralization vary in detail from place to place within the district, but the general sequence of mineral formation shown in Figure 17 holds for the greater number of veins in the northern part of the district. The order of formation of minerals in the veins of the southern part of the district, such as the Eagle vein, is shown in Figure 18.

[73] Allen, E.T., and Day, A.L., op. cit. (The Geysers), p. 81.
[74] Butler, B.S., Primary (hypogene) sulphate minerals in ore deposits: Econ. Geology, vol. 14, pp. 581-609, 1919.

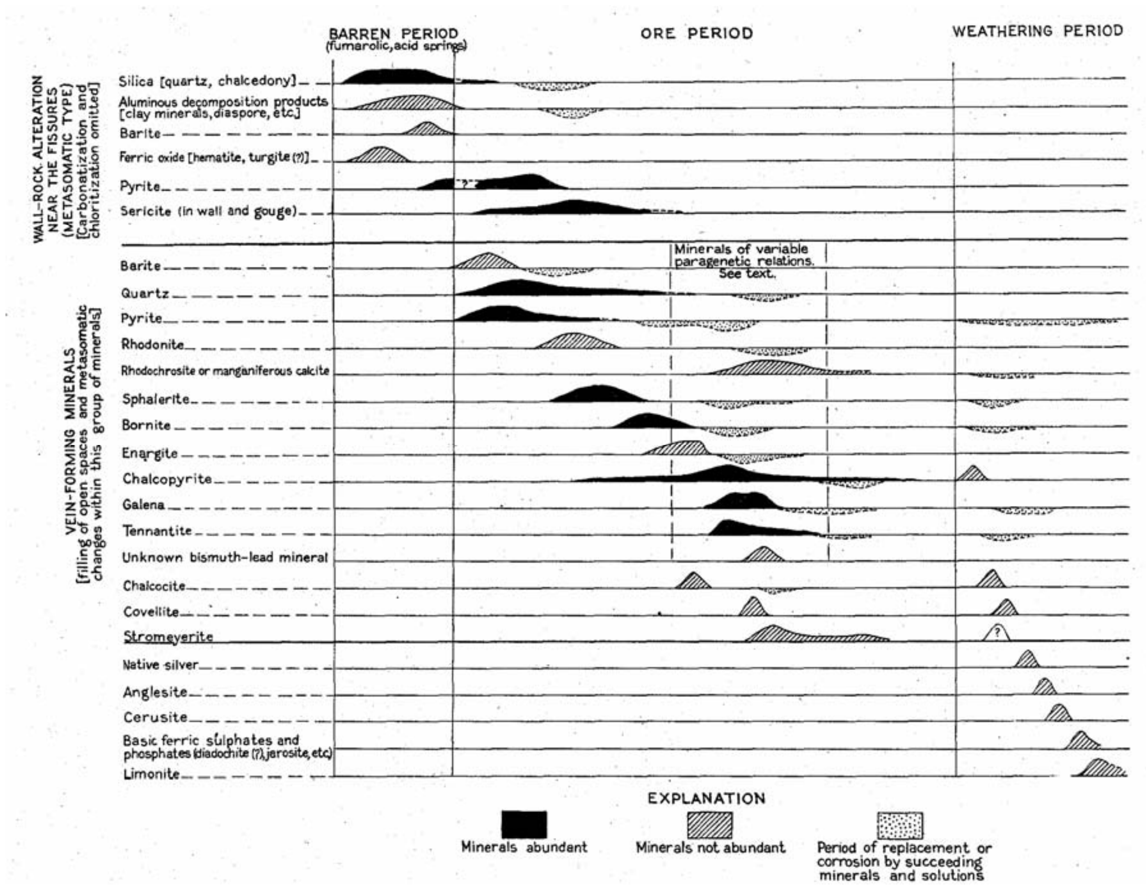

Figure 17. General paragenetic relations of silicification and of the vein minerals of the base-metal quartz-sulphide veins of the northern part of the Bonanza district.

The main stages in the history of ore formation are (1) silicification of the wall rock, in some places with the formation of ferric oxide; (2) deposition of the vein minerals, barite, early quartz, pyrite, and sphalerite, with sericitization and pyritization of the walls probably beginning during the early part of this period; (3) deposition of the later vein sulphides (overlapping the preceding stage more or less in places) in the order (*a*) bornite and enargite, (*b*) galena and chalcopyrite, (*c*) tennantite, chalcocite, and stromeyerite. Photomicrographs illustrating many of the relations of the different ore minerals are given in Plates 13-22.

The greater part of the vein quartz is of early formation, perhaps in many places overlapping the pyrite and sphalerite, but its deposition commonly extended into later stages, and in one specimen from the Cocomongo vein it cements brecciated galena and chalcopyrite. Barite has commonly preceded quartz and is partly replaced by it (pl. 14); in only one specimen, in small amounts, was it seen associated with manganocalcite of a late post sulphide stage. Rhodonite where present in the gangue appears as an early mineral closely following pyrite and intergrown with quartz; it preceded sphalerite. Rhodochrosite invariably followed rhodonite and quartz, both of which it has replaced, although preferentially it replaced rhodonite. (See pl. 13, *B*.) Rhodochrosite and galena are in some places intergrown in such a manner as to indicate essentially contemporaneous formation, but the deposition of the carbonate continued after that of galena. Manganocalcite or calcite and siderite (in places manganosiderite) appear to be late minerals and usually fill cavities or occur in vugs between the sulphides. They are not abundant vein minerals. All the carbonates have replaced the vein quartz to some extent.

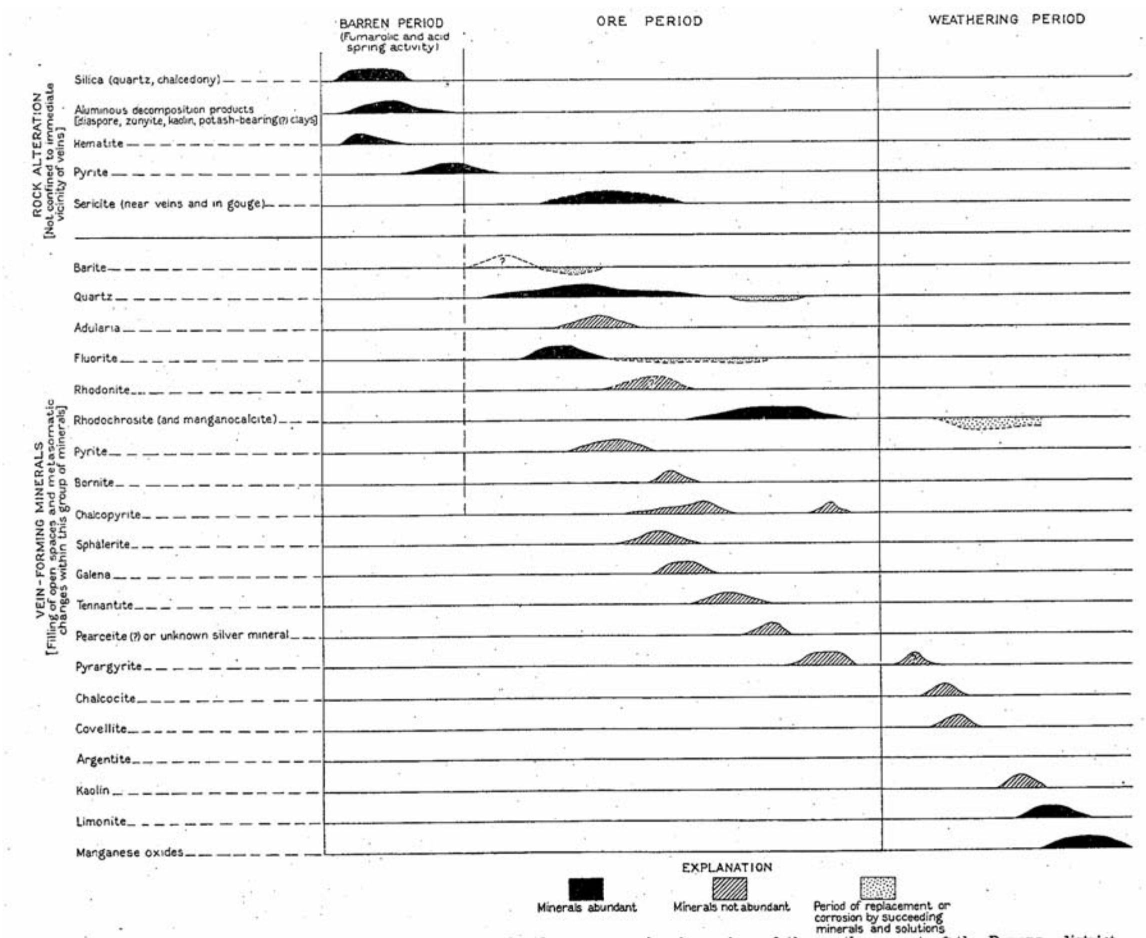

Figure 18. – General paragenetic relations of the low-sulphide manganese-bearing veins of the southern part of the Bonanza district.

A difference in the mutual relations of the sulphide minerals may appear even in the same vein, the deposition of galena relative to that of the copper minerals being the most variable. Galena both followed and preceded chalcopyrite, and in general it may be said that the chalcopyrite, galena, and tennantite greatly overlap. In the upper levels of the Rawley vein, where galena is the most abundant, it appears to be a very late mineral and followed chalcopyrite, but in some of the lower levels where copper minerals are common the paragenesis is more variable and complex. The relations suggest an overlapping history in which the earlier minerals after ceasing to be deposited became unstable in the presence of the solutions depositing the later ones and hence were slightly corroded and partly replaced. Less commonly sphalerite, chalcopyrite, and galena may all have been deposited in overlapping sequence, the grains interlocking in an irregular manner. (See pl. 15, *C*.)

The minerals most subject to advanced replacement by later ones are pyrite and sphalerite. Bornite and chalcopyrite in particular have both replaced pyrite extensively. (See pl. 15, *A*, *B*.) Galena has replaced sphalerite and pyrite. Rarely sphalerite has replaced pyrite.

Relations more nearly universal than any others are the deposition of sphalerite interstitially to pyrite grains and of the later sulphides interstitially to sphalerite. Replacements other than those mentioned above were common but do not appear to have involved any extensive change of material; they consisted rather in a moderate or slight corrosion of the different grains. Both chalcopyrite and galena have replaced bornite locally. Chalcopyrite and chalcocite occur in two stages, of which the later is represented by small veinlets of one or both minerals in most of the earlier sulphides. (See pl. 18, *B*.) These occurrences are probably of supergene origin, as they follow either capillary cracks or even cleavage lines of galena. Covellite is observed in similar relations, having replaced galena, bornite, or chalcocite. Where covellite and chalcocite occur as primary minerals they are later than bornite and galena and form eutectoid intergrowths with them that probably are in the nature of replacements.

Stromeyerite is undoubtedly in large part a primary mineral, occurring in irregular blebs in bornite or intimately intergrown with galena, tennantite, and primary chalcocite. (See pls. 17, *C*, *D*, and 18.) Its relation to tennantite in some places suggests that the components of these two minerals were deposited in a solid solution which at later vein stages separated into an extremely fine intergrowth containing many ramifying veinlets of stromeyerite. These intergrowths may be so fine as to be hardly resolvable without oil-immersion objectives and appear as one mineral until differentially etched with some reagent. (See pl. 18, *A*.)

CHANGE OF ORE IN DEPTH

One of the main geologic features to be considered from the point of view of the miner is the changes that may be expected in the character of the mineralization below depths of the present explorations. The only criterion which the geologist has at present for such predictions is an empirical comparison, based upon mineral composition and types of rock alteration, between regions of similar igneous activity and mineralization. Two main classes of ore deposits are found in the district. One of these classes includes quartz veins of moderate sulphide content, containing lead, zinc, copper, and silver. The minerals of these veins are quartz, barite, pyrite, sphalerite, galena, chalcopyrite, bornite, tennantite, and stromeyerite, with small amounts of enargite, covellite, chalcocite, rhodonite, rhodochrosite, and calcite. These veins are considered to be of the shallow intermediate-temperature type.

The veins of this class have been developed through the greatest vertical range, amounting to about 1,200 feet at the Rawley mine and to much shallower depths in the other veins. The Rawley and Whale veins show an increase in copper content on their lower levels, with a corresponding decrease in lead. As the Whale vein is not accessible, conclusions regarding the significance of this change must be based solely on the Rawley vein. During the development and mining of the Rawley vein in 1926, 1927, and 1928 the ore obtained below the 600-foot level and that obtained from and above the 500-foot level were mixed before treatment in the Rawley mill. The mill heads therefore fail to reflect the full difference in character of the ores of the upper and lower levels, although they show a gradual falling off in the ratio of lead to copper. The table on page 87 shows from what data are available the change in the ratio of lead to copper from the upper to the lower levels.

The change from a lead ore in the upper levels to copper-silver ore in the lower ones is not as abrupt mineralogically as the change of the metal content shown by the analyses would indicate, as small bodies of massive galena ore are encountered at several places below the 600-foot level. These small sporadic bodies are merely indicative, however, of the irregular nature of the bottom of the main body of lead ore as it fingers out in depth. The mixed character of the ore on the 500-foot level, which lies about at the horizon of the change from predominating lead to predominating copper, indicates that the change is a gradual one rather than caused by two widely separated periods of copper and lead mineralization. Microscopic examination of the relations of the lead and copper minerals also fails to support two periods of mineralization, as the galena, bornite, and chalcopyrite are in some ores nearly contemporaneous, particularly in ore from the lower levels. Such ore perhaps represents the early stages of the formation of galena. The segregation of massive galena ore from the other sulphides which is noticeable in parts of the Rawley vein appears to be due to the greater tendency of galena to be precipitated in the more open parts of the fissures and to local reopening of the fissures during the later stages of formation of galena.

It is probably then, justifiable to conclude that the change in character of the ore in depth is a primary downward change. The physiochemical causes of such primary changes are not understood, but studies of ore deposits throughout the world have shown that a certain succession of metals usually holds, and that many lead and zinc veins pass downward into veins of predominating copper and iron.[75]

Similar changes are common in other parts of the San Juan region. Regarding this feature in the mines of the Silverton quadrangle, Ransome[76] says in part:

*In spite of the diversity shown by the different ore bodies, there is, after all, remarkable uniformity to be found in the change at very moderate depths – usually less than 300 feet – from ore consisting chiefly of argentiferous galena to highly argentiferous silver-copper ores, and then a gradual diminution of value downward through the increasing proportion of low-grad pyrite in the ore bodies. These changes are best recorded in the Yankee Girl, Guston, and Silver Bell mines. ****

[75] Emmons, W.H., Primary downward changes in ore deposits: Am. Inst. Min. and Met. Eng. Trans., vol. 70, pp. 964-997, 1924.
[76] Ransome, F.L., A report on the economic geology of the Silverton quadrangle, Colorado: U.S. Geol. Survey Bull. 182, pp. 111-112, 1901.

Although there was on the whole a general change from argentiferous lead ores to argentiferous and auriferous copper ores and finally to slightly argentiferous and auriferous iron sulphide (pyrite), yet the progression was an overlapping and irregular one in detail. Iron pyrite and chalcopyrite occurred at practically all depths, while galena in small bunches was sometimes found far below the point at which it had ceased to be the principal ore.

Although both silver and gold are more abundant in many of the Silverton ores than at Bonanza the changes in base metals shown in these veins are sufficiently like those at Bonanza to justify the drawing of some parallel as to what may be expected at still greater depths. Copper ore in general probably has a much more extensive vertical range than high-grade lead ores. The vertical range in the lead ore of the Rawley vein is about 400 to 450 feet, and there is no reason to think that the copper-silver ores will not continue downward though at least as great a range. Up to the present time productive copper-silver ores have not been found below the 800-foot level, although the reasons for this possibly lie in structural conditions or in insufficient development.

The galena of the ores of the Bonanza district is not notably argentiferous (p. 2), and the range of silver content corresponds very closely to that of the copper content. The silver of many of the veins in the district is partly present as stromeyerite. To judge from the microscopic study of the ores, this mineral has a strong tendency to be associated with tennantite and bornite, although small amounts of it are later than all the other copper minerals. In general more silver is to be expected in the copper ores than in the lead ores, and this has proved to be almost invariably the rule in the veins of the northern part of the district. The silver of the Rawley vein increases very perceptibly down to at least the 800-foot level. It is probably to be expected, however, that at greater depths chalcopyrite and pyrite will increase in amount and that the silver content will gradually decrease. In the Guston mine of the Silverton district stromeyerite, according to Ransome,[77] had a definite lower limit, being present in greatest abundance between the predominating galena ore of the upper levels and the bornite and chalcopyrite ores of the lower levels.

Probably the vertical range of 900 to 1,000 feet represented by the Rawley shoots is as great as may be expected in any of the veins in the district – in fact, most of those developed have a much smaller vertical range than this. Very few ore shoots in the district have been productive below 300 to 500 feet.

The veins of the second kind are quartz-rhodochrosite-fluorite veins of relatively low sulphide content, the economically valuable metal being mainly silver. Besides the gangue minerals mentioned they contain pyrite, sphalerite, galena, chalcopyrite, pearceite (?), and pyrargyrite. Small amounts of adularia and barite occur in the gangue, and small amounts of tennantite, enargite, stromeyerite, and covellite occur with the sulphides. The veins are clearly of the shallow, low-temperature or epithermal class.

[77] Idem, p. 226.

These veins are confined mainly to the southern part of the district and appear to present an entirely different problem as to the nature of their extensions in depth. The presence of adularia, fluorite, and abundant manganese carbonates in the gangue are indicative of low temperature during their deposition. The large area of altered rock between Chloride and Greenback gulches, which contains quartz, kaolin, diaspore, and perhaps other minerals characteristic of solfataric alteration, is also typical of shallow zones of alteration in volcanic regions. Around some very similar zones rich ores of the “bonanza” type have been found. Few veins have been developed in the southern part of the district, and as none of those most developed are accessible, conclusions based upon sound premises cannot be drawn as to changes of mineralization in depth. The Eagle vein has been opened to a depth of 600 feet. The ore of the lowest levels, according to available information (p. 157), though of high grade occurred only in small discontinuous pipes or lenses lying between relatively long stretches of barren quartz and rhodochrosite. The pyrargyrite found on the 600-foot level appears from microscopic examination to be a primary silver mineral. Chalcopyrite is a common mineral in small amounts in all the veins of the southern area. It may be expected to increase slightly in depth.

Small amounts of enargite, tennantite, and stromeyerite are found with the other sulphides, as in the “rhodochrosite vein” of the Express property. This particular association of minerals suggests that some of these veins may change downward into sulphide veins of the type common in the northern part of the district. Experience in the development of veins of this type in other regions does not, however, support this suggestion, as many such deposits have passed into barren gangue in depth. Whether the copper, lead, and zinc ores would reappear at still greater depths cannot be definitely stated. Such barren zones, which are commonly found at the base of silver deposits in volcanic regions, have never been explored far below the base of the productive shoots. The outcrop of the Eagle vein lies about 2,500 feet below the summit of Hayden Peak. The Hayden Peak formation appears to thin somewhat rapidly westward, so that the amount of cover removed by erosion from above the present outcrop of this vein cannot be easily estimated. It may, however, have been as much as 2,000 feet. If this is true the Eagle ore shoot probably represents only the roots of the original mineralized portion of the vein. Many of the other veins may bear similar relations to their eroded portions, as they have characteristically a low sulphide content.

Many veins in this part of the district show conspicuous outcrops of manganese oxides, some of which may furnish manganese ores but of a siliceous grade. Well-oxidized manganese ores probably can be expected to extend only a few hundred feet downward, although where they cross high ridges the veins may be partly oxidized to much greater depths. The oxidation in the Eagle vein was not strong below 100 feet. Just below such oxidized zones in veins of moderate sulphide content some silver enrichment may have occurred, as in the Eagle. On the other hand, rhodochrosite veins originally nearly barren of sulphides may show only negligible enrichment. A careful study of the oxidized ore would be the only means of determining if sulphides were originally present in abundance. Here and there some masses of partly oxidized sulphides should be preserved.

The only encouragement for extending developments below the bottom of the zone of silver ores in this part of the district would appear to be the possibility of finding metal deposits of a higher-temperature origin in the Paleozoic sediments, which presumably underlie certain parts of the southern area of volcanic rocks. Such a possibility is of a very speculative nature and is discussed in more detail in the section on future exploration in the district (p. 73).

GEOLOGIC RELATIONS OF THE ORE DEPOSITS

RELATION BETWEEN MINERALIZATION AND FAULTING

A large proportion of the veins of the district occupy fault fissures or fissures closely associated in origin with the faulting of the volcanic rocks. As many of these fault fissures do not separate recognizable stratigraphic units that would permit displacements to be measured, the relative favorableness of faults of different magnitude as sites of ore deposition is a matter that cannot be determined by accurate statistical study. Some ore bodies of the district occupy openings along fractures, where there has been little or no relative movement of the walls; others occupy faults that are known to have displacements of several hundred feet. It would be desirable if possible to classify the vein fissures according to their origin in relation to faulting, but only a small proportion can be rigidly classified in this manner. Among the several kinds are the following: (1) Fissures or openings that have been formed along fault planes or within fault zones, which are usually known as fault fissures. Many of the fault fissures of this district were produced by rupture of the volcanic rocks under gravitational stress. The Cocomongo and Paragon faults are examples. (2) Fissures which are formed in the walls of gravitational faults by the opening of tension or compression fractures but along which there is comparatively little or no faulting. The vertical fissure veins of the Cocomongo mine represent this type. (3) Fissures of uncertain origin that are less directly related to large faults. These may be tensional or torsional fractures that were formed by stresses developed in bodies of rock during the period of faulting. Their relation to any individual fault is perhaps remote. Some faulting may have subsequently taken place even along fissures of this type. Certain features of the different types of faults are considered in the section on structures.

In the Bonanza district not only the fissures but even some of the larger fault zones seem to have served as channels of circulation for ore-bearing solutions. Large openings in those major fault zones that have been mineralized were rather irregularly distributed and comprised only a small proportion of the total volume of the fault zones. Movements that continued during the period of ore deposition were apparently of vital importance in the mineralization of these large faults and in aiding the movement of the solutions and their access to neighboring fissures that perhaps did not have direct connection with the deep-seated sources of the metals. It will therefore be well to consider in detail the relations between the period of faulting and the period of ore formation. Practically all the faults that separate dissimilar rocks and are known to have appreciably large displacement exhibit some degree of mineralization, such as the deposition of quartz and sulphides along them or alteration of their wall rocks by silicification, sericitization, or pyritization. In some large faults the only noticeable alteration at the outcrop was silicification. Alteration of this type has occurred in the walls of many faults along which the displacement is probably measured in hundreds of feet, such as the fault contacts between pre-Cambrian rocks and andesite near the head of Squirrel Gulch. Many fault contacts between the Rawley andesite and Bonanza latite, where the displacement is 400 or 500 feet or more, show both silicification and bleaching of the wall rock. (See pl. 1.) Vein minerals such as quartz, barite, and minor amounts of sulphides commonly occur in small amounts and have encouraged the prospecting of many such fault zones, although a large proportion of them were either too tight or too gougy for ore formation or perhaps did not have direct enough access to the source of the ore-bearing solutions of high metal content. This latter possibility is also suggested by the fact that at some distance from the centers of stronger sulphide mineralization the only vein matter present is barren quartz or chalcedony.

Silicified zones in the walls of faults are of much more common occurrence than the mineralized zones of commercial importance, in which, superimposed upon the early silicification, occurred other types of wall-rock alteration specifically related to sulphide deposition. There can hardly be any doubt that the phenomenon of silicification, evidence of which is so common throughout the district, represented the earliest stage of hydrothermal activity. (See pp. 20-27) It may therefore be assumed that faults which show only this stage of alteration are older than the ore deposits, even though they are comparatively barren of sulphides or vein matter. Many faults whose walls were silicified have subsequently been relatively inactive, so that, although they were, when formed, comparatively permeable channel ways, they have been effectively sealed against later mineralization. This seems to be true of many faults of large displacement. The evidence so far as it relates to premineral faulting therefore favors the view that this faulting was very intense and that most of the major faults of the district were in existence before the period of ore formation.

Few examples of an ore body displaced by faults that are entirely of post mineral age have been recognized. Post mineral fault displacements of a few feet, where the fault zone is essentially open and unaltered, have been recognized in the Cocomongo mine. Such small faults seem to be of little significance, because minor adjustments of the rocks commonly continue in regions of intense deformation for long periods of time. Minor faulting continued even into Pleistocene time in the Leadville district.[78] In other places, however, ore ends abruptly against faults that give evidence of having been in existence before ore formation, yet the ore may be crushed and apparently faulted off where it abuts against the fault. Where the cross fault is clearly premineral it is apparent that movements along this fault have

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[78] Emmons, S.F., Irving, J.D., and Loughlin, G.F., Geology and ore deposits of the Leadville mining district, Colorado: U.S. Geol. Survey Prof. Paper 148, pp. 85-86, 1927.

continued even after the formation of the abutting vein. It is well recognized not only from geologic evidence but from seismologic studies of modern faults that fault movements are commonly of an intermittent nature and have extended over long periods of time. That many of the faults of the Bonanza district were not only active before and during the period of mineralization but continued so for some indefinite time afterward is well demonstrated by the nature of the vein filling and by the crushing of vein matter. In the Rawley vein, along which there has been comparatively little faulting, at least several major periods of movement may be easily recognized. (See fig. 13.) Along faults of large displacement, such as the Paragon fault, there were probably many successive major movements. As each movement may be in a somewhat different or even an opposite direction from the others, it is easy to see that the early history of a fault may be largely obscured by the effects of its latest movements. Thus it may not be possible to determine whether the greater part of the fault movement occurred before, during, or after the period of ore formation. The relations already deduced, however, that the major displacements of many large faults were premineral and that post mineral dislocations were of minor amount indicate that the main adjustments along old fault lines had established approximate equilibrium either before the period of mineralization or early in that period.

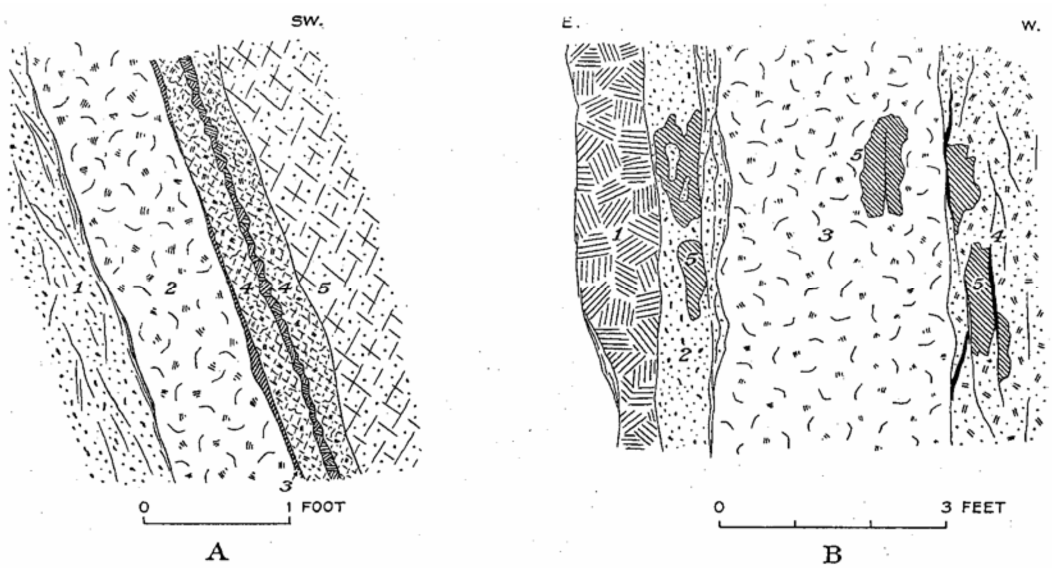

Figure 13. Arrangement of ore in the Express and Tip Top veins. A, Express vein: 1, Altered sericitized country rock, broken and gougy; 2, quartz with chalcopyrite, enargite, and pyrite; 3, calcite seam; 4, mostly fluorite, with quartz carbonate and species of galena, sphalerite, and other sulphides, seam of rhodochrosite in center; 5, silicified wall rock. B, Tip Top vein: 1, Massive galena with minor amounts of other sulphides; 2, sericitized gouge with fragments of jasper (red silicified country rock); 3, quartz vein with pyrite, chalcopyrite, enargite, etc., showing small ragged cavities in quartz partly filled with quartz, pyrite, chalcopyrite, and latest minerals, rhodochrosite and galena; 4, amygdaloidal andesite, partly silicified (early) and sericitized and chloritized, with stringers of pyrite and disseminated pyrite; 5, remnants of silicified country rock.

Evidence of post mineral movement along intersecting veins or fissures, if sufficiently pronounced, may be easily misinterpreted as showing that the brecciated ore found in one fissure is drag ore that has been derived entirely from the other one. Even ore that has been dragged many feet by movement on an intersecting fault does not in itself prove that this fault zone is of post mineral age. It has been said that ore from the Rawley vein was dragged 10 or 15 feet into the Paragon fault, yet it can also be shown that the Paragon fault zone, because of its content of vein matter, must have been in existence before the main period of ore formation. (See pp. 81-85.) Other criteria than faulting of ore must be applied to determine the age of formation of a fault zone. It is probably rarely possible, however, on faults of this kind to determine the relative amounts of the movements that preceded and followed ore formation. The distribution of ore in a vein with relation to a cross fault may give some evidence on this problem. If the ore in a displaced vein on both sides of a fault is much the same and continues uniformly to the fault on each side it is probably reasonable to assume that the faulting was mostly of post mineral age. If, on the other hand, the vein noticeably widens or becomes choked near the fault, if the ore shoots bear some relation to the fault, or if the mineralization and banding of the vein on the two sides are greatly different, it is clear that the cross fault has influenced the width of the fissures and the distribution of the mineralization in them. Under such conditions the fault movements are more likely to be partly premineral and partly of the same age as the mineralization. Minor changes in the structure of the vein across a fault fissure cannot be considered very conclusive evidence, because different parts of a once continuous vein might be faulted into juxtaposition and so give the appearance of a change in character of the vein.

The parallelism of an ore shoot to a cross fault or change in metal content near the fault is excellent evidence that the fault has influenced ore deposition. Where a vein has been formed by repeated openings of the fissure, so that the vein structure is more complex in one or the other wall of the cross fault, the possible influence of the fault on ore deposition should be suspected. For example, if a vein were reopened along a cross fault at such a time during the period of mineralization that the fissure filling of this stage consisted largely of galena, then the occurrence of galena shoots paralleling the sides of the fault would constitute evidence of its influence. Minor galena shoots that are probably of this origin are noticeable in the Rawley vein under the footwall of the Paragon fault. The Empress Josephine and Now What veins also exhibit ore shoots that follow the walls of cross faults. In the Empress Josephine these shoots consisted of telluride ore high in silver and gold, so that the influence of cross faulting was of considerable economic importance. If the mineralization is only of the base-metal type these shoots may enrich or widen the vein sufficiently to “sweeten” the ore near the faults, but small base-metal shoots of this character occurring in small veins would rarely be of economic importance in themselves.

If the vein ends against a cross fault and nothing is known regarding the distribution of ore shoots relative to this fault other than is exposed in a single drift, the determination of the age of the fault must depend upon the presence or absence of drag ore, or of mineralization within the fault itself. Mineralogic criteria can generally be applied to determine if any given fault or fissure is of premineral origin. The presence of silicified rock or jasper in the wall or of altered rock of the other types previously mentioned constitutes an indication that the fracture existed before the ore period. The jasper may have been brecciated and subject to later alteration, such as sericitization or pyritization, which would show that it continued to be active during the period of ore formation. If this later faulting movement was sufficient to form open cracks in which sulphides and quartz were deposited the evidence is of course conclusive. Too great formation of gouge may, however, have effectively sealed the fissures from later veins and sulphides, with the possible exception of pyrite. Even though the gouge may have choked the fissures so that veins were not formed, most of them were sufficiently permeable to be subject to some degree of hydrothermal alteration. The kind of alteration associated wit the ore period resulted in the formation of sericite, quartz, carbonates, and pyrite within the gouge. Some gouges in fissures that contain no visible vein material may by examination with a hand lens show the presence of small crystals or cubes of pyrite or of terminated crystals of quartz.

Microscopic and chemical examination will enable the easy recognition of carbonates and sericite. In highly altered fault gouges the titanium that was contained in the rock silicates has commonly been set free in the form of rutile or anatase. (See pp. 13, 102.) The presence of these minerals can be recognized only under the high power of the microscope. Their association with sericite may be considered conclusive evidence that the altering solutions were of comparatively high temperature and belonged to the ore-forming period.

Although in different parts of the district the fault systems differ in their directions and relations to one another, the same general time relations between ore deposition and faulting holds true throughout the district.

INFLUENCE OF COUNTRY ROCK ON ORE DEPOSITION

The influence of country rock on ore deposition in the Bonanza district is difficult to evaluate, but all the evidence accords with the conception that the basis of this influence lies in the physical rather than the chemical properties of the rocks. Most of the developed deposits lie between walls that are either entirely andesite, or andesite and latite in fault contact, or entirely latite, but no constant differences in the character of the gangue or ore minerals are apparent under these different conditions, although the greater number of ore bodies occur in mines in andesitic lavas, which have yielded the greater part of the production.

The formation of premineral gouge, which probably had an important influence on the migration of ore-bearing solutions and the deposition of ore, seems to have been dependent on several factors – the reaction of the rocks to fissuring, the amount of softening caused by wall-rock alteration, and the displacement and attitude of the faults. Faults of comparatively gentle dip, such as the Cocomongo, Clark, Rico, Hanover, and Exchequer, and those of great displacement, such as the Paragon, contain large amounts of sericitized gouge filling. However, many fissures and faults in the younger latitic and rhyolitic lavas, including the upper rhyolitic member of the

Bonanza latite, seem on the whole to be more choked with altered gouge and rock fragments than those in the underlying, more massive flows. It must be admitted that such a comparison is based on rather unsatisfactory statistical evidence, as the amount of development in the different formations is not comparable. Even casual observation of fissures exposed in small prospect pits and tunnels, however, suggests the conclusion that the lavas in which platy partings are well developed parallel to the flow banding tend to form shatter zones and small stringers and to break into fragments that are smaller and more platy than those formed in massive structureless rocks such as andesite.

The distribution of sericitized and carbonatized rocks with reference to fissured zones and the conditions revealed by microscopic examination of such rocks suggest the importance of surface attack of the solutions outward from the larger fissures along small fractures, grain boundaries, or permanent cleavage lines. Thus as the amount of chemical reaction of the wall rocks with the ore-bearing solutions appears to be dependent primarily on the surface exposed to attack, rocks that shattered more completely would expose greater surface to this attack and would become softened near the fissures. Recurrent fault movements during the period of alteration would thus more readily reduce the partly altered rock to gouge. The amount of chemical attack involved in sericitization and carbonatization may in this manner have played a part by hindering the formation of openings favorable to ore deposition in certain of the lavas.

The field relations of the silicified rocks, on the other hand, indicate that the silicifying solutions gained access to the rocks by diffusion through the pores of the rocks from nearby open trunk channels. The boundaries of the silicified zones end sharply, without any very definite relation to major or minor textural features of the rock, although here and there the silicification of latites and rhyolites is seen to have proceeded along prominent parting planes.

Although the diffusion of alkaline solutions into the pores of rocks was a factor in the process of sericitization, there is ample evidence that the diffusion of acid solutions, which promoted silicification, was of a vastly greater order of magnitude. Perhaps for this reason silicification seems to have affected all types of volcanic rocks about equally. So far as can be observed it had no unfavorable effect on later mineralization; on the contrary, there is good reason to believe that silicification of the walls favored later fissuring. Moreover, as it tended to strengthen the wall rock and rendered it more resistant to the formation of the relatively soft carbonates and of the much softer micaceous minerals, such as sericite and chlorite, silicification reduced the later formation of gouge. The walls of practically all the larger veins in the district were silicified to different degrees. Many good ore shoots have walls of brecciated jasper, indicating that movement occurred along the fissure after the silicification of the walls but before the ore was deposited. It is generally noticeable that under such conditions minimum amounts of premineral gouge were formed.

Besides the chemical and mechanical effects of wall-rock alteration on ore precipitation, there is the effect of the reaction of different formations to deformation during the period of faulting. Lavas that are characterized by pronounced platy partings or flow structure undoubtedly reacted to stresses producing deformation somewhat differently from the more massive lavas. This difference is particularly noticeable in the western or northwestern part of the district, where the Bonanza latite and overlying flows are the predominant surface rocks. Throughout this area these flows are tilted to moderately high angles, so that where they were faulted there has been a strong tendency for shearing to occur approximately parallel to the parting planes. The result has been the formation of parallel branching fissures which constitute a shear zone rather than a simple break. (See pl. 2 and fig. 6.) The effects of this change in formation may be seen by comparing the structural pattern of the faulting in the areas mentioned with the more blocky pattern occurring in the massive andesitic lavas to the east. (See pl. 1.)

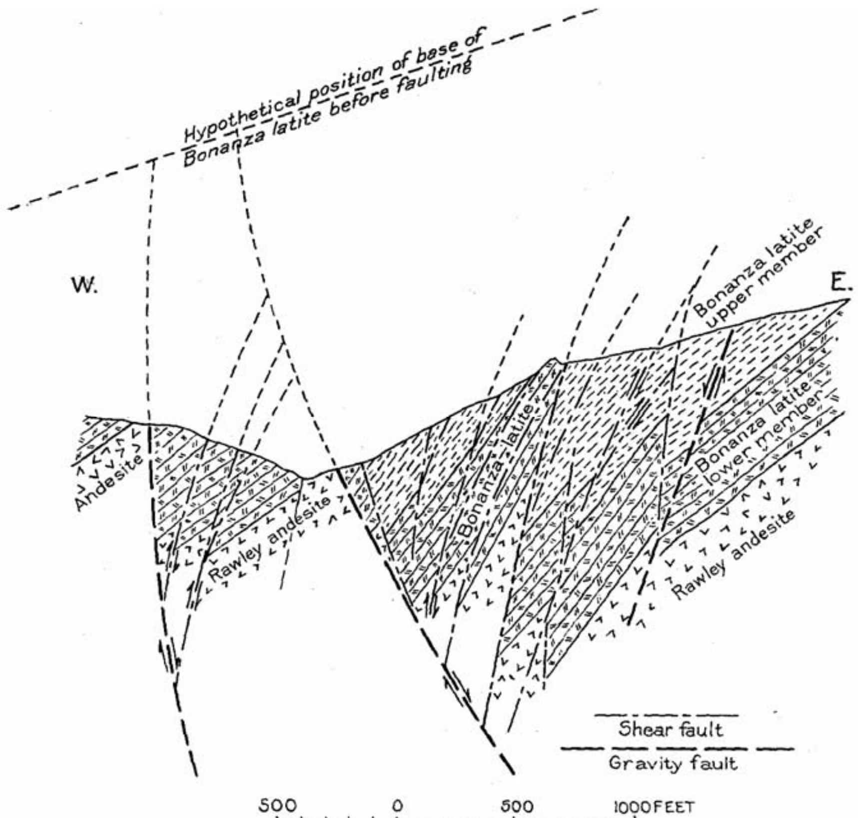

Figure 6. – Hypothetical conception of the structure of a major fault zone on Squirrel Gulch.

Effects produced by change in country rocks on fissure systems have been noted in other districts in the San Juan Mountains. Purington[79] refers to this subject in describing the fissure veins of the Telluride quadrangle, saying:

The fissure systems enumerated, and consequently the veins, penetrate all the rocks occurring within the area. There seems to be little doubt, however, that a mechanical influence of both the nature and degree of development of the fissured zones has been exercised by the rocks of the various horizons which they traverse.

Thus in the case of the Smuggler and Tomboy veins it is evident from observation that the lodes[80] are continuous from the breccias of the San Juan formation through

[79] Purington, C.W., U.S. Geol. Survey Geol. Atlas, Telluride folio (No. 57), p. 15, 1899.
[80] Purington defines lodes as "narrow zones of closely spaced fissures, which have been filled with ore."

the andesite and rhyolite flows above. In the upper workings on the Smuggler vein, however, where excellent exposures on the vein may be seen in both the rhyolite and underlying rocks, considerable differences are apparent. No change was observed in the amount of fissuring between the breccias and the overlying andesite, but in the upper rhyolite, although the fissures are constant in direction and although the zone is equally wide, the amount of space now filled with ore is much less, and the fissures themselves did not apparently afford as much open space as did those below. It seems probable that the upper rock offered a greater amount of resistance to the rupturing force than those below.

A similar constriction of the Camp Bird vein,[81] in the same region, has been noted, where it passes from the andesite breccias and flows into the overlying Potosi volcanic series.

It is clear from the conditions observed at Bonanza, as well as from the similar examples cited above from other areas in the San Juan Mountains, that the mode of deformation of volcanic rocks differs appreciably from one formation to another. In deposits of certain types of high-grade ores the existence of irregularly fissured ground, comprising many small fractures or fissures that form a zone of the lode type, is especially favorable; on the other hand, for base-metal deposits of the kind found in the Bonanza district, the existence of a few openings of large size is distinctly more favorable than these more complex types of fissuring. But whether the mechanical effects of such differences can account for the distribution of ore between the different formations in the Bonanza district or whether other factors have been equally or more important is difficult to judge. The principal reason for this difficulty is that the upper rhyolite members of the Bonanza latite and the overlying rhyolites and latites have been eroded from the parts of the range where the mineralized fissures have received the bulk of the mining development.

In Figure 12 some of the larger veins of the northern part of the district are plotted, showing their vertical range relative to the surface of erosion and to the base of the Bonanza latite. Nearly all the veins occur within a vertical range that extends 500 to 1,000 feet below the base of the Bonanza latite and several hundred feet above it. The Rawley, Whale, and Joe Wheeler veins, in the andesite, probably reach the greatest depth below the base of the latite, and the Cocomongo and Bonanza veins are the highest productive veins above its base. In many of the developed veins the better bodies of lead ore ceased to be profitable several hundred feet below the outcrops. In relatively few of the mines mentioned above were deeper explorations attempted, and these gave different degrees of success, but all of them indicated that the lead decreases markedly in depth. Little or no evidence is available to show how much of the upper parts of the ore bodies has been eroded from veins that cropped out, but the lead and zinc ores could not have extended upward above their present outcrops indefinitely, as the nature of some of their minerals is such that they would hardly have formed under conditions existing close to the surface. The overlying cover of lavas, now eroded, probably was within a range in thickness of not

[81] Spurr, J.E., The Camp Bird compound vein dike: Econ. Geology, vol. 20, p. 129, 1925.

less than 1,500 to 3,000 feet, judged only by what is known of the lava sequence. As none of the lavas above the lower member of the Bonanza latite have been found to contain lead-zinc ores or other vein deposits of favorable nature, it becomes necessary to consider the possibility of a definite upper limit as well as a lower limit to the valuable base-metal mineralization.

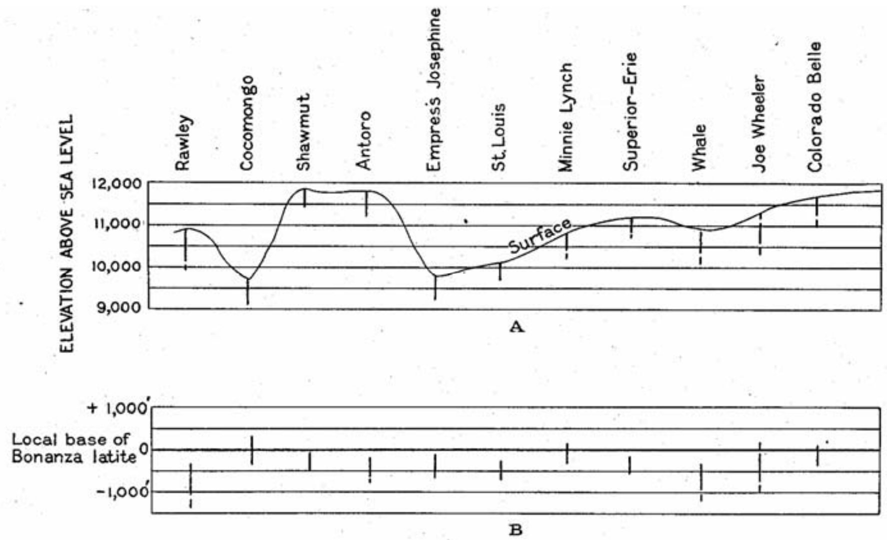

Figure 12. – Relations of ore bodies in the Bonanza district to the present topography and to the horizon of the Bonanza latite. A, known vertical range of ore bodies with relation to sea level; B, known vertical range of ore bodies with relation to base of Bonanza latite. The horizontal relations are not shown to scale. See Plate 1 for relative positions of mines.

One of the outstanding features of the distribution of ore in the northern part of the district is that the zone of productive veins bordering Rawley and Copper Gulches stops relatively abruptly toward the west or southwest beyond Kerber Creek. West of a line along or near Kerber Creek extending from the town of Bonanza northward to a point above the Cocomongo and Bonanza veins there are no veins that have yielded production of any importance. There appear to be at least two possible explanations of this – (1) that the zone of mineralization, which may be assumed to be related to some favorable structural feature, such as a zone of particularly strong tensional conditions, or to an underlying intrusive body, is limited to the belt within which productive veins crop out; or (2) that the exposures of the zone of mineralization are limited by reason of unfavorably fissured surface rocks, and that part of the zone lies concealed beneath the lavas. If the upper limit of deposition of high-grade galena ores had occurred roughly at the horizon of lavas overlying the massive lower member of the Bonanza latite, some ore bodies are perhaps concealed beneath unfavorably fissured ground in the region just west of the northern area of mineralization. The only means of definitely deciding this question will be exploration to greater depths in this part of the district. At present the deepest known exploration along Kerber Creek is at the Cocomongo mine, which extends only to a vertical depth of a little more than 400 feet below the outcrop of the Bonanza vein. That the character of the fissuring might become more favorable in depth in these parts of the district is suggested by reasoning that the underlying andesite would have promoted the formation of more open fractures and that the increased pressure at greater depth would have favored less complicated fissure systems. On the other hand, there are certain unfavorable features to discourage deeper explorations, such as the possible existence of temperatures that were too high for the formation of lead ores. Moreover, the evidence on the whole favors some major structural feature of the district, rather than change in character of country rock, as a primary cause of the limits of the strongly mineralized zones.

In the southern part of the district any relation of deposits to country rock does not seem to be well defined. So few veins have been developed that generalizations cannot be made. Veins are found in many of the different kinds of rocks. Practically all production of the southern part of the district has come from one mine, the Eagle mine, in Eagle Gulch (No. 21, pl. 1). The Eagle vein lies in the Eagle Gulch latite. The Oregon vein also lies along the border of this intrusive porphyry, and numerous smaller veins have been prospected within its boundaries.

On the north flank of this porphyry mineralization seems to have been comparatively feeble, at least at the horizons exposed by the present erosion surface. The zone of mineralization extends south of Eagle Gulch practically to the southern limit of the area mapped, but in the extreme southern part of the district the fissure filling is largely quartz with manganese and iron oxides and relatively small quantities of sulphides. The veins occur in the Rawley andesite, in some of the Hayden Peak latite flows, or associated with intrusive bodies of quartz latite and rhyolite in fault fissures. So far as can be told from the few developed veins the effect of the country rock on the nature of the fissures and vein filling was not marked. The present development of this part of the district seems to furnish little reason for considering any of the formations particularly unfavorable for exploratory work with the possible exception of the rhyolite intrusions. Exploration in the Express mine is not yet of sufficient extent to indicate the influence of the country rock on the vein system. The rocks at present encountered in the workings are of two types – intrusive porphyries associated with the center of intrusive activity north of the mine and andesitic lavas representing the older country rock, which lies mainly to the south. So far as known little mineralization of economic value has occurred in the neck of intensely altered rhyolitic intrusive rocks and breccias which lies between Express and Chloride Gulches. The general impression obtained from studying the small veins and meager explorations in this part of the district is that veins in the andesitic lavas or in the Eagle Gulch latite are more favorably mineralized than those close within the area of the rhyolitic intrusives.

The Hayden Peak latite is also devoid of productive ore bodies, but here again the reasons are possibly structural rather than related to some chemical or textural effects of the vein walls. Alteration in the main part of the Hayden Peak latite has been relatively weak compared to that in the areas to the west, and it would appear that for some reason the faults in this part of the district were less favorably situated for the ore-depositing solutions to gain access to them. This statement is not intended to imply, however, that the area occupied by this formation is entirely unfavorable for prospecting but merely that the possibilities appear less promising than in certain other parts of the district.

RELATION OF ORE SHOOTS TO STRUCTURE

INFLUENCE OF MINOR STRUCTURAL FEATURES

The problem of the formation of ore shoots largely resolves itself into an investigation of the causes of openings in rocks, as the veins are due much less to the replacement of wall rock than to the filling of fissures. As there are many structural conditions which may produce favorably fissured ground but many of which are not understood, even as to structural mechanics, it is apparent that there are many difficulties in predicting the position of an ore shoot much in advance of actual development. However, it seems possible that ground toward which exploration should be directed may be recognized by the application of structural studies.

Many of the causes of the formation of ore shoots have been discussed at length in mining and geologic literature, and some of the favorable conditions are mentioned incidentally in this report in the sections on mineralization and faulting. It will be well, however, to review and discuss briefly certain of the causes of ore shoots that appear to have been effective or that may have application in this district. These causes may be enumerated as follows: (1) Changes in either strike or dip of fault fissures, or in both, aided by the relative faulting motion of the walls; (2) intersections of fissures and the presence of cross faults; (3) simple opening of fissures, by tensional or torsional stresses developed by movements on nearly transverse major faults, or by stresses developed by gravitational adjustments of large fault blocks in which the fissures lie; (4) intrusion of dikes between fissure walls; (5) production of breccia or gouge during faulting and mineralization.

1. The greater part of the production of the district has come from a comparatively few veins of steep dip. The Cocomongo and Bonanza veins are partial exceptions, although the production from these came largely from stopes in which the dips ranged from 40º to 60º, the flatter portions of the veins having so far yielded little ore. Some of the veins and faults in the district have a tendency to flatten in depth, those in the northwestern part of the district flattening toward the east. This phenomenon is believed to have been produced by normal faulting of the gravity or landslide type. In the western part of the district some of the faults may be expected to flatten in depth, and this is probably a condition unfavorable to the existence of large or continuous shoots of high-grade lead or zinc ores at still greater depths. It is obvious that flat faults cannot remain open under great pressures except over short stretches, as the hanging wall will be deformed under its own weight and tend to close any opening produced during fault movements. The intense fracturing and jointing of all the formations within the area of greatest faulting is very likely the result of small adjustments of this nature. Many flat faults are mineralized, however, although they are characterized by small lenticular ore shoots separated by barren gougy stretches. Unless such ore shoots are of high enough grade to pay for finding and developing them, which is rarely the case in base-metal veins, the gently dipping fault fissures are commonly unfavorable as major sources of ore. They are

likely, however, to have had favorable effects on the mineralization of neighboring steeper fissures in the hanging wall or footwall. None of the very low angle faults of the district have ever been profitable, except in a small way, and the total amount of production from them has been small.

As most of the fissures show fault movement, changes in dip or strike, which are caused by curved or abrupt angular irregularities of the fault planes, are probably among the common causes of openings in which ore shoots lie. In practice these irregularities can be detected and to some extent predicted by continuous recording of the strike and dip of both walls and plotting of such records on mine plans and sections. The effect of irregularities of the walls depends on the character and direction of fault movement. If the movement is predominantly down the dip, as in normal faulting, an abrupt flattening of the dip may cause an opening above the flatter portion of the vein, owing to the unconformity of the adjoining walls. (See fig. 19, a.) An abrupt steepening or reversal of the dip in a normal fault may cause an opening below the flatter portion of the fissure. (See fig. 19, b, c, d.) Changes in strike may cause similar openings along the vein by reason of a horizontal component of movement along the fault plane.

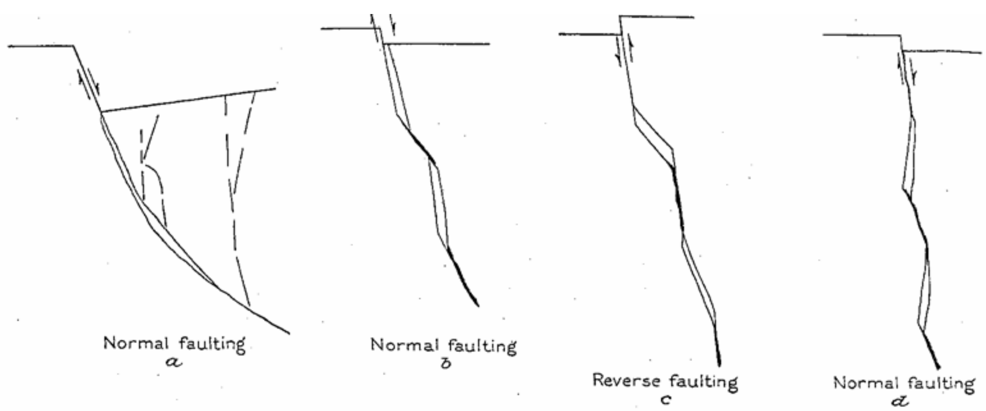

Figure 19. – Formation of open spaces in fault fissures such as are encountered or likely to be encountered in the veins of the Bonanza district. *a*, Conditions encountered in a large normal fault of the Cocomongo-Bonanza type; *b*, *c*, *d*, ideal formation of openings caused by normal and reverse faulting where the fissure undergoes irregular changes in dip; *d* is a special case of *b* showing reversal of dip where opening is formed.

An opening that appears to be due to a local steepening or reversal of dip is shown in the Joe Wheeler vein, but this was not sufficiently developed to disclose the normal dip of the fissure. An ore shoot possibly due to flattening and reversal of dip is also shown by the section between the 600 and 700 foot north levels of the Rawley vein. (See pl. 26.) The 680-foot level showed the richest ore body, which as seen from the sections lies in a very favorable position below a slight reversal of the dip (the normal dip of the Rawley vein is 85º E.) and above a flattening portion of the vein. The exact amount of the movement on the Rawley fissure could not be determined, but there was probably a small displacement of the normal type – that is, downthrow of the hanging wall of the fissure (pp. 82-83).

2. Cross faults intersecting a mineralized fissure appear to have favored the formation of small ore shoots at the intersection. The ore shoots in the Empress Josephine vein have a pitch to the east in conformity with a series of small faults of the same pitch. Many of the shoots are said to be bounded on one or both sides by these faults. (See pl. 33.) The Empress Josephine vein was not accessible during the present investigation, but what is apparently a relation very similar to that above mentioned was seen in the Now What vein, on the opposite side of Copper Gulch. This is an east-west vein that is faulted by a series of small north-south faults, most of which dip eastward. (See fig. 40.) The main vein is noticeably wider and more strongly mineralized immediately in the footwall of several of the eastward and westward dipping cross breaks. The cross breaks, though showing some alteration, are tight and gougy and not strongly mineralized themselves. It is probable that the cross faulting occurred in part during the period of mineralization and therefore controlled the movement of solutions in the segments of the slightly faulted vein. Some of the cross faults show slight post mineral movement.

Probably, however, ore shoots closely related to cross faults are not as a rule large enough to be of economic importance unless the mineralization has produced high-grade ore, such as was found in the Empress Josephine. Shoots that probably had this origin have been found in the Rawley vein close under the footwall of the Paragon fault. The openings containing these shoots were formed at such a time during the period of mineralization as to become filled largely with galena and to enrich the ore near the fault.

3. The formation and opening of transverse fractures in the walls of major faults is clearly one of the causes, but possibly a minor one, by which ore shoots are formed. On a small scale the hanging-wall or so-called "vertical" veins of the Cocomongo well illustrate this in principle. The exact cause of the formation of these fractures is obscure, but they are restricted to the hanging-wall block and are steeper than the main fault. Their strike is transverse to that of the main fissure, and their intersection consequently rakes down the dip. The position of some of these vertical faults appears to be related to variations and "rolls" in the strike or dip of the main Cocomongo fault, and so they were presumably caused by tensional stresses produced in the hanging-wall block where it bore against the ridges in the footwall (see pl. 29), or by shearing induced where the support of the hanging wall was in some manner unequally distributed. The gaping of these fractures also appears to be related to tensional stresses developed by movements on the major fault, as the fissure or fissured zone becomes narrower outward and upward from the main fault. (See pl. 28.)

Fissured zones of this type are probably more likely to be found in the hanging-wall blocks of normal faults that are of fairly large displacement and not very steep. One of the favorable features of this type of fissuring is that some of the fissures show but little faulting movement and are in consequence relatively free of gouge, but the veins may be more or less "frozen" to the altered wall rock. In regions of high-grade ore or replaceable wall rock small fractures of this type in the walls of mineralized faults assume considerable importance. Fractures in the Creede district that are probably like these have been figured and described by Larsen.[82] In base-metal deposits the only parts of these transverse fractures likely to be of economic interest lie near the intersections of the fractures with the main fault. (See fig. 20.) In the Cocomongo mine, where the development of one hanging-wall vein was carried to a distance of about 300 feet from the main fault, the fissure became reduced to only a foot or so in width. It is conceivable that in a region so intensely faulted as the Bonanza district fractures of this origin, especially if developed early in the period of deformation, may have later become fracture zones along which faulting took place. (See fig. 21.) The structure of the Bonanza vein of the Cocomongo mine, which is considered in more detail in the description of this mine, is believed to have resulted from a hanging-wall fracture of the Cocomongo fault that later developed into a fault fissure.

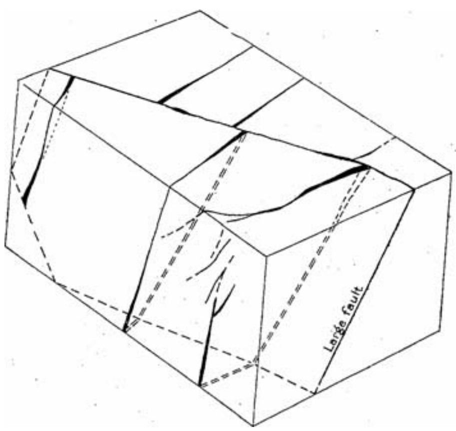

Figure 20. – A series of fissures transverse to a main fault, in which the more strongly mineralized parts of the fissures lie near the main fault. Movements on the large fault during ore deposition tended to keep the fissures open. The main fault may perhaps be too choked with gouge to contain large ore bodies.

It appears likely that where the main fault undergoes a change in dip transverse hanging-wall fractures may swing appreciably in their course, tending to parallel the main fault, and consequently may develop into gravity faults by reason of stresses that exist in the active hanging-wall block. That the Bonanza fault fissure may have had this origin is suggested by the fact that in the broken zone near the intersection of the Bonanza and Cocomongo fissures the fractures have the direction and characteristics of steep transverse fractures developed by torsional or tensional stresses in the wall (pl. 28), but the Bonanza vein veers southeastward away from the Cocomongo fault and assumes the characteristics of a gravity fault more nearly paralleling the strike of the Cocomongo fault. This is illustrated diagrammatically in Figure 22.

[82] Larsen, E.S., Geology and ore deposits of the Creede district, Colorado: U.S. Geol. Survey Bull. 718, pp. 150-151m 1923.

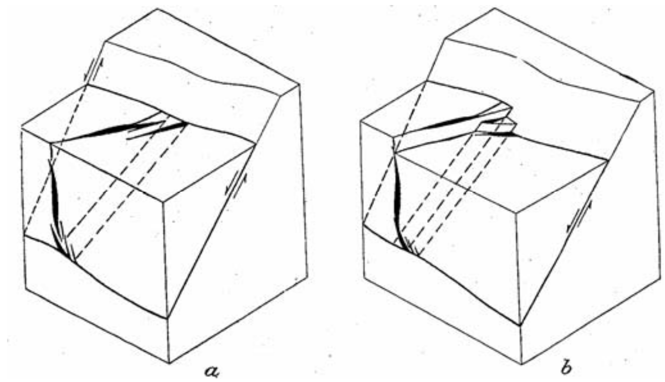

Figure 21. – Development of transverse fractures in the walls of large faults. *a*, Simple hanging-wall fracture; *b*, hanging-wall fracture later developed into a fault.

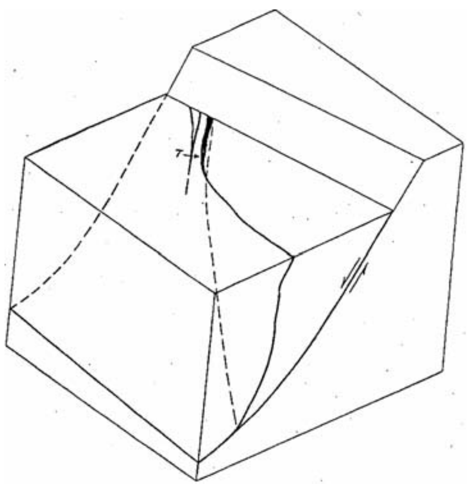
Figure 22. – A transverse fracture from its transverse strike to one nearly parallel to the main fault, forming a gravity fault supplementary to the main fault.

The development of complex systems of tensional stresses in fault blocks induced by gravitational adjustments may very likely have been more influential in producing ore shoots than the formation of the minor transverse fractures just described. In the examples cited the stresses had their maximum development fairly close to the fault plane, and their influence became weak at distances of several hundred feet from the fault. Near major faults of large displacement, such as the Paragon fault, the influence of secondary stresses developed during the subsidence of fault blocks may extend much farther from the place of its origin. Large fault blocks that are bounded by major faults may become subjected to combinations of such systems of stress, which are called torsional stress. If preexisting fractures are present in the fault block these stresses may be partly relieved by movements of the walls of such fractures; if there are no preexisting fractures and the stresses are great enough, new fractures may be developed transverse to the bounding faults. The possibility that stress of this nature may have had an influence on the opening of fissures and the consequent formation of ore shoots may be illustrated by the major fault and fissure systems near Rawley and Sosthenes Gulches. In this vicinity the north-south fissures are generally disrupted by a series of east-west faults, the largest of which is the Paragon fault. Running east and west roughly along the line of Sosthenes Gulch is another zone of faults, of less magnitude than the Paragon.

South of Rawley Gulch there is a third series of parallel east-west fault fissures. Practically all the economically important ore bodies of this area that have been discovered up to the present time lie in the north-south fissures but near the strongest zones of east-west faulting. The east-west faults are nearly all mineralized, but most of them have been too choked with gouge to be themselves especially favorable to the formation of ore shoots. The character of the mineralization in them shows that the latest faulting movements were of greatest strength along these faults. The north-south fissures, though having in general less fault displacement, are so mineralized as to indicate successive reopenings during the period in which the east-west faults were active. (See fig. 16.) Therefore as the forces that caused the gaping of the north-south fissures probably had their origin near the major faults, their influence would have become less effective away from these faults, because of the dispersion of the relief along minor branching fractures. This condition is possibly illustrated by the Rawley fissure, which splits and becomes less productive northward from the Paragon fault. The productive part of the Michigan fissure also lay well within 1,000 feet north of the Paragon fault. On the south side of the Paragon fault is the Rawley-Tip Top vein, which to the time of writing had been developed only a few hundred feet into the hanging wall of the Paragon and had encountered other east-west breaks. The Whale vein is inaccessible, but it is likely that the vein lies between east-west faults paralleling the Paragon and other east-west fissures to the south, such as the Superior and others beyond. The Merrimac and Vallejo fault of Sosthenes Gulch dips southward like the Paragon. North-south ore shoots that have been developed near it are the Sosthenis on the north and the Little Jennie on the south, which splits southward from the gulch. At the north end of the Antoro vein there are cross faults, and the south end of the ore shoot is limited by the east-west mineralized Poverty fault. The Payson ore shoot, which may lie in the northward continuation of the Antoro fissure zone, also lies between zones of cross fissuring.

4. The intrusion of dikes between fissure walls may assist to some extent in holding apart the walls subsequent to the solidification of the dikes, and as some the dikes apparently terminate upward without having reached the surface these bodies may play an important part in controlling the movements of mineralizing solutions. The dikes themselves, other than as an indication of the depth to which the fractures extend, probably bear no direct relation to mineralization. They are certainly not the source of the mineralizing solutions. The porphyry dike of Rawley vein lies in lean parts of the fissure, but it may have exerted some control on the structure of the fissure immediately adjacent to it, or it may have acted as a barrier to free circulation of the solutions and in that way indirectly influenced the position of ore shoots. So far as is known the dikes in the district are of premineral age, as they are nearly all altered in a manner similar to the wall rocks and are not seen to intrude ore bodies. Some of the coarse-grained monzonitic dikes may be of very late age, as they are but slightly altered, but their time relation to ore deposition has not been determined.

5. In some of the ore shoots in the district the ore shows clear evidence of being due to filling and replacement of breccia material. The breccia fragments are generally siliceous, the original minerals having been replaced by quartz, with some pyrite and zinc, and between the fragments heavier sulphide ore has been deposited. The relations indicate that the space between vein walls was more or less filled with rubble sufficiently coarse to be easily permeable to migrating solutions. Coarse brecciated material of this character would appear in general to be very favorable ground for deposition. If, however, the size of the material is too greatly reduced by attrition, as would result between fault surfaces of great displacement and low dip, the clayey gouge thus produced would act as a barrier to circulation and free deposition. Clayey or gougy breaks are present in many veins on one or less

commonly both walls of an ore body, but the heavy gouges that are characteristic of flat faults in the district are generally found to be unfavorable. Gougy breaks in the walls of even the steeper veins have, however, caused some difficulty in the district in several places where shrinkage-stope methods have been used, as the barren wall has partly fallen in and diluted the ore. Exceptions to the non-occurrence of ore shoots adjoining heavy gouges are found in parts of the Cocomongo vein and in the Clark vein of the Rawley drainage tunnel, but the shoots are apparently lenticular and liable to be cut off abruptly either horizontally or vertically. A few of the small lenses of silver-bearing ore that occur in such gouge material, as mentioned above, may be mined.

RELATION TO MAJOR STRUCTURAL FEATURES

Within the area north of Elkhorn Gulch (see pl. 1) about one-half of the rock exposed at the surface is andesite. Exclusive of the production of the Rawley mine since 1926, about 65 percent of the total production from this area since 1880 has come from veins in andesite; the remainder came from veins in the lower part of the Bonanza latite. There has been no production of any consequence from overlying lavas which flank this area on the west, yet these lavas are equally faulted, and the effects of the hydrothermal activity that accompanied mineralization extended for a mile or two west of the zone of producing veins. It is of importance with a view to guiding future exploration to examine the geologic setting of the mineralized fissures and to consider possible causes of this restriction of the productive veins. It seems probable that the influence of structural features has been much greater than that of the chemical properties of the rock. Two main kinds of faulting have occurred in the district — tensional faulting due to the vertical force of gravity and compressional or shear faulting caused by the bulged area of the crust. During the deformation of the rocks, large blocks of the crust were tilted in various directions, as shown in Figure 10. The productivity of the fissures is much less in zones of steeply tilted rocks than in the zones of flatter-lying formations. The strongly mineralized areas in the north seem to coincide with the zones within which fault blocks were undergoing rapid change in tilt. (See fig. 5.) Within such areas in the vicinity of Alder Creek dropped wedges of Bonanza latite are inlaid into the Rawley andesite. (See pl. 2, section A–A' and A_1-A_1'.) Whether or not the prevalence of tensional faulting in certain areas has localized the zones of favorable mineralization cannot be definitely answered, but it appears to be the most plausible explanation of the conditions found.

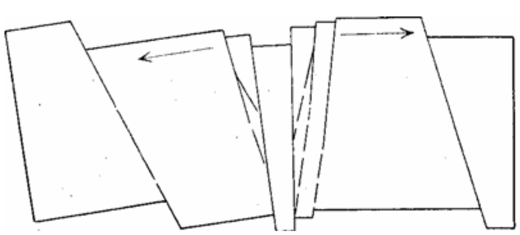
Figure 5. – Formation of a zone of maximum tensional conditions within a series of fault blocks tilted at different angles.

In the southern part of the district the difference in structure between different areas is less pronounced than in the north. The most steeply tilted fault blocks, however, lie in the vicinity of Hayden Peak, and most of the mineralized veins lie farther southwest or west.

TYPICAL FISSURE AND VEIN SYSTEMS

RAWLEY GULCH

Extending north from the vicinity of the Rawley and Whale mines in Rawley Gulch is a strong zone of mineralized fissures which has an average width of several thousand feet and is traceable northward at least as far as the vicinity of Round Mountain. The north-south direction of fissuring in this zone is very strongly developed and is indicated at the surface by roughly parallel fissure and joint systems of this trend. The continuity of the north-south fissures is broken, however, by a smaller number of more or less prominent easterly faults, the best known of which is the Paragon fault. None of the north-south fissures are traceable for great distances, apparently in part because they are interrupted by the easterly cross faults and in part because the individual fissures tend to branch and fray out in one direction or the other. The Rawley fissure has been explored north of the east-west Paragon fault for about 1,000 feet to a point where the vein splits into diverging fissures. The east split of the upper levels may possibly be traceable into Antoro property nearly 800 feet farther northeast, but this extension has not yet been proved by developments. It cannot be accurately traced on the surface. The 1,000 feet of development on the Rawley fissure north of the Paragon fault constitutes the greatest length to which a fissure has proved profitable in this entire north-south zone. Although it is possible that some fissures of this zone may extend essentially uninterrupted for even greater distances, little confidence can be placed in the continuity of commercial mineralization over such extensions.

Many of the larger fault fissures form barriers of comparatively low permeability between different fault blocks and have exerted a noticeable influence on the mineralization of abutting veins. In the vicinity of Rawley Gulch the most prominent east-west cross fault is the Paragon fault; east of the Rawley vein this strikes N. 70°–80° E. and dips about 50°–55° S., but west of the Rawley vein the strike seems to swing somewhat north of west. This fault may be traced for a distance of about 8,000 feet with certainty and perhaps for several thousand feet more, as the zone appears to extend from Squirrel Gulch at the west eastward nearly to the head of Rawley Gulch. The displacement on this fault 2,000 feet west of the Rawley vein where it faults latite into contact with andesite is perhaps roughly 1,000 feet. It is pretty certain, however, that the displacement becomes smaller in either direction from this position. As the rock, particularly in the hanging wall of the fault, is broken into minor fault blocks by abutting faults, it is probable that the displacement may change abruptly at some places by being partly taken up on certain of these transverse faults.

On the north side of the Paragon fault in the Rawley Gulch area there are two main abutting north-south veins — the nearly vertical Rawley vein just mentioned, the average strike of which for 1,000 feet is a little west of north, and the Michigan vein, which strikes N. 15°–20° E. and dips about 50° or 55° E. Between these two developed veins there are a number of parallel north-south fissures exposed at the surface, but none of these, so far as known, are well mineralized. On the south side of the Paragon fault is a north-south fissure which lies about 50 feet east of the strike line of the Rawley vein. Although this fissure may be the faulted continuation of the main Rawley fissure it lies in a different fault block, which is rather effectively sealed from the north side of the Paragon by the wide zone of crushed and gougy material of the fault. Other north-south fissures on the south side of the Paragon are the Hanover, the Whale, and several other small fissures encountered in the 400-foot adit-level crosscut of the Rawley mine. Farther east, on the south side of Rawley Gulch, is the Essie-Little Jeff vein, a north-south fissure dipping east which has been explored to some extent.

The relations between these several north-south fissures on the Paragon fault have been exposed in the workings of the Rawley and Paragon mines. The relation of the Paragon fault zone and the Rawley vein at the end of the 500-foot south level of the Rawley mine is shown in Figure 23. The Rawley vein narrows as it nears the Paragon fault and is displaced a foot or so at a time in small step faults that parallel the Paragon. Some of these small faults are at least partly postmineral. At its end the drift penetrates one of the main fault fissures of the Paragon fault zone, which strikes east and dips 58° S. This fault contains sericitized gouge and vein material composed of quartz, pyrite, galena, and sphalerite. Although this ore is partly crushed by postmineral movement, the mineralization was caused by the circulation of ore-bearing solutions within fissures of the fault zone. In the Paragon No. 2 adit (fig. 33), 1,000 feet east of the Rawley vein, the continuation of the Paragon fault is more strongly mineralized, but here also the ore is partly crushed, indicating similar postmineral movement on the fault. Still farther east in the same tunnel the intersection of the northeasterly Michigan vein and the fault is exposed. The ore in the Michigan vein gradually pinches close to the Paragon fault and spreads laterally to some extent into the Paragon at the intersection. There is little evidence of dragging of the Michigan ore at this tunnel level, and the mineralization of the two fissures could have been contemporaneous.

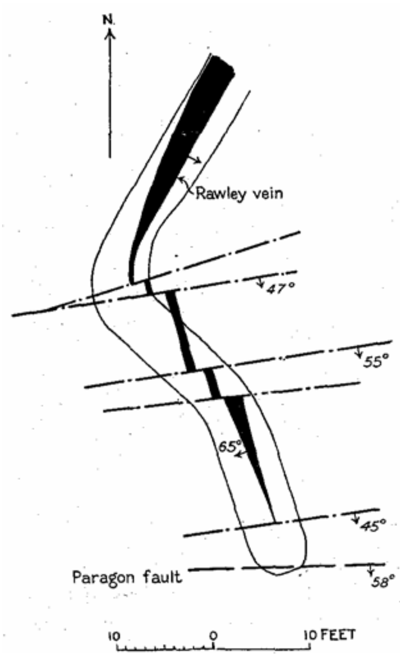

Figure 23. – Relations of the Rawley vein and the Paragon fault on the 500-foot level of the Rawley mine.

Now, if it is assumed that the Paragon fault movement was for the most part later than the formation of the Rawley and Michigan veins it becomes necessary to assume two periods of similar mineralization to account for the ore found in the Rawley and Paragon mines. The relations shown, however, can be somewhat more simply explained by assuming that there was only one period of mineralization, which followed the formation of a large part of these intersecting fissure sets, and that minor faulting movements continued on the Paragon fault after ore formation.

Probably in part the north-south fissures are older than the Paragon fault and have been displaced by it, but other transverse fissures very likely owe their origin to stresses developed by movements on this large fault. Faulted continuations of fissures of this origin will of course not be found in the other wall of the fault.

It has been shown in the experimental production of intersecting fracture sets by torsional stress that apparent displacements of fracture may result, even though the intersecting sets are of the same age. The two sets of fractures in Rawley Gulch resemble very much those produced by torsional stress in brittle materials, so that their initial development may represent the result not of two separate and different stresses developed in the crust at different times but of stresses that were essentially contemporaneous. Steplike displacements of the Rawley fissure by the Paragon fault show, however, that movements continued longer on the east-west fault. To accept as the most common relation between the two sets that the north-south faults are interrupted or slightly displaced by the east-west faults does not imply that the east-west faults are all of postmineral age and have faulted off the veins, as many fissures of both sets are found to be mineralized. The sequence of the fissure and vein formation may be summarized for this region somewhat as follows, although the actual conditions are probably much more complicated and exceptions are to be expected.

1. Formation of north-south fissures and faults, closely followed or in many places essentially contemporaneous with No. 2.
2. Formation of east-west or northeast faults and associated transverse fractures.
3. Intrusion of dikes into fissures.
4. Early stage of barren wall-rock alteration (jaspers).
5. Continued movement on fault fissures and brecciation of jaspers, probably with the formation of new breaks and production of gouge.
6. Formation of ores in fissures and in brecciated jasper zones, accompanied by bleaching and micaceous alteration of wall rocks. Small adjustments continued on fault fissures during ore deposition, brecciating ore, forming new openings, and producing gouge streaks.
7. Minor postmineral faulting and movement on mineralized fissures. Probably the strongest on the large faults, such as the Paragon and its parallel breaks. Further production of gouge and minor brecciation of ore.

The postmineral brecciation of ore in the larger fault fissures at some places in this part of the district has been incorrectly interpreted as a result of the dragging of ore from intersecting veins.

SOSTHENES GULCH AND ANTORO MINE

The gulch lying north of the Rawley Gulch is unnamed on most maps of the district but may conveniently be referred to as Sosthenes Gulch, from the Sosthenis mine, which is near the head of the gulch. Across the head of this gulch, extending 2,000 to 3,000 feet west from the Antoro shaft, there is a zone of closely spaced north-south fissures within which is the somewhat narrowed northward continuation of the mineralized zone of Rawley Gulch. Partly because of the configuration of the topography the north-south fissures are the more prominently indicated at the surface. Among those which are mineralized are the Antoro, Payson-Radcliff, Wisconsin, Sosthenis, Little Jennie, and Gypsy Queen. Among the known east-west fissures which are mineralized and developed are the May Queen (Merrimac) and Vallejo and the Poverty vein of the Antoro tunnel. Tunnels near Sosthenes Gulch, however, intersect many other east-west faults and fissures, and although many of them are of premineral age few are strongly mineralized. The general relations between the two sets are similar in most respects to those of Rawley Gulch. Several of the mineralized north-south fissures in Sosthenes Gulch are displaced by the intersecting east-west faults, but these are mostly of premineral age, and there is also some indication on the north side of the gulch of a late system of fissures striking about N. 30°-40° E.

The Antoro vein (pl. 31) is cut off at the north end of the Antoro mine by a nearly vertical northwesterly fault. About 350 feet south of this position the northwesterly Poverty fault forms a second cross fault of the east-west series. All the developments on the Antoro vein proper lie between these two cross faults. As the relation between the Antoro fissure and the Poverty fault is not well exposed in the mine workings it is not known whether this fault displaces the Antoro vein, but it presumably interrupts it. About 200 feet south of the Poverty fault is exposed a north-south vein, known as the Zinc vein, that lies about in line with the Antoro fissure but has not been connected with it by workings. At its south end the Zinc vein ends abruptly, however, against an east-west fault. Of the east-west fissures in these workings the Poverty fault is the only one well mineralized, and a small amount of stoping has been done on this fault west of the tunnel level. A few other east-west fissures contain some vein material. The conditions suggest that the Antoro fissure was broken into several short segments by the east-west faults and that later both sets were partly mineralized.

VICINITY OF ROUND MOUNTAIN

In the vicinity of Round Mountain the Maybelle, Shawmut, Vienna, and Rico explorations are practically the only accessible workings that show the character of the fissuring and mineralization. The Yellow Type vein was inaccessible. Nearly all the veins of these groups strike northeast and dip southeast. The fissures in this area show a greater tendency to strike northeast than the fissures of the zone between the Antoro and Sosthenis mines, 3,000 to 4,000 feet to the south. The north-northeasterly set of fissures represented by the Shawmut (N. 30° E.), the Maybelle (N. 45° E.), and the Yellow Type or Vienna (north-south?) possibly represent the north end of the wide mineralized fissure zone that extends from the vicinity of the Rawley mine, in Rawley Gulch, north across the head of Sosthenes Gulch. No east-west cross faults were seen in any of the underground workings examined, although the geologic structure at the surface indicates the presence of several cross faults.

COPPER GULCH

To the south of Rawley Gulch, in the vicinity of Copper Gulch, a somewhat different and possibly more complex relation is exhibited between the fissure and vein systems. At least two main systems and perhaps several minor systems of fault fissures can be recognized. The Rawley andesite and the Bonanza latite, the two formations exposed at the surface, are broken into sets of complex fault blocks bounded by fault planes striking northeast and northwest, so that the Bonanza latite is inlaid into the Rawley andesite in an irregular pattern. The relation between the two sets does not appear to be consistent and is difficult to establish by observations at the surface alone. A few short accessible tunnels which are driven on nearly east-west mineralized fissures show that these are rather consistently faulted by a northerly set and a northwesterly set of fissures. This condition is encountered in the Empress Josephine, Hortense, and Now What veins. The northerly fissures at their intersections with the mineralized east-west fissures have exerted a noticeable influence on the width and grade of the ore. According to those familiar with the Empress Josephine mine the richer ore shoots of the mine are said to lie against and to pitch parallel with the dip of northerly or northwesterly faults that have displaced the Empress Josephine fissure at several places. The fact that the northerly faults are themselves in part mineralized and the influence which they had on the ore deposition in the faulted fissures show that both sets are of premineral age. This influence on the ore is to be ascribed to renewed movements on the cross faults during ore formation.

The results of the early stage of barren siliceous replacement of the andesite and latite in the walls of the fissures are especially conspicuous in this area. There are many ledges of jasper which have apparently sealed many of the early fissures so completely that they were not reopened and mineralized by the later stage. In the Empress Josephine fissure both stages of mineralization are represented, the later stage apparently occurring alongside the jasper or in brecciated parts of it.

Some of the north-south cross faults in the Hortense and Now What tunnels were affected by only the later stage of mineralization and hence may have formed by fracturing of the major fault blocks after the earliest period of faulting and silicification.

At the risk of being considerably in error because of the meager opportunity for underground observations in this area, a tabulation of the geologic events is offered below — mainly, however, as a basis for further investigation.

1. Formation of the northeast, northwest, and other sets of faults during the subsidence of the region, producing the complex block-fault pattern of the andesite and latite shown on the map.
2. Early stage of barren silicification in both sets of fissures.
3. Continued movements on the early faults and some fracturing of the major fault blocks by later fissure sets, possibly represented by some of the minor north-south and east-west fissures. Some of the silicified fault zones were reopened; others were not.
4. Second stage of the mineralization, represented by quartz, barite, and base-metal sulphides with some silver.
5. Minor reopening of some fissures, especially near cross faults, and third stage of mineralization, represented by gold and silver tellurides and native tellurium. Minor

amounts of base metals accompanied the tellurides, perhaps representing largely a solution and redeposition of early sulphides. In many fissures this stage is wanting or very weak.

6. Minor postmineral movements along the veins and elsewhere.

It should be realized that the stages enumerated above are more or less arbitrary divisions, as the events overlapped, and only those that appear to be of significance are included.

KERBER CREEK

The fissure and vein systems along Kerber Creek near the town of Bonanza are similar to those of the lower part of Copper Gulch. North of the junction of Squirrel Gulch there is a mineralized zone within which lies a series of fault fissures that strike north or northwest and dip at comparatively low angles to the east or northeast. The individual faults cannot be traced for great distances along their strike. The mineralized Cocomongo fault, which strikes N. 30° W. and dips 35°–45° E., has been explored for about 500 feet along its strike and for about an equal distance for the dip. At the north end of the mine it is displaced by a series of cross faults, which seem to form a local limit to the ore body.

Minor mineralized fissures that are found in the walls of the Cocomongo fault are described on pages 99-102. A few barren and open postmineral faults of north-south trend are also found in the Cocomongo mine, but the displacements seen are not more than a few feet.

The Bonanza vein, which strikes N. 50° W. and dips northeast, occupies a fault fissure in the hanging wall of the Cocomongo fault and terminates against it. The Bonanza fissure has been explored for 400 or 500 feet southeast from its intersection with the Cocomongo fault. The Exchequer fault, which lies south of the Cocomongo mine, strikes about north and dips 30° E. and has been explored for several hundred feet. The Cornucopia fissure is another fault dipping eastward at a relatively low angle and lies east of the Cocomongo mine.

These faults together form part of a complex fault zone of a general north-northwesterly trend, which can be traced for about 3,000 feet north from the junction of Kerber Creek and Squirrel Gulch. The total displacement of this fault zone is large and has resulted in faulting down the Bonanza latite toward the east, so that its outcrop is repeated many times on the slopes adjoining Kerber Creek. (See sections D–D' and F–F', pl. 2.) Many of the ore bodies in these larger faults seem to have become narrow and unprofitable in depth, largely, perhaps, because of the low angle of dip of the fissures.

In addition to these large fault fissures there are many steeply dipping fissures which have an easterly strike and some of which are mineralized, such as the Baltimore and Memphis. The most common relation between the systems as shown by surface exposures would indicate that most of the east-west fissures belong to a younger set and displace or interrupt the larger mineralized faults of northerly or northwesterly trend. The possibilities at depth of these east-west mineralized fissures where they enter the Rawley andesite beneath the Bonanza latite still remain untested.

ALDER CREEK

The only underground workings in the Alder Creek region that afford any data on the relation of faulting and mineralization are a few tunnels on the Joe Wheeler fissure zone and some belonging to the Manitou-Sunlight group of claims. On none of these workings are the developments extensive enough to disclose the general relations between different fault or fissure systems. In the Joe Wheeler tunnel, on the slope north of Alder Creek (pl. 1, No. 38), the Joe Wheeler vein is encountered only in the last 100 feet or so of the adit. (See fig. 47.) The fissure in which the vein occurs strikes about N. 10° W., with an irregular but nearly vertical dip, and is probably a fault fissure. At the north this fissure ends abruptly against a gougy mineralized fault striking about N. 10°–20° E. and dipping west. Although both of these fissures probably belong to north-south fault zones, the mineralization in the two was somewhat different, the northeasterly fault containing a heavier gouge and more sphalerite. The N. 10° W. fissure contains a compound vein filling of barite, quartz, and copper minerals on one wall and mainly sphalerite and galena with a little chalcopyrite on the other wall, the two parts of the vein being separated by altered wall rock and gougy matter.

The mineralogic differences in the ore of the two parts appear to be the result of recurrent movements on the fault during vein formation, so that first one and then the other wall of the fault became the channel of the ore-forming solutions. As the walls of both of these fault fissures consist of considerably altered andesite it is not possible to determine their displacements. The geologic relations at the surface in this vicinity show that the rocks are broken mainly by two sets of faults, which may be very roughly classified as north-south and east-west systems, and that the Bonanza latite is inlaid into the Rawley andesite by faults of normal displacement belonging to these two systems. Fissures of both systems seem to have been equally subject to mineralization, to judge from the intensity of wall-rock alteration and the vein material seen in outcrops and prospect pits. The Joe Wheeler vein appears to lie within the fault zone which bounds the west side of the latite body that caps the ridge to the north. The dip of this latite body is not known accurately but appears to be gentle toward the northwest. Regardless of this dip, the displacement of the bounding faults cannot be less than several hundred feet. (See section A-A', pl. 2.) The intersecting fissures of northerly trend in the tunnel below the latite suggest that the fault is composed of a number of fissures rather than a single one. The fissures and altered zone in the saddle at the west end of the latite is 100 to 200 feet in width. An altered and fissured zone of about equal width is found at the east side of the latite block, and the northeasterly fissure encountered in the Joe Wheeler tunnel may possibly belong to this group.

In parts of the Alder Creek region where east-west and north-south fissure systems intersect there is some suggestion in the shapes of the fault blocks that the east-west system more commonly interrupts the north-south fissures, but there are evident exceptions. The Colorado Belle vein, which belongs to the east-west system, shows all the stages of mineralization beginning with the earliest period of silicification. However, some small easterly cross fissures in the Joe Wheeler tunnel show only very weak alteration but sufficient to indicate that they are of premineral age. Their relation to the Joe Wheeler fissure is not exposed, but they appear to fault a small northwesterly fissure containing some zincy ore.

In the western part of sec. 5, T. 47 N., R. 8 E., the fault systems swing into northwesterly and northeasterly trends. The northwest faults are the more persistent, though both sets are weakly mineralized. Several small tunnels and shafts in the bottom of Alder Gulch and in the tributary gulches at its head expose both north-south and east-west fissure systems, and both systems are mineralized, although the veins matter is narrow and of low grade.

Evidently the major part of all the faulting in the Alder Creek region is of premineral age. There is evidence that faulting or small adjustments of the fault blocks continued through the period of ore formation and perhaps even later and so influenced the distribution of ore within individual faults and near fissure intersections. The meager developments seen failed to disclose any postmineral faults of importance.

The most strongly mineralized areas of the Alder Creek region lie on the slopes of the high ridge that extends from the vicinity of the Joe Wheeler mine westward to the Colorado Belle mine and on the northeast slope of Round Mountain. The faulting throughout this area produced many dropped wedges of Bonanza latite, a type of faulting believed to be suggestive of conditions of maximum tension, favorable to the existence of open fractures. Whether similar faulting extended southward across Alder Creek cannot be easily determined, because of the difficulty of recognizing the displacements of faults that lie entirely within the Rawley andesite, but to judge by surface indications only the mineralization on the south side of the creek was noticeably weaker. The fault blocks of Bonanza latite on the northwest slope of the Alder Creek ridge are steeply tilted toward the northwest, essentially forming a dip slope to the ridge. The beds are broken by many minor faults which steepen the local angle of tilt, but the faulting was too complex to decipher on the heavily timbered slopes. However, the general character of the structure of the Alder Creek region is believed to be correctly shown in sections A-A', and A_1-A_1', Plate 2.

SOUTHERN PART OF DISTRICT

Most of the mineralized fissures of the southern part of the district have a northerly or northwesterly strike and dip east or northeast. There are many northeasterly faults which displace the northwest system and against which some of the fissures and their ore shoots end. Both systems are commonly of premineral age, however, although possibly the postmineral movement was more pronounced on the northeasterly fault fissures.

Underground explorations in the southern part of the district are not extensive enough to form a basis on which to generalize regarding the fault systems. Hence it is not known whether there are many local variations from the relations mentioned above.

The fault and vein systems of the Eagle mine have been described by Wuensch[83] in some detail, and the conditions in this mine are probably typical of the southern part of the district. The conditions in the Hawk tunnel are described by Wuensch as exhibiting an "unusual example of simultaneous faulting and mineralization."

FUTURE EXPLORATION IN THE DISTRICT

In considering the future of the district it is desirable first to review what has been done in the past. Many of the smaller operations have doubtless been profitable to individual lessees and operators, but the larger ones have not in general returned the principal and interest on capital invested. The ore deposits lie in relatively narrow fissures within which the ore shoots are irregularly distributed, and as the shoots are rarely of high grade, they have not paid for the cost of finding and developing them. The Rawley ore shoot is the only large body of ore in the district that up to the present time has yielded an operating profit on moderately large mining operations. It has not yet, however, returned the large amount of capital which has been invested in the development of the property. Several of the smaller mines, such as the St. Louis, have developed ore bodies of high grade that doubtless were profitable to mine, but the bodies were not large enough to pay for intensive exploration for additional ore shoots, and consequently most of the properties in the district now lie idle.

In some properties, as, for example, the Cocomongo mine, very complex structural conditions greatly increase the cost of exploration, because of the erratic distribution of ore shoots. Ore shoots that appear promising may be abruptly cut off by premineral faults or by sudden pinching or flattening of the fault fissures. In the more persistent ore bodies like the northern ore shoot of the Rawley vein the problems to be dealt with are those relating to efficient mining methods and ore treatment rather than structural or geologic problems. But on the whole future explorations in the district must expect to encounter many difficult problems of structure. The intense fracturing to which the volcanic rocks were subjected before mineralization had a tendency to disperse the mineralizing solutions into many small fissures instead of permitting them to concentrate in a smaller number of larger veins. Partly for this reason the selection of promising veins for further development is difficult, requiring more study than is possible in a general examination of the district. It is natural to assume that the more promising veins have been prospected, and that is the

[83] Wuensch, C.E., Secondary enrichment at the Eagle mine, Bonanza, Colorado: Am. Inst. Min. and Met. Eng. Trans., vol. 69, pp. 96-109, 1923; reprint 1251, June, 1923.

impression one gets from a general study in the field. At almost any place within the more heavily mineralized areas small showings of sulphides and vein material may be detected on the surface, and many of these have been trenched or worked in a small way. Because of the dispersion of the metals into these many small fissures the chances of the existence of many ore shoots as large as the Rawley are not great. On the other hand, owing to the nature of the faulting and fissuring, it is probable that some larger fissures may be concealed at the surface, or their ore shoots may be cut off by weakly mineralized fault fissures, so that they do not crop out prominently. Thus strongly mineralized areas such as are found adjacent to the Cocomongo mine on Kerber Creek, parts of Rawley Gulch adjacent to the Rawley and Whale veins, and parts of Copper Gulch cannot be said to be thoroughly prospected, even though the workings are more extensive than in some other localities.

A fairly continuous area of strong mineralization extends from the ridge near the Superior mine south of Rawley Gulch northward across Rawley Gulch and across the head of Sosthenes Gulch nearly to the south side of Round Mountain. Another area of strong alteration with some developed mineralized veins is found near the head of Alder Creek, in the region of the Joe Wheeler and Colorado Belle mines and thence westward to the northeast slope of Round Mountain. Sufficient exploration has not been done, or at least the workings are not sufficiently accessible at present, to indicate the promise of this northeasterly area. Although favorable sedimentary rocks may lie beneath the western edge of the northern part of the district, there is little assurance that conditions would be favorable here for the formation of replacement deposits. Furthermore, the depth to the basement would be very great, perhaps 2,000 feet or more. For the northern and northeastern parts of the district the presence of pre-Cambrian outcrops in Squirrel Gulch and along Alder Creek is a strong indication that the basement on which the lavas lie consists for the most part of these rocks.

The low-temperature veins of the southern part of the district present a somewhat different problem. They probably lie above a relatively shallow part of the underlying intrusive body, as is indicated by the large number of dikes occupying fissures in this part of the district. The principal minerals of value are silver minerals, with only small amounts of copper, lead, and zinc. There is no assurance that these veins will pass at great depth into veins containing abundant sulphides, like those found in the northern part of the district, but they are perhaps more likely to become slightly impoverished within moderate depths and change to low-grade veins of quartz, carbonates, and pyrite. Chalcopyrite is one of the common sulphides in these veins, though present in only small amounts. It might be persistent or even increase to moderate depths, and an increase in this mineral and in pyrite might reasonably be expected to be accompanied by an increase in gold content. The conditions for explorations to the base of the volcanic formations would appear more favorable here than in the northern part of the district. The temperatures during vein formation at the present depth of erosion were lower than in the north, to judge from the mineralogic character of the veins. As shown on Plate 3 it may be inferred that a synclinal area of the Paleozoic rocks extends beneath the lavas approximately along the course of Kerber Creek, although large thrust faults like those along the lower part of Kerber Creek may also be present beneath the lavas. The depth to the base of the volcanic rocks is probably at least 1,200 feet in some parts of the area, but as there may have been a relief of 500 feet on the old land surface an accurate estimate of the altitude of the basement cannot be made. Also it cannot be foretold what part of the strongly folded sedimentary section will be encountered in any given place. Owing to the risk involved, therefore, blind exploration to the base of the lavas is not justified.

The E. D. vein, on the east side of the road in the southern part of the district, contains dolomite, and as this mineral is an uncommon constituent in the veins of the district the magnesium may have been derived from the underlying limestones. On the other hand, magnesium is known to have been present in considerable quantities in some mineralizing solutions where it was not derived from limestones, so that its source is uncertain. Positions within or too close to intrusive bodies would be unfavorable areas in which to extend operations to great depths to reach the sediments, as the shape or extent of these intrusive bodies in depth cannot be predicted. Thus veins either within the Eagle Gulch latite or within the center of the area of intrusive rocks south of this would not be favorable ones to explore in depth. Even under the most favorable conditions such exploration is likely to be very expensive and uncertain as to results. With the present state of geologic knowledge it would be more in the nature of a scientific experiment than of an economic exploration. The average gold content of the veins in the Bonanza district is only about 0.01 ounce to the ton, although in certain veins it runs much higher than this, as, for example, in several of the veins in Copper Gulch. There is also a slight but definite tendency for the ore of the Rawley vein to increase in gold content with depth. The change in gold content of the veins of the southern part of the district is not known.

The most favorable beds for replacement deposits in the underlying sedimentary rocks cannot be told except by actual exploration. The conditions in similar beds in other parts of Colorado suggest that the Leadville limestone and perhaps some of the pure quartz grits or limy grits, such as the sandstone of the Chaffee formation or the coarser grits of the Kerber formation, with their intercalated layers of carbonaceous shale, might be the most favorable. In very few places in the State have the Carboniferous red beds been found to contain commercial ore bodies. The great thickness of the beds of the Maroon formation overlying the Mississippian limestone and Kerber formation would have to be penetrated unless shafts sunk happened to penetrate the basement near the edge of a synclinal area.

In conclusion, it should be said that the future production of the Bonanza district must depend to a large extent upon the existence of favorable market conditions for metals and upon the development of some custom treatment of the complex ores, as perhaps the Rawley vein is the only one so far developed which has in itself yielded an ore body of sufficient size to warrant the erection of a mill. It is not to be expected that production will be made from crude shipping ores, as shown by the failure of these ores in the history of the district. The possibility of production from the sedimentary formations beneath the lavas appears to be more favorable in the southern than in the northern part of the district, but even in the southern part deep prospecting must be exceedingly speculative.

MINES AND PROSPECTS

A large part of the mining operations in the Bonanza district have been conducted on small prospects which were abandoned as soon as the small bodies of richer shipping ores had been mined out. Few of the mines are developed to sufficient depth or length along the veins to permit detailed descriptions that would be of any general value. A number of the larger veins which furnished the bulk of the output during the early mining operations in the district are not now accessible. In 1926 and 1927 the Rawley and Cocomongo were the only mines on the larger veins that were being operated. The following descriptions are thus necessarily confined to a few typical examples. Such data and maps as are available for some of the older inaccessible operations have been included as a matter of record.

The mines are described from north to south in the order of those lying in the Kerber Creek drainage area, those lying in the Alder Creek area, and finally those in the southern part of the district. The Rawley and Cocomongo are examples of mines now accessible that are developed on veins of two rather different structural types in the northern part of the district and will be described first. These more detailed descriptions will be followed by briefer descriptions of some of the other mines.

RAWLEY MINE

The Rawley mine, owned by the Rawley Mines (Inc.), is developed on a north-south vein that crops out at an altitude of about 10,800 feet on the north side of Rawley Gulch. (See pl. 1, No. 69.) The mine workings on the vein are above a long tunnel used for drainage and haulage, the portal of which is in Squirrel Gulch 6,200 feet southwest from the outcrop of the vein. The present mill and other mine buildings are in Squirrel Gulch at the portal of this tunnel. Ore is said to have been discovered at the outcrop of the Rawley vein in 1880, and in the report of the Director of the Mint for 1881[84] it is stated that the Rawley claim showed one of the largest ore bodies in the district. The ore, however, was of comparatively low grade for shipping and treatment at that time, and prior to 1902 the production from the vein was small. Apparently one small mill had been erected in Rawley Gulch near the outcrop of the vein before 1902, but no authentic records are available as to the amount of ore which was treated.

In 1902 a new 100-ton mill had been erected by the Rawley Mining Co. on the opposite side of Rawley Gulch from the vein. It is reported by the company that this

[84] Burchard, H.C., Report of the Director of the Mint upon the production of the precious metals in the United States during the calendar year 1881, p. 427, 1882.

mill was operated only two months during that year. For several years the operation of the mill was unsuccessful, partly because the flow of water in Rawley Gulch is very fluctuating and was found inadequate to run the mill at capacity for more than a short period during the year. There is no record of production during this period except for small shipments of concentrates in 1902 and 1905. (See table on p. 78.) About 1905 the company was reorganized, and between then and 1910 the work done was entirely for the purpose of developing the vein. In 1910, according to Simonds and Burns,[85] the vein had been proved to a depth of 600 feet and a large body of ore blocked out. To develop the vein below the sixth level and to cheapen the mining of the ore in the upper levels it was proposed at this time to drive a drainage tunnel about 6,200 feet in length to intersect the vein at a point 600 feet below the sixth level. Despite some adverse opinion the company started work on the tunnel May 7, 1911, and reached the vein October 23, 1912. The methods used and the data on driving the tunnel have been given in detail by Simonds and Burns.[86] Two major difficulties were encountered in driving the tunnel — the abrupt changes in character of the andesite caused by silicification and the striking of what is probably the continuation of the Paragon fault zone. The flow of water from the Paragon fault was large and was roughly estimated at 1,000 gallons a minute when it was first struck.

Between 1912 and 1915 no further work was done, but in July, 1916, work was started in preparing the mine and in completing the plans for a new 300-ton mill to be erected at the portal of the drainage tunnel. In 1916 and 1917 some small shipments of crude ore were made. An aerial tramway about 7¼ miles in length was constructed to deliver the concentrates at the Denver & Rio Grande Railroad at Shirley, due north of the mill. An electric power line was also completed to the mine, but work on the mill in Squirrel Gulch was not completed until 1923. The new mill was operated awhile in 1923 by the Colorado Corporation, and some concentrates were shipped, but the mine was again closed in this year.

Thus between 1905 and 1923 a large investment of capital was made in the development of the mine, in driving the tunnel, and in constructing the mine plant and mill, but the production of the whole period was relatively small.

The Rawley Mines (Inc.), a reorganized company, started operations in December, 1925, after remodeling the mill and providing for a 350-ton capacity. Operation of the mine and mill was continued until the later part of June, 1930, and during this time considerable development and exploratory work was done, both north and south of the Paragon fault, which bounded the original ore body on the south. The exhaustion of the ore shoot north of the Paragon fault, the faulted condition of ore-bearing fissures found south of the fault, and the unfavorable results of exploration of the Michigan vein lying east of the Rawley finally led to the closing and dismantling of the property.

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[85] Simonds, F.M., and Burns, E.Z., A problem in mining, together with some data on tunnel driving: Am. Inst. Min. Eng. Bull. 75, p. 370, 1913.
[86] Idem, pp.; 369-402.

PRODUCTION

Complete data on the production of the Rawley mine prior to 1902 are not available. The reports of the Director of the Mint for 1890 and 1891[87] give $1,365 and $5,981, respectively, for these years. In reports for other years no data on the Rawley mine are given. The following table shows the production of the mine since 1902, compiled from mine records of the United States Geological Survey and the United States Bureau of Mines, supplemented by information furnished by the company. Some details of the metallurgical data from operation of the mill during 1926 and 1927 are shown in the second table, based upon data furnished by the Rawley Mines (Inc.).

Production of the Rawley mine, 1902-1930

Year	Ore (dry tons)	Concentrates produced (dry tons)	Gross content of concentrates and smelting ore				
			Gold (fine ounces)	Silver (fine ounces)	Lead (wet assay; pounds)	Copper (wet assay; pounds)	Zinc[a] (pounds)
1902	--------	600	--------	12,000	438,000	60,000	--------
1905	--------	384	--------	4,143	188,720	--------	--------
1916	[b]2,731	--------	102.72	37,335	62,066	134,246	--------
1917	[b]1,875	--------	61.46	21,663	51,523	94,521	Penalized.
1923	34,170	9,032	183.80	146,329	3,267,520	567,093	1,287,066
1926	43,971	5,369	236.27	267,142	3,110,418	1,276,493	--------
1927	112,393	22,742	965.28	842,579	6,683,138	4,846,733	2,488,250
1928	110,595	22,238	1,123.46	903,759	5,285,710	5,391,184	2,406,152
1929	118,647	18,967	1,003.50	720,172	6,442,738	3,329,047	2,465,710
1930[c]	56,262	7,737	456.02	328,385	2,484,756	1,520,267	765,963
	480,644	87,069	4,132.51	3,283,507	28,014,589	17,219,584	--------

[a] Zinc not recovered. [b] Crude ore to smelter. [c] Mine closed late in June.

[87] Smith, M.E., Report of the Director of the Mint upon the production of precious metals in the United States during the calendar year 1890, p. 139, 1891; idem for 1891, p. 184, 1892.

Range in character of concentrates from Rawley ore in 1927, by months

Month	Assay content of concentrates							Recoveries from mill heads (percent)			Ratio of Concen-tration
	Gold (ounce per ton)	Silver (ounces (per ton)	Lead (per cent)	Copper (per cent)	Iron (per cent)	Insoluble (per cent)	Zinc (per cent)	Silver	Lead	Copper	
January ……..	0.050	44.0	17.1	10.8	25.9	2.4	5.43	85.7	92.5	86.1	5.36
February …….	.055	42.6	16.9	12.7	25.8	2.2	4.69	83.5	91.0	88.0	6.53
March ………..	.045	45.1	16.6	11.9	26.4	2.4	4.38	90.6	93.2	91.0	6.37
April …………	.043	36.8	15.9	10.2	26.9	3.4	4.50	91.4	94.0	91.1	6.09
May ………..	.039	32.8	16.6	9.70	26.6	3.7	4.70	92.5	94.1	92.6	5.39
June ……….	.040	31.9	17.2	8.82	.26.4	3.0	5.70	90.3	93.8	89.5	5.20
July …………	.040	32.5	14.8	9.60	25.1	4.9	7.0	88.7	92.5	88.3	4.45
August ……..	.041	33.6	13.1	9.55	27.0	4.3	6.01	91.3	91.7	87.5	3.98
September…..	.040	31.6	9.91	9.06	29.5	4.8	4.92	92.1	91.0	88.1	3.75
October ……	.036	39.4	15.2	11.9	24.6	3.2	6.47	83.8	89.5	82.0	4.63
November …	.040	38.9	13.6	12.8	25.5	3.2	5.33	82.7	90.8	82.8	4.64
December …	.039	42.2	12.7	12.5	25.3	3.9	5.94	85.7	90.2	85.0	4.77

UNDERGROUND DEVELOPMENT

The writer wishes to acknowledge the cooperation of the officials of the Rawley Mines (Inc.) in facilitating the underground study of the Rawley mine and in permitting free use of maps and operating data A. S. Winther, manager during 1926, when the mine was first visited; A. E. Ring, manager in 1927 and 1928; William Blake, mine superintendent; Ira Herbert, and other members of the engineering staff, have personally helped in the study of the mine. The geologic section of the Rawley drainage tunnel and some of the other underground observations are based upon joint examinations made by B. S. Butler and the writer.

The plan of the underground development of the Rawley mine is shown in Plate 23, and the section of the stopes in Plate 24. The general trend of the vein is N. 10° W. and the dip about 85° E. The four upper levels are adit levels, from which the mine was developed prior to driving the drainage tunnel. The second, third, and fourth levels all pass through a large fault known as the Paragon fault, which limits the productive portion of the main ore shoot on the south, so that these levels follow the vein only north of this fault. South of the Paragon fault some exploratory work has been done on the fourth adit level. In 1928 the 600-foot level was driven south through the Paragon fault zone and crosscut east about 50 feet, when a vein south of the fault was intersected. The Paragon fault was subsequently crossed, and development work was done on three other levels south of the fault. There is some development from the third level within the Paragon fault zone, which is weakly mineralized. The length of stoping on the Rawley vein proper north of the fault ranges from about 850 to 1,100 feet on levels between the 200 and 900. On the twelfth level the vein has been followed for more than 600 feet south of the shaft, but as it did not appear encouraging, the drift was not continued to intersect the Paragon fault. Between the second and ninth levels the vein has been stoped out practically to its intersection with the Paragon fault.

On the third level some development work has been done on the so-called Parallel vein, which lies north of the shaft and in the footwall of the Rawley vein. A crosscut was also driven from the fourth level to intersect the Parallel vein, but most of the work on the Parallel vein was done by lessees, and a complete survey of its development is not available. A little development work has been done on the Clark vein, one of those cut by the drainage tunnel.

An underground hoisting station, situated at the intersection of the Rawley vein and the drainage tunnel, allowed the skips to be operated in the main shaft to the fourth level. A small shaft south of the main shaft was used for raising and lowering men and materials between the sixth and third levels. The vein has been mined largely by the shrinkage-stope method. The ore was hauled from the loading bins on the twelfth level by electric locomotives to the mill, a distance of over 6,000 feet. The concentrates from the mill were delivered from the concentrate bins to an aerial tramway which ran due north of the mine plant to the Denver & Rio Grande Western Railroad at Shirley.

GEOLOGIC FEATURES

GENERAL SUMMARY

The rocks in the vicinity of the Rawley mine are the Rawley andesite and the Bonanza latite. These are much broken by north-south faults that drop the formations on the east and also by a series of northeasterly and northwesterly faults that drop the formations successively southward. The Paragon fault is the largest known of the east-west system. Practically all the faults are of premineral age, but the north-south faults are possibly older than the Paragon fault. The Rawley vein occupies a north-south fissure of comparatively small displacement and is largely the result of a filling of open spaces with minor replacement. The main gangue mineral is quartz, but barite, calcite, rhodochrosite, manganiferous calcite, and siderite are found in small quantities. The main ore minerals are pyrite, sphalerite, galena, chalcopyrite, bornite, enargite, tennantite, and stromeyerite. The vein shows a change in metal content from a lead-silver-copper ore in the upper levels to predominating copper-silver ore with a minor amount of lead in depth. A less pronounced change in the metal content is indicated from the south toward the north in the vein on several of the levels. These geologic features are discussed in more detail in the following paragraphs.

DRAINAGE AND HAULAGE TUNNEL

A geologic section from the portal of the drainage tunnel to the Rawley vein is shown in Plate 25. The geologic structure is very complex, and consequently it is not possible to make accurate correlations between the surface and underground data along the line of the tunnel. At the portal in Squirrel Gulch the tunnel starts in andesite, although the debris from the fault block of Bonanza latite that forms a high ledge above the tunnel portal completely obscures the outcrop of the underlying andesite near the portal. The Bonanza latite is encountered 70 feet from the portal and continues about 140 feet beyond this point. Two much smaller fault blocks of latite occur at about 400 and 900 feet from the portal. The remainder of the tunnel lies entirely in intricately faulted andesite. About three-quarters of its length is overlain at the surface by tilted and faulted latite. The large block of latite lying above the portal of the tunnel strikes about north and dips 45°–50° W. The latite is repeated many times at the surface along the line of the tunnel by faults which throw successive blocks downward toward the east. Although the structure appears incredibly complicated because of the steep westward dips of all the latite blocks, any doubts as to the faulting are dispelled by an examination of the tunnel. A great many fault fissures are encountered in the tunnel as may be seen from Plate 31 and the andesite is much fractured between the larger faults. Very little of the andesite is free from alteration, and the rock is either silicified, chloritized, or altered to sericite and impregnated with carbonates and pyrite. The pyritized jaspers, which are very common, are described in detail on pages 22-25. Some of these also contain traces of zinc. The distribution of the main zones of alteration is shown in the geologic section of the tunnel. Despite this extreme alteration of the rocks for nearly the whole length of tunnel, a comparatively small number of economically valuable veins are found. The Clark vein, which is described below, is the largest of these. This vein occupies a fault zone of complex structure, most of the ore so far developed lying at the intersection of north-south and east-west faults.

About halfway from the portal of the tunnel to the Clark vein there is another small mineralized fissure of northward trend and easterly dip, but it has not been explored.

About two-thirds of the way from the portal to the Rawley vein a strong fault zone is intersected by the tunnel. At the time of driving the tunnel a large volume of water issued from this fault, considerably delaying the work. From the position of the Paragon fault at the surface and its approximate dip, it appears reasonable to assume that this fault is the continuation of the Paragon fault, and it has been so indicated on Plate 25. Evidence of strong silicification and fissuring of the andesite is noticeable in the tunnel beyond the fault, and there are a few small veins, but the immediate vicinity of the fault is largely concealed by timber.

Lack of open fissures seems to have been the main reason for the character of the mineralization revealed in the tunnel. As mentioned elsewhere in this report the kind of faulting which occurred in areas of steeply tilted formations seems to have been unfavorable to the production of open fissures.

RAWLEY VEIN AND PARAGON FAULT

General features - The Rawley vein lies about 6,100 feet from the portal of the tunnel and occupies a fault fissure, probably of slight displacement. The country rock of the vein, except for a porphyry dike on the lower levels, consists of the lava flows of the Rawley andesite. These are too much altered near the vein to permit the recognition of individual flows and the measurement of the exact displacement along the fissure. On the third level at the north end of the drift both hanging wall and footwall consist of a conspicuously porphyritic andesite. This particular rock appears to correspond with one of the flows in the upper part of the Rawley andesite and is believed to have a thickness of about 100 feet. As it occurs in both walls of the vein, this thickness would suggest that the displacement at the north end of the vein was less than 100 feet, providing the flow has not been steeply tilted. Some small displacement has also occurred along the Parallel vein fissure on the third level, as the hanging wall there is a porphyritic andesite and the footwall a volcanic breccia. In all probability the displacement on the Rawley fissure does not exceed a few tens of feet in magnitude.

The main ore shoot of the Rawley vein is bounded south of the main shaft by the east-west Paragon fault, which cuts the Rawley vein nearly at right angles. (See pl. 24.) If the southerly dip of 55° to 60° continues below the 900-foot level its intersection with the Rawley vein would lie about 750 to 800 feet south of the shaft on the haulage-tunnel level.

The relative age of the Rawley fissure and the Paragon fault and the relations between them are problems over which opinions have differed. Simonds and Burns[88] say regarding the Paragon fault:

Across the country from east to west, cutting the Rawley vein nearly at right angles, is a zone of faulting some 50 feet wide, dipping at an angle of about 55° S.

This faulting was subsequent to the vein formation, and the zone incloses, at various places, bunches of ore detached from the veins which it intersected. The lateral throw of the fault was slight, if any, but there is reason to believe that the vertical throw must have been considerable. However, no definite data existed at the time, and only meager data have since been developed to indicate the amount of this vertical displacement. There being but little lateral throw, the alinement of vertical or nearly vertical veins was only slightly disturbed by this faulted zone.

Patton[89] concurred in this opinion.
From the character of the Paragon fault in the Rawley mine and at several other places along Rawley Gulch where it has been disclosed by mining operations the writer is of the opinion that the major part of the displacement on this fault is of premineral age, although some relatively late postmineral movement has undoubtedly occurred. The main reasons for this belief are as follows:

1. The Paragon fault is itself mineralized, not only within the Rawley mine but also

[88] Simonds, F.M., and Burns, E.Z., op. cit., p. 371.
[89] Patton, H.B., op. cit., p.77.

in the several openings on it along Rawley Gulch east of the outcrop of the Rawley vein. Except locally the mineralization has not been greatly or at all disturbed by post-mineral movement. The gouge along the Paragon fault is also strongly sericitized and pyritized, showing that it was penetrated by mineralizing solutions. The mineralization in the Paragon fault and its relation to other intersecting veins along Rawley Gulch are described on pages 121-125. This description need not be repeated here except to say that the results of mineralization within the fault and of alteration adjoining it along the Rawley Gulch east of the Rawley vein afford positive evidence of the premineral age of the faulting. If the mineralization of the Rawley vein occurred prior to the formation of the Paragon fault this would indicate two periods of similar mineralization in the veins of Rawley Gulch. There is good reason, however, to believe that this did not happen, as nearly all the veins show a mineral paragenesis that is very similar, although the proportions of different minerals may differ from vein to vein.

2. Where the relation between the Rawley vein and the Paragon fault can be seen only a slight disturbance of the Rawley vein material is evident. The relation between the fault and the vein on the fifth level south are shown in Figure 23. The displacement of the Rawley fissure in small steps as the Paragon fault is approached is quite evident, yet as the Rawley fissure narrows the mineralization follows the turns and offsets in the fissure until close to the main fault zone. Where the drift has penetrated farther into the fault the fault itself is also mineralized. The writer is informed by Mr. A. E. Ring that on the 500 and 600 foot levels, where ore in the Paragon fault was stoped, this ore was as regularly in place on the dip of the fault as in any vein. Slight postmineral movement on fault fissures is almost invariably shown in mineralized regions, and the small amount of crushed ore found at other places within the Paragon fault cannot in itself be considered evidence that it was dragged in from intersecting veins. The greatest disturbance of vein material seen by the writer indicated, under a most liberal interpretation of dragging, a possible movement of about 2 feet on one of the parallel fissures shown in Figure 23. Slight postmineral movement has undoubtedly occurred, and inasmuch as ore deposited within the Paragon fault is crushed at places, some crushing of the Rawley ore close against the fault might have occurred at the same time.

3. The distribution of minerals in the Rawley vein appears to be in part related in position to the Paragon fault.

Several bodies of massive galena lie so closely under the footwall of the Paragon fault on several of the upper levels as to lead to the inference that movements on the fault produced the openings in which the ore is found. This result is like the enrichment of veins noted at other places in the district near cross faults. (See p. 60.)

Just what proportion of the movement on the Paragon fault occurred before the formation of the Rawley ore and what proportion after cannot be definitely proved. But it has been pointed out in the section on the relation of mineralization and faulting (pp. 58-64) that in general the greater part of the faulting movement throughout the district is of premineral age. So far as direct evidence is available there is no indication that the Paragon fault is an exception to this general relation.

The exact amount of displacement on the Paragon fault still remains undetermined in the vicinity of the Rawley mine. About 2,000 feet west of the Rawley fissure the displacement on the Paragon where it faults Bonanza latite into contact with Rawley andesite appears to be between 500 and 1,000 feet down the dip of the fault. Because of the steep tilting of the Bonanza latite it is difficult to estimate the displacement accurately even here. Near the head of Rawley Gulch the displacement is not so readily recognizable in the surface rocks, but it appears to have considerably decreased toward the east. If this is so the movement on the fault was partly of rotational character. Lying intermediate between these positions, the fault in the Rawley mine might have an intermediate displacement, possibly 500 feet, but such an estimate is very crude at best.

At and north of the main shaft on the twelfth level a porphyry dike, with large feldspar crystals half an inch to an inch in length, lies within the Rawley fissure. This dike continues to the end of the north drift but does not appear in the drift south of the shaft. It is again exposed in the vein on the seventh level north as shown in Plate 26. The porphyry dike is clearly of premineral age, as it is much altered and partly mineralized on the twelfth level. So far as is known this dike does not appear at the surface.

Character of the vein — The Rawley vein is fairly well defined between its walls and ranges in width from a narrow barren fissure where pinched to a maximum of about 12 feet. Its average width in the lower part of the mine is 3½ to 4½ feet. It cannot be profitably stoped at most places unless the width exceeds 3 feet. Along some portions of the vein a sericitized gouge a foot or less in thickness lies against the hanging wall, and less commonly against the footwall. Although the vein material is on the whole of fairly uniform character, with no delicate banding, the vein at some places is composed of several bands of somewhat different composition. (See pl. 15, *A, B.)* Bodies of galena may run along either or both walls and here and there may be seen to cut diagonally across the more siliceous part of the vein.

Although replacement of portions of the wall rock has been very pronounced, it was mainly of a siliceous or pyritic nature. The greater part of the commercial ore evidently resulted from filling between the fissure walls. Some replacement of breccia material probably occurred within the fissure. The ore is not notably porous but rather massive, although very small vugs lined with quartz and sulphides are fairly common. In the vein on the 600-foot level south of the Paragon fault rhodochrosite crystals are found lining vugs, with a late coating of pyrite.

The gangue minerals are quartz, barite, calcite, rhodochrosite, or manganiferous calcite, and rarely a little siderite. Quartz is by far the predominating gangue. The sulphides are pyrite, sphalerite, galena, chalcopyrite, bornite, enargite, tennantite, chalcocite, covellite, and stromeyerite. Chalcocite, covellite, and enargite occur only in small amounts and are usually recognized only under the microscope on polished faces. It has been considered that the silver is largely or entirely in tennantite, but microscopic examination shows stromeyerite to be widely distributed in the vein in small amounts. It is associated with bornite, tennantite, and galena. Its presence probably accounts for the high silver content of some of the bornite-bearing ore. At the south end of the ore shoot stromeyerite continues to the twelfth level. It is undoubtedly a primary mineral.

No pronounced oxidation or enrichment of the vein is evident except within 50 feet or less of the surface. Above the first and second levels near the surface some native copper occurs in small seams in the ore or in the adjacent wall rock. As the section on the paragenesis of the ores of the northern part of the district (see pp. 41-44) deals mainly with the Rawley vein, these details need only be summarized here.

The earliest effects of solutions circulating in the Rawley fissure consisted mainly in the hydrothermal alteration of the wall rock. The waters circulating in the fissure during this first stage were evidently hot or warm and perhaps contained some sulphuric acid or halogen acids. (See pp. 34-36.) These waters vigorously attacked the andesitic wall rock, dissolving out nearly all the constituents except silica and a little iron and titanium, and deposited some additional silica in place of the other constituents carried away in solution. The result of this alteration was the formation of a very siliceous rock composed largely of quartz or chalcedony and containing ferric oxide. This rock in many places along the walls of the vein is decidedly reddish or reddish brown because of its content of hematite or some finely divided form of ferric oxide, and it may appropriately be called a jasper. It is encountered in the walls of the vein on practically all levels of the mine but is much more noticeable and evidently more abundant on the lower levels. At some places it is included usually as angular fragments within the vein itself representing fragments of the wall which became detached by movement before the complete filling of the fissure. (See fig. 23.) In places where the walls were broken or cracked by additional movement along the fissure before the formation of the vein, the vein minerals have been deposited in the cracks and in small stringers in the jasper. Such occurrences in conjunction with the evidence of its general position in the walls give indisputable evidence that the alteration of the walls to a jasper-like rock preceded the filling of the Rawley fissure with vein material.

The earliest minerals to be deposited within the fissure were quartz, barite, and pyrite, followed by sphalerite, bornite, chalcopyrite, and galena and finally tennantite and small amounts of other sulphides such as stromeyerite, chalcocite, and covellite. Except for the early quartz, pyrite, and sphalerite, the other sulphides closely overlapped in their formation, and the order of deposition was not strictly uniform in all parts of the vein. Enargite where present is an early mineral, probably later than bornite but earlier than galena and tennantite. Tennantite is usually a late copper mineral, but in ore from the lower levels of the mine some of it has resulted from the breaking down or alteration of enargite. (See pl. 16, *C*.) The deposition of chalcopyrite was highly variable; it is rarely included in minute specks in sphalerite and where very abundant is an earlier mineral than galena, but its deposition in small amounts continued until very late. Stromeyerite also has a wide range of occurrence in the Rawley ore and is found in small irregular areas included in bornite and also as a later mineral replacing many of the other sulphides.

In the upper levels of the mine the deposition of pyrite appears to have been rather sharply separated from the later formation of chalcopyrite, galena, and tennantite. On the other hand, in the lower levels of the mine pyrite is more abundant and more intimately associated with the later copper minerals, such as bornite and chalcopyrite. The texture of the ore from the levels below the 600 foot, where copper and iron are the predominating metals, suggests a rapid precipitation of the pyrite in minute grains or granular masses, followed by the formation of bornite and chalcopyrite. These two copper minerals have replaced granular pyrite to a considerable extent, but the intimate association of the particles of pyrite with the copper minerals cannot be explained entirely as the result of replacement of once extensive pyrite masses. The textures typical of pyretic copper ore are shown in Plate 15, *A*, *B*. Many of the smallest particles of pyrite in the bornite and chalcopyrite in ore from the 680 to 700 foot levels have an actual size of 0.0001 to 0.0002 inch. Although not all the pyrite in the ore is present in such minute subdivision, a considerable proportion of the pyretic copper ore is of the character shown in Plate 15, *A*, *B*. For the purpose of separating the pyrite and gangue from the other sulphides by flotation the practice at the Rawley is to grind the ore smaller than 100 mesh. It is evident that only partial separation can be accomplished, and it has not been found possible in practice to keep the iron in the concentrates low.

Distribution of metals in and value of the vein – The following table shows some of the available data on the character of the ore in different parts of the Rawley vein, together with the ratios of lead to copper. The most noteworthy feature is the gradual but pronounced increase in copper content and decrease in lead content with increase in depth.

Variation in tenor of the ore of the Rawley vein in different parts of the ore shoot

	Number of assays[a]	Ore (tons)[b]	Silver (ounces to the ton)	Lead (per cent)	Copper (percent)	Ratio of lead to copper
200-foot level	--------	9,415	10.00	11.60	2.11	5.47
300-foot level	--------	6,490	9.72	12.70	1.70	7.47
400-foot level:						
South of shaft	--------	314	12.8	18.50	1.40	13.20
	11	--------	6.75	12.50	1.57	8.00
North of shaft	--------	2,749	9.86	11.0	2.45	4.48
500-foot level:						
South of shaft	--------	3,784	12.20	7.78	3.25	2.39
North of shaft	--------	12,563	10.30	5.78	3.02	1.90
	18	--------	6.77	3.31	2.79	1.20
600-foot level:						
South of shaft	--------	2,423	13.40	5.60	3.54	1.58
North of shaft	--------	6,354	9.90	1.04	3.85	0.27
	26	--------	15.10	2.06	5.07	0.41
680-foot level:						
South of shaft	28	--------	10.70	1.52	3.18	0.48
North of shaft	32	--------	12.50	0.84	5.22	0.17
700-foot level:						
South of shaft	--------	3,008	11.80	2.41	3.17	0.76
North of shaft	--------	92	6.84	0.69	2.25	0.31
	18	--------	16.00	1.50	6.33	0.24
800-foot level, north of shaft	--------	2,817	8.48	6.67	2.36	2.80
1,200-foot level, south of shaft	--------	193	25.20	3.20	3.60	0.89
	27	--------	4.48	0.80	0.59	1.40

[a]Assays reduced to average foot percentages, representing the weighted mean of the percentages according to the widths of individual samples.
[b]Ore mined by lessees.

The horizontal change in the ratio of lead and copper toward the Paragon fault seems to be definitely shown by the data available, though it is not nearly as pronounced as the vertical change. The enrichment of the ore in lead noticeable at places near the Paragon fault is believed to be due to openings formed during the later stages of ore formation, caused presumably by contemporary movements on the Paragon fault.

The correspondence between the silver and copper content of the ore from the Rawley vein is very close in nearly all parts of the mine. The average silver content of the ore from the four upper levels mined prior to 1923 was about 5.6 ounces to the ton, or about 5 ounces of silver to 1 percent of copper. The ratio of silver to copper in 11,820 tons of ore from the four upper levels mined by lessees in 1926 and 1927 is practically the same, 4.9 ounces of silver to 1 percent of copper. This ratio is somewhat higher than that of the average mine-run ore of the lower levels, which ranges between 2.8 and 3.9 ounces of silver to 1 percent of copper. There appears to be no definite relation between the silver and lead content. The minerals that probably carry most of the silver are tennantite and stromeyerite. In the Rawley ore stromeyerite is nearly always associated with bornite or tennantite and less commonly with other minerals. The bornite-bearing ore from the 700-foot level averaged about 10 ounces of silver to the ton, which is considerably higher than the average of mine-run ore from the upper levels.

The average value of ore from the Rawley vein is not fairly represented by the table on this page, as the ore was mined by lessees and the average value thus influenced by selection. The total ore mined and milled in the period from 1926 to 1930 had an average assay value of close to 8 ounces of silver to the ton, 3.2 percent of lead, and 2 percent of copper. Data as to the zinc content of the ore at various places in the mine are not as complete as those for lead and copper, but on the whole zinc is rather persistent. The highest content of zinc in the vein is said to have been encountered on the fourth level near the north end of the ore shoot, where it was about 4 to 5 percent. The zinc content of the vein, as a whole, lies between 2 and 3 percent. The average gold content is close to 0.01 ounce to the ton. The table on page 91 covering the mine production approximately by levels during 1927 shows the variation in value of the vein and also brings out strikingly the decrease in lead content of the ore with increasing depth of operations.

The close association of silver and copper is shown by Figure 24, based on the early production of the mine, prior to 1923, and on the monthly production of company mine ore during 1927. This chart shows that the percentage of lead in the company ore from the lower levels during November and December, 1927, was exceptionally low. The average for the lower levels is probably nearer 1 percent, if several months' run is considered. The silver, however, shows no relation whatever to this fluctuation in the lead content but follows the copper curve very closely.

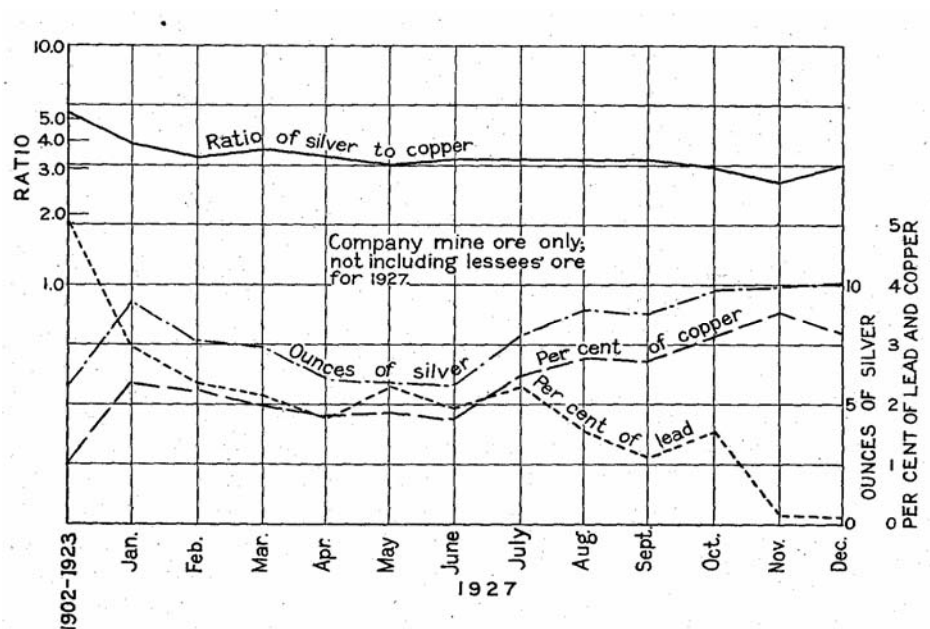

Figure 24. – Correspondence between silver and copper content in the ore of the Rawley vein.

Structural relations of the ore shoot —The north end of the Rawley ore shoot appears to be limited by the pinching of the fissure walls and by the splitting of the main Rawley fissure into flatter breaks. The split on the third level is shown in Plate 26. A north-east vein encountered in the Antoro tunnel workings is believed by local miners to correspond to the east split of the Rawley (p. 121). The correlation appears reasonable, as shown by the relative position of the workings on Plates 23 and 31. The mineralization on the east split of the Rawley fissure on the 200 and 300-foot levels does not appear to encourage further development. The west split on the 300-foot level strikes about N. 20°–25° W. and dips 35°–40° NE. It is also relatively tight and poorly mineralized. In the northern part of the 500-foot level, beginning about 250 feet north of the shaft, the vein pinches, and although it opens up in small stretches it continues narrow and for the most part too lean to stope to a point about 450 feet north of the shaft, where the drifting was stopped in 1927. The lead ore on the 400-foot level continued considerably beyond this north limit of the 500-foot level, and more recent developments (1928) on the 600-foot level encouraged further drifting toward the north on the 500-foot level. The vein was found to widen again only a short distance beyond the point where the drift had been previously abandoned. Such local pinching of the fissure walls is characteristic of the ore shoot as a whole and of many other veins in the district.

On the 700 and 800 foot levels a split and pronounced change in strike of the vein is encountered about 200 feet north of the shaft. This split was first recognized on the 700-foot level, where the west split of the vein was first followed, as there was no indication whatever of the east split when the level was driven. The west split soon narrowed and became barren, and later, because of the relative position of the vein in the 600 and 680 foot levels, the drift was turned, and a crosscut was driven until the east split was encountered. The east split on both 700 and 800-foot levels appears to be the main mineralized fissure and is high in copper and silver, with subordinate lead. The vein shows a strong tendency to turn to the northeast and to flatten somewhat north of the split, although the ore continues good on the 600-foot level for 600 to 700 feet north of the shaft. A plan of the lower levels and a section of the Rawley vein are shown in Plate 26.

In the west split on the 700 and 800-foot levels a porphyry dike was encountered which is similar to and very likely the upward extension of the "Birdseye porphyry" dike encountered in the north drift on the 1,200-foot level. It is noteworthy that wherever this dike has been encountered next to vein material the ore is pyritic and of low grade. The porphyry is probably a latite or quartz latite but is generally so soft and so much altered close to the vein that its exact original composition cannot be determined. It is easily recognized where encountered by its large white phenocrysts of altered feldspar, in places half an inch or more in length. The cause for the low grade of the ore lying next to the dike walls is most likely the softness of the altered porphyry, which has locally choked the fissure. Pyrite commonly penetrates gouge-filled fissures much more readily than the other sulphides, which in contrast show a preference for deposition in openings.

On nearly all the north levels the Rawley fissure swings northeastward and tends to flatten in dip (see pls. 23 and 26), a change that is accompanied on many of the levels by the occurrence of splits such as those illustrated on the 300-, 700-, and 800-foot levels in Plate 23. On lower levels the turn in strike of the vein and the positions of the larger splits lie successively farther to the south. Although the distribution and width of the openings that formed the Rawley fissure do not vary uniformly, a gradual reduction in the total volume of these openings toward the north is in reality the cause for the limitation of the Rawley ore shoot at the north. A possible inference that may be drawn from this condition is that the forces which produced these openings had their greatest concentration at the south end of the ore shoot — that is, near the Paragon fault. Further indirect evidence bearing on this relation is afforded by the distribution of metals in the Rawley vein as shown by the table on page 87. Attention was drawn to the fact that an enrichment of the ore shoot in galena was especially marked in close proximity to the Paragon fault. It is evident that if temporary openings were produced along the Rawley fissure by movements on the Paragon fault, the effects of this action would die out northward away from the fault, owing to dispersion of the forces along secondary splits and other minor fractures. Regardless of the origin of the Rawley fissure itself, whether it was related to stresses produced only in the footwall of the Paragon or whether it was formed before or at the same time as the Paragon, the most important structural feature is the evident relation of the ore shoot to the larger and more active fault.

Very little new evidence is afforded by the latest mining operations as to the deeper extension of the main Rawley ore shoot. There are, however, stringers of galena ore present on the 1,200-foot level north of the shaft, a body of pyritic copper ore near the shaft, and showings of mixed ores all along the level south of the shaft. The lead assays average under 1 percent. (See table, p. 87.) However, the width and grade of the vein material found on the lower levels, such as the 1,000- and 1,200-foot levels, did not permit profitable stoping under existing conditions of the mining industry. The porphyry dike in the fissure north of the shaft on the 1,200-foot level can be considered unfavorable in the effects which it had on ore-shoot formation in the northern part of the fissure. On the other hand, it may be reasonably inferred that in a zone near the Paragon fault small bodies of pyritic copper ore with some lead, such as those partly stoped near the shaft, would exist at appreciably greater depths. This inference is based upon an assumption that movements of the Paragon fault have favored the temporary formation of open spaces, but it is stated without implication as to the profitable development and mining of such possible ore.

Production of Rawley mine in 1927, by months[a]

Month	Assay content of ore milled			Percentage of ore from different sources										Average content						Ratio of silver to copper in mine ore
				Company mine ore by levels										Mine ore			Lessees' ore[b]			
	Silver (ounces per ton)	Lead (per cent)	Copper (per cent)	300	400	500	600	700	900	1,000	1,200	Lessees' ore[b]	Other sources	Silver (ounces per ton)	Lead (per cent)	Copper (per cent)	Silver (ounces per ton)	Lead (per cent)	Copper (per cent)	
January	9.57	3.45	2.36	-----	34	19.5	19.5	13.6	6	-----	0.4	3.6	3.4	9.32	2.95	2.38	16.22	11.69	1.75	3.9
February	7.94	2.78	2.26	0.8	21	14	30	13	11	-----	2.2	4.3	3.7	7.61	2.26	2.27	15.43	17.10	1.99	3.35
March	7.82	2.80	2.04	3	27	22	19	12	8	-----	2	5.9	1.1	7.43	2.18	2.01	14.04	12.67	2.62	3.7
April	6.61	2.76	1.84	-----	35	14	20	12	8	-----	2	7.8	1.2	6.09	1.78	1.82	12.79	14.41	2.00	3.35
May	6.57	3.27	1.95	-----	23	22	23.5	14	4	-----	0.5	10.4	2.6	5.87	2.37	1.86	12.65	11.06	2.66	3.15
June	6.80	3.53	1.90	-----	17	21	22	19	3	-----	-----	16.7	1.3	5.81	1.93	1.79	11.74	10.34	2.42	3.25
July	8.25	3.61	2.44	-----	17	4	16	40	3	-----	-----	14.8	5.2	7.88	2.30	2.43	10.39	11.15	2.48	3.4
August	9.23	3.58	2.74	-----	6.5	0.5	4	51	13	-----	-----	19.3	5.7	8.99	1.55	2.79	10.24	12.06	2.55	3.22
September	9.15	2.90	2.75	-----	7	-----	-----	76	1	-----	-----	15.5	0.5	8.78	1.13	2.70	11.14	12.54	3.03	3.25
October	10.16	3.67	3.13	-----	13	-----	-----	61	7	1	-----	17.6	0.4	9.75	1.56	3.17	12.07	13.58	2.93	3.06
November	10.11	3.22	3.33	-----	1	-----	-----	70	5	-----	-----	24	-----	9.93	0.15	3.58	10.68	12.64	2.53	2.77
December	10.33	2.94	3.06	-----	-----	-----	-----	68	3	-----	-----	29	-----	10.00	0.10	3.20	11.14	9.85	2.73	3.12

[a] Modification of table prepared by A.E. Ring, general manager of Rawley Mines (Inc.).
[b] About 85 to 90 percent of lessees' ore mined from stopes above 500-foot level and other levels above this.

TIP TOP VEIN

Crosscutting and drifting on the 400-foot adit level, driven earlier in the history of the mine, had failed to reveal commercial ore south of the Paragon fault. In a search for new ore bodies in 1928 the 600-foot level was driven south through the Paragon fault, and a crosscut was driven eastward, disclosing a north-south vein in the hanging wall of the fault about 40 to 50 feet east of the strike line of the Rawley vein. (See pls. 23 and 26.) This vein, which underlies the Tip Top claim, was later developed and partly stoped from the 500, 700, and 900-foot levels. (See pl. 24.) During 1928 and 1929 about 34,000 tons of ore was mined from the Tip Top vein, and in 1930 some additional production was made, for which figures are not at hand. The following description of this vein is based upon brief examinations by the writer in 1928 and 1930 and upon personal communications from Mr. A. E. Ring.

The strike of the Tip Top vein on the 600-foot level is about N. 15°-18° W., and the average dip of the vein is about 83° W. For the first 100 feet or so south of the Paragon fault on the 600-foot level this vein was narrow, but farther south it attained a width ranging between 5 and 10 feet. The general appearance of the vein matter is much like that of the main Rawley vein, shoots of galena ore lying alongside of the siliceous part of the vein. (See fig. 25.) The mineralogy of the vein on this level differs slightly in detail from that of the Rawley vein at corresponding levels, in that it contained a greater amount of rhodochrosite occurring in small vugs in the quartz. The sulphide minerals present include pyrite, bornite (partly in small crystals), chalcopyrite, sphalerite, and galena. The proportion of galena is somewhat higher than at a corresponding altitude on the Rawley vein. On the 500-, 600-, and 700-foot levels of the Tip Top vein the lead probably averaged 4 to 5 percent; it was lowest on the 700-foot level. On the 900-foot level only a few places show ore, and the lead is still lower in amount. There is probably a slight increase in copper with depth. The ore shoot that was developed had its greatest length of about 330 feet between the 500- and 600-foot levels and fingered out below irregularly, with only short bunches of ore on the 900-foot level. Only on and just above the 500-foot level did this ore shoot extend northward close to the Paragon fault. On the other levels the Tip Top fissure was generally narrow near the Paragon fault or consisted of a zone of fractures and ore stringers. In this structural feature the ore shoot differed appreciably from the Rawley ore shoot, which for some distance extends close under the footwall on the north side of the Paragon fault. As was pointed out on page 50, such a difference in the occurrence of the ore and structure of the fissure on opposite sides of a cross fault may be considered contributory evidence toward establishing the premineral origin of the fault.

On the other hand, the argument might be advanced that the higher lead content of the Tip Top ore shoot as compared with that of the Rawley shoot at the corresponding altitude indicates a late post-mineral downfaulting of this ore body relative to the Rawley ore body. This argument, however, loses some of its force when it is considered that local bodies of high-grade galena ore were found on even lower levels of the Rawley vein, a feature indicating that conditions which favored deposition of galena fingered out irregularly in depth. A parallel condition was noted by Ransome in the lead-bearing ores of the Red Mountain district, Colorado. (See pp. 45-46.) It is reasonably clear from other evidence cited above that the Paragon fault is of premineral age, and it is therefore fair to assume that physicochemical and structural conditions during mineralization would have been different on the opposite sides of the fault, owing to the sealing action of its gouge. For these reasons it would appear that the change in lead content of the shoots on the two sides of the fault does not necessarily indicate a late post-mineral downthrow of the block on the south side. The writer does not consider that the change in lead content has any further direct bearing on the question of the premineral or post-mineral origin of the Paragon fault, as evidence of a structural nature is believed to have independently answered this question.

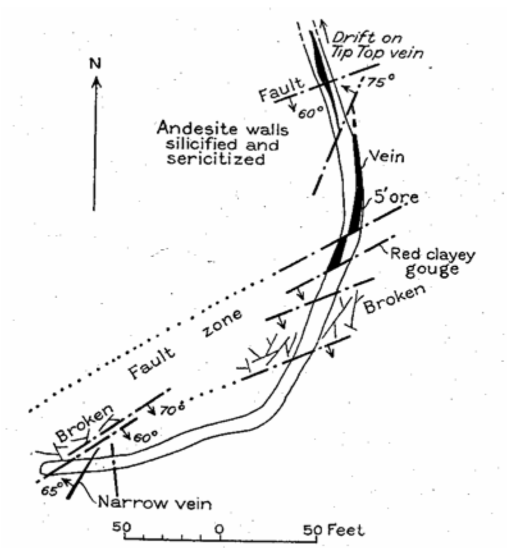

Figure 25. – Sketch map of south end of 900-foot level, Tip Top vein.

The south end of the Tip Top ore shoot is delimited on the 600-foot level by cross faults of southerly dip more or less paralleling the Paragon fault. On higher and lower levels the ore shoot generally pinches out before these cross faults are reached. In Figure 25 is given a plan of the extreme south end of the 900-foot level which shows the character of this cross faulting. Many of the faults shown in the figure show alterations of their walls that include the earliest type of jaspery or siliceous alteration, as well as later stages of sericitization and pyritization. The silicification of the wall rocks shows that these faults had a premineral origin, but the jasper reveals further gougy slips of post-silicification age. These later gouges are pyritized in some of the faults. The conclusion may be stated that movements on these faults began prior to silicification and continued at least until and probably throughout the period of sulphide mineralization. Some fracturing of the rocks showing weak alteration probably indicates moderate post-mineral adjustments of the fault blocks. This broken condition discouraged explorations farther south, especially in view of the generally scattered distribution of the ore on the 900-foot level.

The nature of the structural relations between the Rawley fissure, Tip Top fissure, and Paragon fault offers no conclusive evidence regarding the question of identity of the Rawley and Tip Top fissures. It is clear, however, that both of these fissures were formed, like the Paragon fault, very early in the period of deformation of the lava beds in this region. In the discussion of the general structure of this area the belief was expressed that north-south faults were in part earlier than east-west faults. It is possible that the Rawley and Tip Top fissures represent a single comparatively minor fracture of the north-south set that was later enlarged and separated into segments by movements between adjoining fault blocks.

PARALLEL VEIN

In the years 1926 to 1929, inclusive, 12,412 tons of ore was mined from the Parallel vein, which is developed on the 300-, 400-, and 500-foot levels. About 70 percent of this ore was obtained from the 300-foot level, as the vein pinches and flattens below this level. (See pl. 26.) Most of the work on this vein was done under lease, and complete maps of the drifts and stopes are not available. The ore mined by the lessees averaged about 8.6 percent of lead, 2.55 percent of copper, and 9.4 ounces of silver to the ton.

CLARK VEIN

The Clark fault fissure strikes a little east of north and clips 35°-40° E. Developments along it on the drainage tunnel level are shown in Figure 26. The vein matter lies within a very complex fault zone 10 or 15 feet in width in which the andesite has been greatly sheared, with the formation of thick gouges, and the ore shoots in the vein pinch and swell very irregularly. In this respect the ore bodies resemble those of the Cocomongo fault. On the tunnel level the ore shoot appears to be confined between oblique cross faults of northerly and easterly trend, both of which are mineralized, but the development is not sufficient to determine the complete length of the mineralized parts of these faults. The vein matter consists of well-crystallized sphalerite, galena, and a little pyrite and chalcopyrite in a gangue of calcite, rhodochrosite, a little quartz, and siderite. It is not nearly as siliceous as the Rawley vein. The ratio of zinc to lead is nearly 2 to 1, and copper and silver are rather low. The production from the vein has been small. The low angle of dip of the vein and its position relative to the Black Bess vein on the surface above the tunnel would suggest that the two veins may occupy the same fault zone, but definite correlation in this intricately faulted area is not possible. (See pl. 25.)

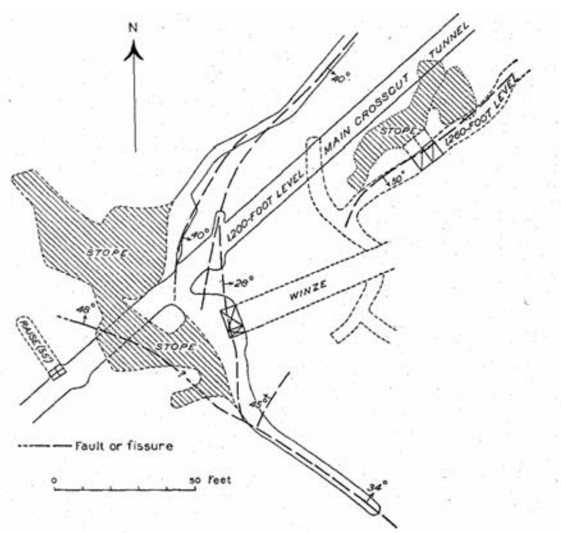

Figure 26. – Plan of developments on the Clark vein, Rawley drainage tunnel.

COCOMONGO MINE

The Bonanza-Cocomongo group is owned by the St. Louis Smelting & Refining Co. and is situated on Kerber Creek a little over 1¼ miles above the town of Bonanza. The mine is a consolidation of the old Bonanza and the Cocomongo mines, which develop a series of intersecting fissures, and includes the Bonanza, Bonanza No. 1, Cocomongo, Cocomongo Camp, and Hilltop claims. The consolidated group is now referred to as the Cocomongo mine.

The Bonanza claim was located in 1880,

and in 1883[90] the Bonanza mine shaft had reached a depth of 90 feet and had encountered galena and gray copper ore. The Colorado Mining Directory for 1883[91] states that the ore was valued at $25 to $50 a ton when sorted and gives an output of 150 tons from this shaft. In 1887, 1888, 1890, and 1891 either the mine is reported as not producing or no record is given. According to an estimate by J. P. Poole[92] the Bonanza mine shipped 2,000 tons of ore between 1881 and 1900. The value of this ore is not known. Part of this ore may have been treated in the old Bonanza mill, west of Kerber Creek just below the town of Bonanza. This mill was erected about the year 1900 by the Bonanza Milling Co. and was a custom mill but is said to have treated mainly ore from the Bonanza mine.

In 1902 the Bonanza mine was operated by the Hanover Mining & Milling Co. which shipped 592 tons of concentrates. (See accompanying table.) There was no production from 1903 to 1909, and the small shipment in 1910 was made by lessees. The mine was operated under sublease to the Saguache Mining Co. during 1912 and part of 1913, and the ore was treated by the Bonanza Milling Co., a subsidiary company. During the years 1913 to 1917 the mine was further subleased by the Saguache Mining & Milling Co., and small shipments of crude ore were made.

Production of Bonanza and Cocomongo mines, 1902-1926[a]

Year	Ore (dry tons)	Concentrates produced (dry tons)	Gross content of concentrates and smelting ore				
			Gold (fine ounces)	Silver (fine ounces)	Lead (wet assay, pounds)	Copper (wet assay, pounds)	Zinc (pounds)
1902	5,000	592	---------	1,224	178,000	---------	93,200
1910[b]	115	-----------	3.29	1,781	85,249	2,948	----------
1911	74	-----------	0.74	1,429	29,250	1,240	56,098
1912	8,568	1,071	65.91	9,170	486,570	8,818	597,652
1913[c]	706	34	69.07	5,327	285,338	9,625	10,444
1914[d]	293	-----------	47.36	5,917	133,995	23,146	10,898
1915	346	-----------	15.15	5,327	124,687	22,620	45,963
1916	164	-----------	5.23	2,698	128,474	6,029	----------
1917	732	-----------	89.70	27,235	30,150	47,006	----------
1918	1,285	-----------	114.48	83,417	54,311	127,585	----------
1919	406	-----------	34.25	27,995	43,354	48,441	----------
1920	4,754	443	148.76	60,062	137,590	94,800	Over 10%
1921	1,402	119	27.50	22,436	142,473	37,017	----------
1922	229	-----------	33.40	16,514	100,451	34,075	----------
1923	91	-----------	5.58	2,952	33,874	5,995	----------
1924	1,203	231	5.94	5,779	91,109	1,309	148,193
1925	27,000	3,628	64.55	60,248	1,541,070	1,064	2,062,159
1926	6,752	796	18.75	18,558	362,816	2,652	377,784
1927[e]	---------	-----------	----------	---------	----------	---------	----------

[a]No production in years omitted from table since 1902. See text for production prior to 1902. Compiled from mine records of U.S. Geological Survey and Bureau of Mines.
[b]Mogul and Bonanza mines.
[c]Bonanza and Yellow Type mines.
[d]Ore possibly Exchequer and Yellow Type mines in large part.
[e]Mine operated Jan. 1 to May 5, 1927. No production.

[90] Silver, Herman, Report of the Director of the Mint upon the production of the precious metals in the United States during the calendar year 1883, p. 403, 1884.
[91] Published by Colorado Mining Directory Co., Denver.
[92] Patton, H.B., op. cit., p. 68.

The Cocomongo claim is a later location than the Bonanza and was patented in 1910. The Cocomongo Mines Co. developed this property in 1917 to 1921 and shipped some crude ore. During the later part of this period and in subsequent years, after the properties were acquired by the St. Louis Smelting & Refining Co., the Cocomongo and Bonanza mines were operated jointly. Production was discontinued in 1926, but development work in blocking out ore and exploratory work were continued until May, 1927. The property has since remained idle, up to December, 1930.

UNDERGROUND WORKINGS AND MINE BUILDINGS

The underground workings on the Bonanza and Cocomongo veins are reached through two shafts – a vertical shaft 300 feet deep on the west side of Kerber Creek known as the Cocomongo shaft, and an inclined shaft on the Bonanza vein on the east side of the creek, known as the Bonanza shaft. (See pl. 27.) The present mill buildings are just below the shaft house of the Bonanza shaft, on the east side of the creek. The capacity of the present mill is 50 to 75 tons a day with nonselective flotation. It is the intention of the owners to provide for selective flotation when the mill is operated and to produce both lead and zinc concentrates. At present all of the work is done through the Bonanza shaft, which extends to a depth of about 450 feet vertically below the collar and is operated by an electric hoist. The Bonanza and Cocomongo veins are opened on five main levels and several sublevels. The greatest length of drifting is on the 300- and 350-foot levels, which extend about 1,500 feet in a northwest-southeast direction. The deepest drifts are on what is called the 500 level, which lies about 380 feet vertically below the collar of the shaft, but the shaft has been sunk about 70 feet below this level. There is somewhat more than 350 feet of drifting from the second level of the Cocomongo shaft, but this level was not examined, as it is not connected to the second level of the Bonanza shaft and is not readily accessible. The third level is the only one by which the two shafts are connected. The extreme northern part of the third level was not accessible at the time of examination, as it was partly caved and had been abandoned. The drifts in the mine amount to about 7,000 feet.

GEOLOGIC FEATURES

GENERAL RELATIONS

At the outset the writer wishes to acknowledge the assistance of the officials of the St. Louis Smelting & Refining Co., in providing facilities for the underground study of the Cocomongo mine, and particularly that of Mr. F. M. Stephens, superintendent of the mine, who has cooperated in the underground work and supplied data and mine sections which together with the writer's observations furnish the basis of the following discussion.

The Bonanza-Cocomongo vein system consists of two main mineralized faults and several related veins occupying fractures in the hanging walls of the main faults. The greater bulk of the ore that has been taken from these veins lay above the fourth level of the mine between walls of Bonanza latite. At and below the fourth level of the mine the andesite which underlies the latite has been encountered and in places forms at least one wall of the veins, usually the footwall. The greatest amount of faulting appears to have occurred on the Cocomongo fault. This has an average strike of about N. 30° W. and an eastward dip which ranges from about 47° in the upper levels to about 20° in the lowest. The change in dip of the Cocomongo fault is fairly uniform, although the sharpest change occurs at or somewhat below the 300-foot level. (See section A—A', pl. 28.)

The hanging wall of the Cocomongo fault as far down as the fifth level and the bottom of the Bonanza shaft consists of Bonanza latite. The latite has a north to N. 30° E. strike and a dip of 30°-60° W. The footwall of the Cocomongo fault at and below the 400-foot level is composed of Rawley andesite at many places in the mine. The normal dip of the Bonanza latite in both walls of the fissure has been disturbed near the fault zone. No consistent difference between the hanging wall and footwall could be detected, however, in the normal strikes and dips of the latite and andesite. The present depth of developments on the Cocomongo fault does not disclose the entire amount of displacement but indicates that it exceeds 250 feet. (See sections B-B' and C-C', pl. 28.) The Cocomongo fault is probably one of the series of similar faults in the vicinity of Kerber Creek that forms a zone of very large total displacement. The Cocomongo fissure is developed mostly by the mine workings northwest of the Bonanza shaft, but one drift on this fault has been extended into the footwall of the Bonanza shaft.

The geologic relations between the Bonanza and Cocomongo veins on the 300- and 350-foot levels of the mine are shown in Plate 28. The Bonanza vein has a strike of N. 45°-55° W. and so far as is known is confined entirely to the hanging wall of the Cocomongo fault. The dip of the Bonanza vein ranges from about 70° on the first and second levels south of the Bonanza shaft to about 40°-42° on the 400- and 500-foot levels. The Bonanza vein also occupies a fault, and although the amount of displacement cannot be estimated, it is probably less than on the Cocomongo fault. The Bonanza fault is characterized more by fracturing and brecciation of the wall rock; the Cocomongo fault by heavy gouges and intense shearing of the wall rock.

On the 300-foot level the intersection between the two veins lies north of the Bonanza shaft but probably pitches eastward. The intersection is not simple and cannot be represented by a single line. The Bonanza fault particularly has a tendency to split into a compound fracture zone near its intersection with the Cocomongo fault. The character of the termination of the Cocomongo fault at the north end of the 300-foot level could not be examined, as the drift is caved, but several cross faults or branching faults are said to have been encountered. Development work north of these cross faults appears to have been unsuccessful in locating any veins.

On the 500-foot level the irregular fracturing shown near the Bonanza shaft suggests the intersection of the two faults. The Bonanza shaft below the 500-foot level is probably on the Cocomongo fault, which at the bottom of the shaft dips only 18°-20° E. For about 100 feet south of the shaft on the 500-foot level the latite is much fractured and silicified, but no single well-defined break is evident. This zone probably represents the splitting of the Bonanza fault into a compound fracture zone similar to that shown on the map of the 300-foot level.

The termination of the Cocomongo fissure at the north end of the mine on the 400-foot level is shown in Plate 28. The fissure shows a tendency to swing into a north-south strike and appears to terminate against a strong gougy fault zone which dips northward or northeastward at angle of 47°. This fault has a strongly altered micaceous gouge and, like the Cocomongo fault, is probably of premineral origin. At the end of the 500-foot north drift on the Cocomongo fissure another premineral flat fault is encountered which strikes N. 17° E. and dips 28° E. The Cocomongo fissure as it approaches this fault shows a tendency to swing into a north-south strike. The footwalls of both the Cocomongo fissure and the N. 17° E. fissure on this level appear to be the upper latite member of the Rawley andesite.

It would appear that at the north end of the mine workings the Cocomongo fissure lost its individuality and either terminated against other premineral faults of the same general nature or was displaced by them. In either case these faults appear to limit the mineralization of the Cocomongo fissure on the north.

The Cocomongo fault passes into the footwall of the Bonanza fault on the 300-foot level and has been followed by a drift for about 250 feet, to the footwall beneath the Bonanza shaft. It shows good mineralization in parts of this drift, but at the south end of the drift it splits into several weakly mineralized fissures of steeper dip. It has not been explored farther south, and whether the conditions near the end of this drift are local is not known.

The Bonanza fissure zone has been followed by a drift southeast of the Bonanza shaft for about 480 feet on the 350-foot level and for about 300 feet on the 500-foot level. On the 350-foot level in the last 180 feet of the drift the fissure is tight and irregularly mineralized and splits into several steeper fractures. The mineralization becomes weaker in this fissure toward the southeast on all the levels.

STRUCTURAL RELATIONS OF FISSURES IN THE HANGING WALL OF THE COCOMONGO FAULT

In addition to the Bonanza vein there are also a series of so-called “vertical” veins which branch upward into the hanging walls of the Cocomongo fault. Several of these have yielded ore of good grade. Their relations to the Cocomongo fault are shown in Plates 28 and 29. The transverse “vertical” fractures were presumably the result of stresses developed in the hanging-wall blocks during the period of faulting. They are for the most part steeper than the main fault planes, but several of them were found to flatten and pinch as they were stoped upward into the hanging wall. This flattening is particularly pronounced in the "Gold vein," which occurs near the intersection of the Bonanza and Cocomongo veins. Another vertical vein, in which some ore has recently been developed, lies parallel to it and somewhat offset to the north. Still another vein lies about east of the Cocomongo shaft in the hanging wall of the Cocomongo vein. It has been explored by drifts on the 300- and 400-foot levels and stoped in some places above the 300-foot level. Its strike is S. 70°-80° E., and the dip is nearly vertical, although the vein flattens and dips northeast between the 300- and 400-foot levels near the Cocomongo fault. The greater part of the explored length of this fissure has not been productive. The intersections with the main faults at the bases of these vertical veins are not easily detected. As shown in Plate 28, the fissures appear to branch off near curves or rolls in the Cocomongo fault plane. Whether or not these rolls were instrumental in producing the fractures cannot be determined, as there is insufficient evidence. These fractures appear, however, to be confined to the hanging walls of the faults.

The Bonanza vein bears a relation to the Cocomongo fault plane very similar to that of the transverse or vertical veins. Probably the Bonanza fault was incipiently formed in the same manner as these fractures, but subsequent movement on it was much greater than on the other hanging-wall fractures that have been explored. It would appear that the Cocomongo was the first fault formed, and as a result of stresses active in its hanging wall, the block on that side was fractured by several more or less parallel fissures diverging southeastward from the main fault plane. With the continuation of the downthrow of the hanging wall of the main fault, the block on the hanging-wall side of the incipient Bonanza fault participated in the movement to a greater extent than the wedge-shaped block between the Bonanza and Cocomongo faults.

This conception is illustrated in Plate 29. The presence of several vertical fractures near the intersection of the Bonanza and Cocomongo faults on the 300- and 400-foot levels, and the fractured condition of the rock near their intersection on the 500-foot level would support the contention that the Bonanza fault starts in the hanging wall of the Cocomongo and is not to be regarded as the faulted portion of some earlier continuous fractures.

Similar transverse fractures in the hanging walls of veins that occupy faults have been found in other districts in the San Juan region. These are well illustrated by the fractures in the hanging wall of the Amethyst fault in the Creede district, described by Emmons and Larsen.[93]

DISTRIBUTION OF MINERALIZATION IN THE FISSURES

The ore bodies that have been mined from the Cocomongo and Bonanza fissures were for the most part above the 400-foot level. A wide body of high-grade lead-zinc

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[93] Emmons, W.H., and Larsen, E.S., Geology and ore deposits of the Creede district, Colorado: U.S. Geol. Survey Bull. 718, pp. 150-151, 1923.

ore was taken out of the Cocomongo fissure between the 300 and 400 foot levels, just north of its intersection with the Bonanza fissure, and is known as the 403 stope. The width stoped out amounts to 15 or 20 feet in the middle portion. The pitch length of the shoot was about 160 feet, although the shoot was not equally productive throughout this length. The stope length of the shoot was about 80 or 90 feet in its longest part. The exact character of the ore is not known, as only the open or partly caved stopes now remain. The width of this ore body, which is unusually wide for this district, may have been caused partly by the change in dip of the Cocomongo fault at this position. The differential movement between the hanging and foot walls evidently left an open space because the two adjacent walls were unconformable. (See cross section B–B', pl. 28.)

The intersection between the Bonanza and Cocomongo fissures, which lies just at the southern boundary of this shoot, may have been a factor contributing to its formation. However, as the Cocomongo fault plane becomes flatter below the 400-foot level the shoot fails to maintain its width and does not follow the intersection of the two fissures to the 500-foot level. It is possible that the shoot was produced by the combined effect of change in dip on the Cocomongo fault and the intersection of the two fissures. A shoot of less width (the 408 stope) occurs between the 300 and 400 foot levels of the Cocomongo fault northeast of the Cocomongo shaft. (See cross section A–A', pl. 28.)

In the Bonanza vein a large shoot of ore lay above the 200-foot level south of the Bonanza shaft. This shoot was stoped out to the surface in places. The vein is very steep above the 200-foot level, dipping 60°–70° NE. The shoot was 10 or 12 feet wide in some some places, and its stope length was about 100 feet. It is said to have contained bodies of galena and quartz 2 to 3 feet in width in the midst of the vein. Between the 200 and 300 foot levels a block of ore extending about 100 feet south of the shaft still remains. It has an average width of about 3.5 feet and indicates some pinching of the fissure below the 200- foot level as the dip flattens. (See section D–D', pl. 28.)

The amount and character of the vein material stoped out above the old 200-foot level north of the Bonanza shaft could not be determined, as these openings are not accessible. Additional bodies of unstoped ore estimated at about 25,000 tons still remain (1927) in the different veins. Above and below the 350-foot level south of the Bonanza shaft there are some bodies which have a width of a little over 4 feet, and between the 300 and 400 levels north of the Bonanza shaft there is a body 3.5 to 4 feet wide. Several other bodies of ore including those in some of the vertical fissures have average widths ranging from 3.5 to 5.5 feet.

GENERAL CHARACTER OF THE ORE

Like the other veins of the northern part of the district, the Bonanza and Cocomongo veins contain quartz as the most abundant gangue mineral. Smaller amounts of barite, rhodochrosite, manganocalcite, calcite, fluorite, and rhodonite are also found.

Apatite or the carbonated apatite, dahllite, is associated with carbonates and quartz in parts of the gangue. The sulphide minerals are pyrite, sphalerite, galena, tennantite, chalcopyrite, stromeyerite, and covellite. Limonite, cerusite, anglesite, and covellite occur in small amounts as secondary minerals in the upper levels and were produced by the action of surface waters on the primary ore. Delicate banded texture is never or rarely seen in the vein matter in either the Bonanza or the Cocomongo vein. In places streaks of galena and quartz 2 to 3 feet in width are said to have been found in the wider parts of the Bonanza vein on the first level. These massive ores exhibit a rough banding due to the distribution of the coarsely crystallized galena. In addition to the streaks of massive galena ore the vein at its widest part contained some mixed zinc-lead-copper ore with pyrite, some bodies of which still remain along the hanging wall of the old stope above the 200-foot level. The footwall of the stope still shows vein matter with little or no gouge clay. In a raise above the 350-foot level south of the Bonanza shaft the lead-zinc ore occurs partly as a cement between fragmental material filling a 3 to 4-foot fissure. The included wall-rock fragments were completely silicified but not replaced to any extent by the sulphides with the possible exception of a little pyrite. This cementation of wall-rock fragments appears to be typical of the ore from some parts of the Bonanza fissure. The walls of the Bonanza vein are well defined on the 300- and 400-foot levels in this part of the mine and have small gouge streaks along them in places. On the 500-foot level south of the Bonanza shaft, in the shattered zone which perhaps marks the intersection between the Bonanza and Cocomongo veins, the vein matter is frozen to the walls of the fractures, is very siliceous, and has a massive texture.

In the large stope on the Cocomongo vein known as the 403 stope, north of the Bonanza shaft, the vein matter was 10 to 14 feet wide between walls. Remnants of the vein that are left near the edges of the stope indicate that the vein had an open vuggy texture. The large openings were probably to some extent filled with breccia and gouge clay in addition to the vein matter. At the north end of the stope, where the fissure has pinched, there remains a 2-foot vein against the hanging wall consisting of a mixture of sphalerite and galena. The sulphides form a porous intergrowth, which is not noticeably banded, however, as the open spaces are small and irregularly distributed. The sphalerite and galena show crystal faces in the openings, and carbonate crystals of a late stage line some of the openings. The texture as a whole testifies to crystallization in an open space that was incompletely filled by the sulphides. The walls of the vein are well defined by altered gouge seams.

In the northern part of the mine, in the vicinity of the Weaver winze, the Cocomongo vein shows 2 to 4 feet of sericitized gouge and brecciated material with irregularly distributed streaks of ore. Some post-mineral movement has occurred. The footwall at this end of the mine is strongly silicified. Above the 300-foot level north of the Weaver winze the vein lies against the strongly silicified footwall without much intervening gouge but is separated from the hanging wall by an altered gouge which ranges in width from a few inches to a foot or more. In the hanging wall the silicification is less intense. The main alteration products of the hanging-wall latite are sericite, carbonate, pyrite, chlorite, and quartz. Microscopic examination of the thick gouges from the Cocomongo fault in this end of the mine show them to be composed largely of finely divided muscovite (sericite). Pyrite is commonly scattered through the gouge in small crystals. Other minerals present in the gouge are quartz, carbonates, rutile, anatase, and apatite. This extreme alteration of the Cocomongo fault gouge was clearly caused by the alkaline solutions that deposited the ores and offers good mineralogic evidence of the premineral age of the gouge. However, the distribution of mineralization in the Cocomongo fault in itself substantiates a premineral origin of the faulting, even though there has been some slight post-mineral movement. The vein at the north end of the mine contains more copper than is found in the south end of the mine. The copper is largely in tennantite, which is locally associated with massive quartz and also occurs as sulphide streaks in the gouge.

In the transverse vertical fractures in the hanging wall of the Cocomongo fault rhodochrosite, manganocalcite, and rhodonite are more common than in either the Bonanza or the Cocomongo vein. The vertical veins contain little or no gouge and fail to show evidence of much displacement of the two walls. The vein matter is evidently a filling of an open fracture and is at many places frozen to the altered wall rock.

DISTRIBUTION OF METALS IN THE ORE SHOOTS

The relative proportions of lead, zinc, and silver in blocked-out ore from different parts of the mine are shown in the following table:

Silver, lead, and zinc in ore from Bonanza mine

Location of ore block	Silver (ounces to the ton)	Lead (percent)	Zinc (percent)
Between 200 and 300 foot levels, extending about 100 feet south of Bonanza shaft	1.50	3.1	4.75
350-foot level, from about 110 to 230 feet south of Bonanza shaft	2.50	5.4	3.85
Between 350 and 400 foot levels, extending about 90 feet south of Bonanza shaft	1.12	11.6	9.60
Between 300 and 400 foot levels, from about 60 to 160 feet north of Bonanza shaft	4.40	7.1	14.10
Between 400 and 500 foot levels, from about 60 to 150 feet north of Bonanza shaft	3.40	2.6	7.10
Above 400-foot level, along raise between fourth and third levels, about 480 feet northwest of Bonanza shaft	10.60	7.3	14.93
Vertical vein in hanging wall of Bonanza vein between 300 and 400 foot levels, north of shaft	2.50	5.9	10.50
Drift at 300-foot level in footwall of Bonanza shaft on Cocomongo vein	2.00	3.7	7.50
Between 400 and 500 foot levels extending about 90 feet south of Bonanza shaft	1.30	4.4	9.90
Winze between 350 and 500 foot levels, about 250 feet south of Bonanza shaft	2.40	12.5	13.80

The figures are based on mine assays that were used for the determination of ore reserves and are given in foot percentages. No accurate data are available on the ratio of lead and zinc in the ore from the old stopes above the 200- and 100-foot levels of the Bonanza shaft. Most of this ore was taken out by lessees, but the ratio of lead to zinc was high, so far as the information available indicates. Patton[94] reports that in 1914, when he examined the vein, a galena streak was present in the midst of the main vein on the first level. This streak was 2 to 3 feet wide and "consisted of galena to the extent of 30 to 50 percent of the bulk of the ore." Above each of the 200, 300, 350, and 400-foot levels, south of the Bonanza shaft, lead and zinc occur in about equal proportions, the average ratio of zinc to lead in the different blocks ranging from 0.71 to 1.5 to 1. In the winze between the 350 and 500-foot levels, 250 feet south of the Bonanza shaft, lead and zinc also occur in about equal amounts. On the other hand, between the 400 and 500-foot levels, just south of the Bonanza shaft the ratio of zinc to lead is slightly above 2 to 1.

The evidence of these assays would indicate an increase in the ratio of zinc to lead in depth and possibly an increase in this ratio toward the northwest. An increase in zinc is well shown by the assays of the ore shoots lying northwest of the Bonanza shaft where the average ratios of zinc to lead are all very near 2 to 1. The highest average ratio of zinc to lead, 2.7 to 1, is found between 60 and 150 feet north of the Bonanza shaft in a block of ore lying between the 400 and 500 foot levels. The mineralization in the northern section of the Cocomongo fault consisted in the deposition of zinc and lead with a larger proportion of copper than in other parts of the mine. In places large amounts of ore high in silver and containing tennantite have been taken from the stopes in the north end of the Cocomongo vein. One lot consisting of 13.8 dry tons sorted for shipment ran 1.9 percent of lead, 4.7 percent of zinc, 8.8 percent of copper, and 124.6 ounces of silver and 0.038 ounce of gold to the ton. The iron content was 10.75 percent, and the insoluble matter 50.15 percent. Picked samples of ore of this character show as much as 374 ounces of silver to the ton and around 15 percent of copper. This ratio of silver to copper is much higher than the normal one throughout the mine. Although part of this silver lies in the tennantite, the very high silver content may be due largely to stromeyerite. This copper-silver shoot extends below the 400-foot level to the 500-foot level, but the vein is much more siliceous on the 500-foot north level. The shoot is bounded on the south side by a barren broken zone in which the vein matter is very pyritic and on the north side by the gougy faults and slips mentioned in the description of the structure.

The ore shoots as a whole, then, tend to become richer in zinc in depth and toward the northwest, and the copper tends to increase in the northwestern part of the Cocomongo vein. Data are not available as to the increase in copper with depth, but the ore highest in copper lies near the 300 and 400-foot levels in the northern part of the mine. In detail a uniform change in the character of the ore is not evident. In the shoots south of the Bonanza shaft the ratio of lead to zinc is in places as high as 4 to 1, and the ore contains from 2 to 30 percent of lead. The individual lead shoots also do not show in detail the increasing proportion of zinc in their lower parts. For example, the raise above the 350-foot level about 120 feet south of the Bonanza

[94] Patton, H.B., op. cit., p. 100.

shaft started in ore in which the lead was two to three times as high as the zinc. In the upper part of the raise, about 50 to 60 feet vertically above the 350-foot level, the vein was somewhat narrower and zinc was in excess of lead. The ore as a whole in all parts of the mine runs very low in copper, and only where silver is high, as in the copper-silver shoot at the north end, does the copper content reach or exceed 2 or 3 percent.

PARAGENESIS OF THE ORES

A wide range of relations, in part contradictory, is shown between the ore minerals from different parts of the mine and as a whole indicates a closely overlapping deposition of the different minerals. Pyrite, quartz, and sphalerite are minerals of an early stage in all the ore. The quartz continued in decreasing amount after sphalerite and was at places deposited with the latest sulphides. Galena, chalcopyrite, and tennantite are later than the early abundant quartz and sphalerite. Galena occurs interstitially to sphalerite and less commonly has replaced both sphalerite and pyrite. Evidence of a brecciation of the early sulphides and cementation by later quartz and sulphides is seen in the ore from the Cocomongo and Bonanza veins. The brecciation was not uniformly distributed nor everywhere equally intense.

In general, chalcopyrite, galena, and tennantite are of nearly contemporaneous formation, but contradictory relations are exhibited in places. For example, in some ore chalcopyrite occurs with later quartz cementing brecciated pyrite, sphalerite, and galena, but in ore from the old stopes above the 200-foot south level galena has replaced tennantite to a slight extent, whereas in other parts of the same ore the two minerals appear contemporaneous. Where galena is very abundant, as in the upper levels, its crystallization has continued after the depletion of the ore-depositing solutions in copper. On the other hand, in the stopes at the north end of the Cocomongo vein, where copper is more abundant, tennantite appears to be a later mineral than galena. This apparent inconsistency in the relative ages of the lead and copper mineralization can perhaps be explained by changes in the proportions of metals in the ore solutions during the period of vein formation.

The carbonates commonly belong to a late stage and occur as veinlets together with some quartz in brecciated sulphides or fill cavities between the sulphides. Carbonates continued to be deposited after quartz and have replaced it to some extent.

SOURCE OF THE MINERALIZING SOLUTIONS

The complex nature of the fissuring in the mine makes it difficult to determine which of the fissures was the main conduit that supplied the mineralizing solutions. The increase in zinc and copper toward the northwest and in the Cocomongo fissure perhaps indicates that the direction of local circulation was outward from this part of the fissure systems. Although little development work has been done in the footwall of the Cocomongo fissure, a crosscut running from the 500-foot level about 100 feet into the footwall of the Cocomongo fissure shows only a few weak faults, which are not appreciably mineralized. At the end of the crosscut the alteration in the andesite country rock is also very weak. The crosscut to the Cocomongo shaft on the 300-foot level likewise shows only weak alteration and mineralization. To the present depth of exploration it would appear, then, that the source of the solutions was not in the footwalls of the fissures but rather down their dip. The extremely low dip of 20° or less shown by the Cocomongo fissure below the 500-foot level would appear to be unfavorable to large ore bodies at greater depth within the fissure itself, but favorable openings in the vicinity of the fissure might contain additional systems of ore shoots.

RICO MINE

The Rico vein (No. 71, pl. 1) lies in the saddle on the north side of Round Mountain. This vein is developed by a crosscut tunnel about 130 feet in length and by about 300 feet of drifts on the vein at the tunnel level. The portal of the tunnel is at an altitude of about 10,700 feet. The vein has been partly stoped above the tunnel level, and a 70-foot winze with some stoping has been sunk below the tunnel level. (See fig. 27.) The fault in which the vein lies strikes N. 45°–50° E. and dips about 25°–30° SE. In the stopes above the tunnel level it has a dip of about 29° and in the winze below about 24°. Some subsidiary fault planes dipping as low as 19° are exposed in the drift south of the crosscut tunnel. The country rock is largely altered andesite. Bleaching and silicification of the andesite have been very intense close to the vein. The vein matter occurs as lenses distributed irregularly through a sheared fault zone that is in places 30 feet or more wide. The displacement on the fault plane is not determinable, but to judge from the intensity of the shearing and the width of the sheared zone it is several hundred feet. This is probably a normal fault, the steeper part of which has been eroded. The ore occurs in pockets and lenses within the fault zone, either between layers of sericitized gouge clay or cementing siliceous breccia material. The gangue of the ore is chiefly quartz and brecciated jasper with minor amounts of barite and pinkish manganocalcite. The ore minerals are pyrite, sphalerite, galena, chalcopyrite, tennantite, and probably stromeyerite. There is a minor amount of secondary chalcocite, which forms a bluish-black sooty coating on some of the sulphides. As is common in the district the early silicification was very pronounced.

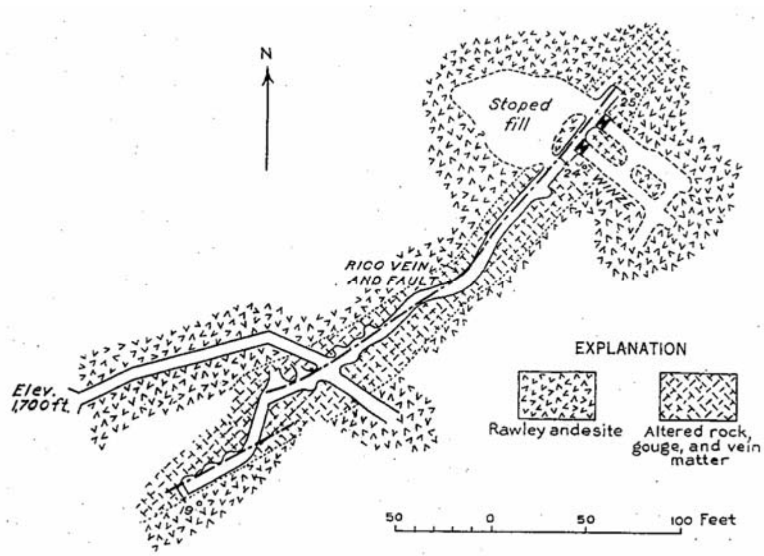

Figure 27. – Sketch map of the Rico tunnel.

The wall rock adjacent to parts of the vein was entirely altered to quartz, and some of it was clearly brecciated before silicification, probably by the movement on the fault. Part of the silicified and brecciated rock has been replaced by later sulphides and sericite.

Tennantite ("gray copper") is fairly abundant as a vein mineral in the sulphide pockets in the fissure. The ore is in places vuggy, and where the tennantite is associated with quartz and lines vugs it is well crystallized in modified tetrahedrons. An assay of carefully picked tennantite freed from other sulphides ran 385.4 ounces of silver to the ton. The gold content of the tennantite is small, probably less than 0.10 ounce to the ton. (See p. 9.)

The sulphide ore in the vein occurs in rather small lenses and pockets, of which those now exposed in the workings are not over a foot or two in width. Some pockets that were apparently wider have been stoped out above the tunnel level, and their dimensions could not be estimated. The very flat dip of the fissure and the width of the gougy shear zone in which the ore lies are apparently unfavorable to the existence of wide and continuous ore bodies. The vein has not been explored sufficiently to indicate its promise or to permit a search for steeper and more open fractures in the hanging wall of the fault that would be more favorable for ore deposition.

Small shipments of crude ore have ranged from 30 to 120 ounces of silver to the ton, from less than 1 to 5 percent of lead, and from 2 to 4 percent of copper. The gold ranged from 0.2 to nearly 0.6 ounce to the ton. One shipment of 15 tons of crude ore carried 4.9 percent of lead, 4.25 percent of copper, and about 63 ounces of silver and 0.6 ounce of gold to the ton. The iron content was 20 percent, and the insoluble matter about 33 percent. The total production has been very small, probably less than 150 tons of crude ore.

SHAWMUT MINE

The Shawmut mine (No. 76, pl. 1) is on the south slope of Round Mountain. The vein is developed by a shaft 300 feet deep, the collar of which is at an altitude of 10,827 feet, and by an adit about 1,100 feet in length, the portal of which (No. 76, pl. 1) is west of the vein on the west slope of the Round Mountain ridge at an altitude of about 11,420 feet. It intersects the vein about 400 feet below the collar of the shaft. As shown on the topographic map, the mine may be reached by unimproved wagon roads, either from Alder Creek, on the east side of the range, or by way of Rawley Gulch from the town of Bonanza. The distance from Alder Creek is about 7 miles.

The following history of the Shawmut mine is taken largely from a report on the property by W. H. Wright to the Kapi Mining & Milling Co., the present owner. The Shawmut claim was located by Peter Johnson, who received the patent in 1885. In 1893 William Bennet acquired part ownership. In 1905 a 90 percent interest in the property was sold, and the Shawmut Gold, Silver & Copper Mining & Milling Co. was organized. This company expended $68,000 in development work after an examination of the property in March, 1906. As a result of the development of the Shawmut connecting claims as far south as the Sosthenis were purchased. A tunnel was begun with the intention of opening all claims from the Sosthenis to the Shawmut, but owing to the failure to meet large payments coming due in 1907, all the claims became forfeited to the former owners.

The Kapi Mining & Milling Co. was organized shortly afterward, and the Maybelle, Maybelle No. 1, and Maybelle No. 2 claims were located. These claims are not yet patented. In 1912 this company started an adit to intersect the Shawmut vein below the old workings. This was completed about 1918 and connected to the shaft by a raise, but no further work has been done on the vein, as it proved to be of too low grade to mine.

The Shawmut mine was one of the early producers in the Bonanza district, but complete or accurate records of its production are not available. According to Patton[95] an estimate of the production prior to 1900 gives 700 tons of ore. In the report of the Director of the Mint for 1888[96] the Shawmut is credited with a total production of $4,006 for this year, which was divided as follows: Gold $80, silver $2,586, and copper $1,340. Details of the production are not given for other years. The old stope on the 120-foot level is said to have been mined and the ore shipped many years ago, but the records of shipment have been lost.

The geologic plan and section of the adit level (pl. 30) and the 280-foot level are based upon personal examination, but discussion of the upper levels is based upon a report prepared in 1919 for the Kapi Mining &, Milling Co. by S. J. Burris, jr.
The vein on the 280-foot ("300") level and the adit level below strikes N. 15°-25° E. and dips 70°-80° E.

The country rock of the Shawmut vein on the lower levels and along the entire length of the adit level consists of lavas of the Rawley andesite. There may be some fault blocks of the Bonanza latite in the upper levels of the mine, but most if not all of the rock exposed in the broad, flat saddle between Round Mountain and Manitou

[95] Patton, H.B., op. cit., p. 94.
[96] Munson, G.C., Report of the Director of the Mint upon the production of the precious metals in the United States, 1888, p. 133, 1889.

Mountain is altered andesite. The Bonanza latite overlies the andesite and caps Round Mountain, and the base of the latite on the south slope of Round Mountain lies about 80 feet above the collar of the Shawmut shaft. The Shawmut ore shoot extends at least 300 feet below the base of the latite, and thus lies well within the stratigraphic range of other shoots in the district. Most of the veins cut by the drainage adit contain a high proportion of pyrite, chalcopyrite, and sphalerite, which suggests that the lower limits of the lead shoots have been reached. Although the exact position of the bottom of the lead ore in the Shawmut vein is not known, it probably is not more than 200 feet below the surface. This is about 1,000 feet vertically above the base of the lead ore in the Rawley vein and about 2,200 to 2,500 feet above the base of the lead ore in the Bonanza vein. The available evidence (see pp. 54-55) indicates that the larger proportion of the lead shoots in the district do not extend more than 500 feet below the base of the Bonanza latite. Although it cannot be considered proved that the ores of the district bear so definite a relation to the structure, this general vertical range in conjunction with the character of the mineralization in the Shawmut vein at the adit level appears to be unfavorable to the existence of commercial bodies of lead ore below the present depth of exploration on the vein.

The Shawmut fissure is probably a fault fissure, and on the fifth and adit levels it contains an altered sericitized gouge and is relatively narrow and tight. A few lenses of siliceous or pyrite vein matter from a foot to 2½ feet in width occur in the fissure on these lower levels. The fissure is said to have been well mineralized in the levels near the surface and to have carried mainly lead and silver. The lead apparently diminished rapidly in depth, as the production cited above for 1888 shows that the value of the ore was divided between silver and copper. The ore consists of pyrite, sphalerite, galena, tennantite, and chalcopyrite in a gangue consisting chiefly of quartz. Shipments of 111 tons of crude ore from the vein in 1911 and 1917 show an average content of about 1 percent of lead, 2 percent of copper, and 0.07 ounce of gold and 16 ounces of silver to the ton. It is not known from what part of the mine these shipments came, but the low lead content suggests some of the lower levels. No records are available to show the average content of the ore of the upper levels, but an assay of ore taken from the first level by channeling across the vein is given by Patton[97] and shows 40.2 ounces of silver and 0.2 ounce of gold to the ton.

Several mineralized fissures besides the Shawmut are cut by the drainage adit (pl. 30), but these have not been explored, and several of the larger fault fissures are timbered, so that little can be told of their character. About 200 feet from the portal an altered fault zone striking about N. 28° W. and dipping 50° E. is crossed. This zone is mostly timbered, but a short drift caved near the entrance was driven south along the footwall of this fault. The fault zone is about 50 feet wide, and the andesite in the hanging wall is considerably brecciated.

About 500 feet from the portal there is a strong vein striking about N. 20°-25° E., which is timbered but may correspond to the Maybelle vein. The fissured zone is

[97] Patton, H.B., op. cit., p. 95.

about 40 feet in width and dips about 70° E. The mineralization produced mainly pyrite on the adit level. The Maybelle vein is said to be similar in character to the Shawmut and to be composed of galena, tennantite, chalcopyrite, and pyrite in a gangue consisting mainly of quartz with some barite. The fissure in the Maybelle tunnel is said to be about 11 feet in width.

At about 960 feet from the portal a mineralized fissure containing pyrite and sphalerite is cut, but there are no drifts on it. This fissure strikes about N. 50°-60° E. and dips 45° SE. Several other small mineralized fissures were encountered in driving the adit, and most of them show the effects of strong sericitic alteration, with some pyrite but little other vein matter.

LEGAL TENDER MINE

The Legal Tender mine is about 1,300 feet southeast of the Shawmut shaft, on the large flat area between Round Mountain and Manitou Mountain. The property includes the Legal Tender claim, which is a patented claim and is owned by the Baldwin Mining Co. The Legal Tender mine is one of the oldest mines of the district, and its production prior to 1900 has been estimated at 100 tons of $40 ore.[98] The mine plant consists of several buildings, now largely in ruins, which include a large shaft house. The underground workings are said to consist of a shaft 300 feet deep and 700 feet of drifts, but no maps of the mine are available. The collar of the shaft is at an altitude of about 11,780 feet. The mine has not been operated for many years except for about two months in 1917.

The character of the vein and its strike and dip are not known. The ore is said to be partly oxidized to a depth of 300 feet. The vein presumably carries a considerable proportion of copper. A shipment of 38 tons of crude ore carried 0.27 percent of lead, 2.8 percent of copper, and 9.8 ounces of silver and 0.02 ounce of gold to the ton. It is not known, however, from what part of the mine this ore came, and no records of the content of the ore shipped prior to 1900 could be obtained.

VIENNA MINE

The Vienna vein crops out on the west slope of Round Mountain and is developed by an adit whose portal is at an altitude of about 10,650 feet. This vein was not examined but is said[99] to contain galena and gray copper. A shipment of 26 tons of crude ore from this vein showed an average content of 8.8 percent of lead, 3.1 percent of copper, and 31.5 ounces of silver and 0.96 ounce of gold to the ton. Another lot of 2 tons assayed 3.8 percent of lead, 1.6 percent of copper, and 28 ounces of silver to the ton.

[98] Patton, H.B., op. cit., p. 68.
[99] Idem, pp. 96-97.

SOSTHENIS MINE

The Sosthenis mine (No. 77, pl. 1) is near the head of Sosthenes Gulch, on the west slope of Manitou Mountain, at an altitude of about 11,300 feet. The mine is developed by four tunnels, all but one of which are now caved near the portals. The mine was worked mainly between 1887 and 1893 and during this period produced over $40,000 mainly in silver and gold. The production records given by the Director of the Mint are shown in the accompanying table. These records are incomplete, no details being available as to the production of mines in the district in 1889, but they are probably close to the total production of the property. The total output of crude ore is not known but is probably at least 400 tons.

Value of metals produced at the Sosthenis mine[a]

Year	Gold	Silver	Lead	Total
1888[b] ………..	$2,500	$29,080	---------	$31,580
1890[c] ………..	750	4,202	$283	5,235
1891 ………..	557	4,287	---------	4,844
	3,807	37,569	283	41,659

[a]No production in 1887 (Munson, G.C., Report of the Director of the Mint upon the production of the precious metals in the United States, 1887, p. 181, 1888) and no record of production in 1889. Value of gold used, $20 an ounce; silver (coinage value), $1.29 an ounce; lead, $87 a ton.
[b]Munson, G.C., op. cit. for 1888, p. 121, 1889.
[c]Smith, M.E., idem for 1890, p. 187, 1891.

The original mine plant, now in a ruined condition, consisted of boiler and compressor house, besides several other buildings. A geologic sketch plan of the lowest adit level, the portal of which is at an altitude of 10,238 feet, is shown in Figure 28. The other adit levels are caved near the portals. Most of the ore that was mined presumably came from one or more of the upper adit levels, as there are no stopes from the lowest level. The total length of drifts and crosscuts on the lowest level is about 1,280 feet. Three principal veins, all in andesite, are exposed by the lowest tunnel, which follows the first one for 300 feet or more from a point about 180 feet in from the portal. The fissure is clearly a fault fissure with slickensided walls and altered micaceous gouge and consists of a series of branching and parallel fault planes. Its direction changes gradually from N. 20° W. where first encountered to about N. 20° E. near the end of the drift. The fault planes near the portal dip 70° or more westward, but near the end of the drift the dip is 75°-80° E. The vein is timbered in parts of the drift, but no strongly mineralized rock is exposed. Near the end of the drift, about 450 to 500 feet from the portal, the fissure zone consists of several parallel fault planes exposed by a short west crosscut, one of which contains 1½ to 2 feet of siliceous vein matter which has in part replaced brecciated wall rock and is in part a filling between the fragments, and which is accompanied by pyrite and tennantite, with some galena and sphalerite. This northerly series of veins is presumably the Sosthenis vein. The mineralization shown on this level was not sufficiently strong to encourage stoping. Drifts were also run along several parallel fractures to the east. (See fig. 28.)

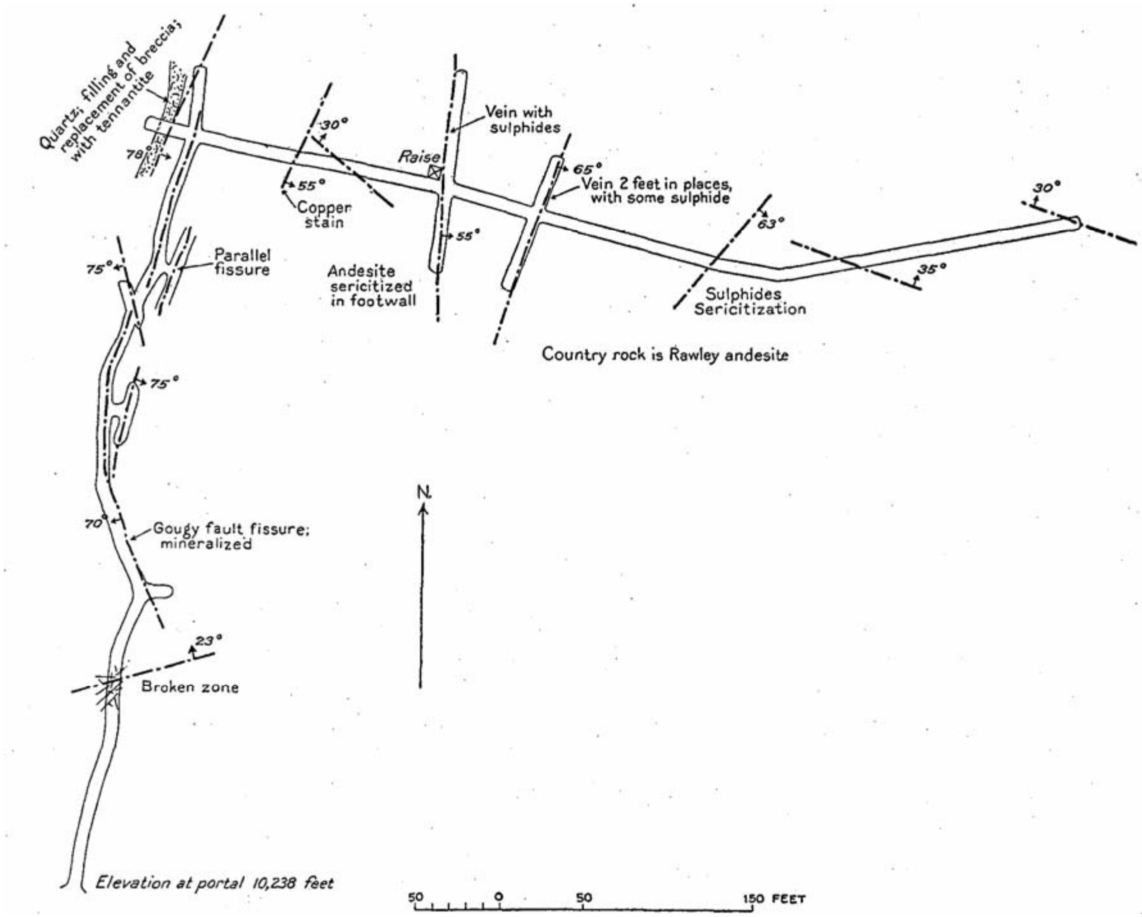

Figure 28. – Sketch map of the workings of the Sosthenis mine.

According to information cited by Patton[1] the Sosthenis vein in the upper adit levels was oxidized and yielded silver and gold. This statement is borne out by the record of production given above, in which the gold content is relatively high in proportion to the the silver in comparison with the ratio in most of the unoxidized veins in the district. On the assumption that estimates of the total ore are approximately correct at 400 to 600 tons, the gold content of the ore would have been between 0.04 and 0.05 ounce to the ton. Patton publishes an estimate of the grade of the shipping ore at 0.04 ounce of gold and 35 ounces of silver to the ton, with 15 percent of zinc. The average content of the unoxidized sulphide ore is not known, but a few tons of crude ore for which a record is available assayed 9 ounces of silver to the ton, with 11.4 percent of lead and about 1 percent of copper. The character of the vein in the lowest adit level indicates that iron and copper have increased in depth and the lead has decreased considerably.

In the cross cut from the drift two other veins are intersected – one about 150 feet eastof the adit tunnel and another about 200 feet east. There is a drift about 120 feet long on the first vein and a raise near the crosscut. This vein strikes N. 5º E. and dips about 55º E. The second vein strikes N. 20º E. and dips about 65º E. It

[1] Patton, H.B., op. cit., p. 97.

shows about 2 feet of vein matter in places of rather low sulphide content. Beyond this vein in the crosscut several other fissures are cut but have not been explored by drifting. Bad air near the end of the crosscut and in the short drifts prevented very detailed observations.

LITTLE JENNIE MINE

DEVELOPMENT AND PRODUCTION

The Little Jennie mine (No. 45, pl. 1) is 11,300 feet above sea level on the south side of the gulch a few hundred feet south of the workings of the Sosthenis mine. The adit (fig. 29) is about 550 feet in length and for about 350 feet from the portal is driven on a fissure zone striking south to S. 15° E. and standing nearly vertical or dipping steeply westward. At a point about 350 feet from the portal the vein splits, and thence for about 200 feet the adit follows the east split, which strikes about S. 45°-50° E. and dips about 70° NE.

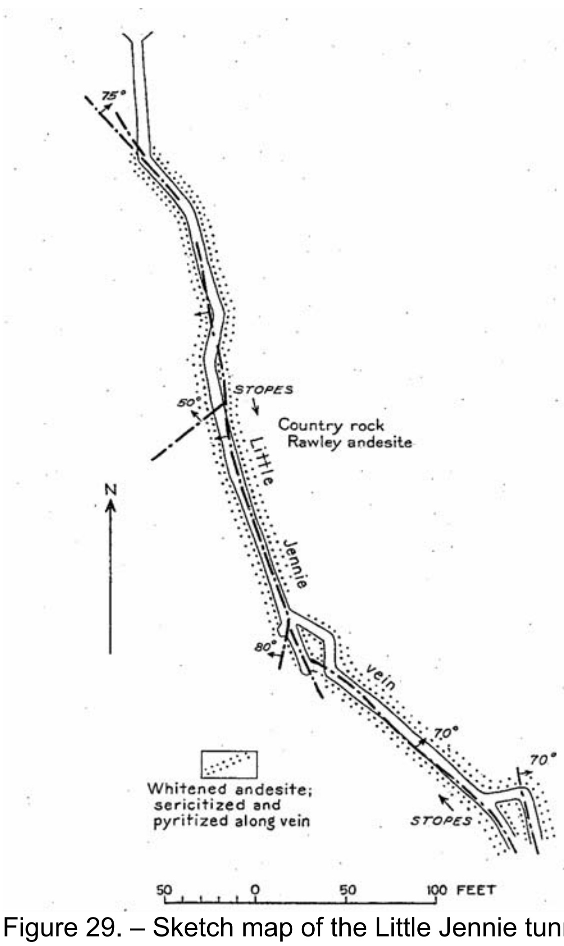

Figure 29. – Sketch map of the Little Jennie tunnel.

The Little Jennie claim lies on the hillside a few hundred feet east of the adit, on a different vein from those developed by the accessible part of the workings. The Little Jennie workings were started early in the history of the district. Burchard[2] states that the vein on the Little Jennie claim was opened by a shaft, but in driving a tunnel 200 feet below the shaft, in order to cut the vein, a blind lode was encountered. This load had an ore streak about 18 inches wide, consisting of quartz impregnated with gray copper and chalcopyrite, with some galena. This rapidly widened out to about 6 feet. Burchard states that the ore was not of high grade but occurred in large quantity. This vein is evidently the one shown in Figure 29 and will be referred to in this description as the Little Jennie vein. Aparently the production accorded to the Little Jennie came from stopes in this adit, as there are no extensive workings on the Little Jennie claim, so far as is known. Silver[3]

[2] Burchard, H.C., Report of the Director of the Mint upon the production of the precious metals, 1882, p. 541, 1883.
[3] Silver, Herman, idem for 1883, p. 403, 1884.

states that in 1883 the Little Jennie was being developed and that some ore had been shipped. There was a 30-inch vein with chalcopyrite and gray copper, running 30 ounces of silver to the ton. Details of the production of the Little Jennie are not known, but Patton[4] gives an estimate of 500 tons valued at $25 a ton.

GEOLOGIC FEATURES

The country rock is entirely andesite, most of which is of the porphyritic type. The fissures that the veins occupy are evidently fault fissures, which show a tendency to split into parallel or diverging fractures. Along the veins the andesite is strongly decomposed and bleached, owing to the formation of sericite, quartz, and carbonates. The fault gouge is likewise strongly decomposed and consists largely of sericite, as is common in the altered premineral gouges of the district. Apparently because of the steep dip of the fissures the vein matter is fairly continuous and ranges from 1 to 4 feet in width.

The paragenesis of the minerals in the vein is particularly interesting, as it illustrates rather clearly several steps that are common in the formation of ore bodies in this part of the district. The earliest stage in the formation of the ore after the rupturing of the andesite was the intense siliceous alteration of the wall rocks of the fissures. This was caused presumably by solutions containing sulphuric or halogen acids. The attack of these siliceous mineralizing solutions converted the fractured and partly brecciated andesite into a rock consisting largely of silica with a little amorphous ferric oxide and hematite. There was an additional movement on the fault fissures after this stage of silicification. The vein filling followed, consisting of four stages—(1) early pyrite, quartz, and manganese silicate (rhodonite), (2) continued deposition of quartz and pyrite followed by sphalerite, (3) formation of galena and chalcopyrite with the beginning of deposition of rhodochrosite, and a little vein apatite, (4) deposition of rhodochrosite or manganocalcite with some late chalcopyrite and tennantite. During the period of vein formation the early jaspers and less silicified bodies of wall rock adjoining the fissures were attacked, pyrite, carbonates, and sericite were formed in them, and the jaspers were further recrystallized and impregnated with pyrite. The first stage, in which rhodonite and quartz were precipitated, was clearly early and distinct, but the other stages overlapped considerably. The later carbonates have replaced the early quartz and rhodonite (pl. 13, *B*) and chalcopyrite has replaced pyrite to some extent. Where fragments of the reddish jaspers have been included within the later vein deposits they are completely recrystallized, with the partial loss of some of their red color. Ghostlike outlines of these reddish jasper fragments are seen in the vein filling in some material on the mine dump.

ORES

The ore minerals recognized in the Little Jennie vein are pyrite, sphalerite, galena, chalcopyrite, tennantite, and small specks of a gray mineral that is possibly

[4] Patton, H.B., op. cit., p. 68.

stromeyerite. The gangue is mainly quartz, with rhodonite, rhodochrosite, carbonated apatite (dahllite or podolite), and manganocalcite. The general character and the paragenesis of the Jennie vein suggest that it belongs to the lower part of the epithermal or low-temperature vein zone. The vein has more of a tendency to be banded and vuggy and has a higher proportion of manganese carbonates than the lower parts of such veins as the Rawley.

Some samples of the Little Jennie vein over widths of 16 to 48 inches give assays of 4 to 18 percent of lead, 2.5 to 19 percent of zinc, 1 to 1.5 percent of copper, and 3 to 10 ounces of silver to the ton. In the north-south vein the zinc content exceeds that of lead, and in an average of five assays to which the writer had access the ore showed a width of 2.1 feet with 7.4 percent of lead, 14.1 percent of zinc, and 4.3 ounces of silver to the ton. Siliceous vein matter, due partly to replacement and partly to filling on the hanging wall and footwall of the ore streaks, showed from a trace to 5 percent of lead, from 0.2 to 8 percent of zinc, and a few ounces of silver to the ton, over a width of 1 to 2 feet.

The southeast vein beyond the split showed a higher content of lead than of zinc and in two samples averaged 15.5 percent of lead, 5.3 percent of zinc, and 7.7 ounces of silver to the ton, over a width of 2.3 feet. The Little Jennie is said to have produced a small tonnage of shipping ore, but smelter returns on this ore are not available. One small lot of a little over 7 tons, presumably from the Little Jennie dump, showed a content of 10.66 percent of lead, 0.88 percent of copper, and 4.42 ounces of silver to the ton.

Although the explored part of the Little Jennie vein is narrow and the development work done is small, the steepness of the fissures and the intense alteration of the adjacent rock give some promise of the vein holding its width and mineral content to greater depth, as is also indicated by the kinds and proportions of the vein minerals.

OTHER MINES AND PROSPECTS IN SOSTHENES GULCH

Other veins developed by small workings adjacent to the gulch near the Sosthenis mine are the Merrimac, May Queen, Gypsy Queen, Vallejo, and Wisconsin.

Merrimac and May Queen—The Merrimac and May Queen claims (No. 52, pl. 1) are evidently on the same vein and were worked through the same crosscut adit, but none of the old workings are now accessible. Burchard[5] states that the Merrimac lode where cut by the tunnel is 14 feet wide and carries galena and tennantite. There are some small discovery shafts and pits on the vein south of the portal of the adit. The country rock is andesite.

Gypsy Queen—A sketch map of the Gypsy Queen adit (No. 33, pl. 1) is shown in Figure 30. The workings are partly caved at several places, and a considerable part of the drift is timbered. The main fissure seems to have been encountered about 150

[5] Burchard, H.C., op. cit. for 1882, p. 541, 1883.

feet from the portal. The fissure strikes about N. 30° E. and dips 50°-60° SE. The andesite country rock is altered to a white soft rock adjacent to the vein, and there is a soft micaceous gouge along many of the slip planes. The general direction of the mineralized fractures is northeast, but the drift gradually turns northward in following the vein. Timbering and caved ground prevented detailed study of the faults, but it appears that the fissure has been displaced toward the west at several places. The vein matter where it could be seen was from 1 foot or less to 2.5 feet in width. As the workings are shallow, surface water has deposited limonite, manganese oxides, and green copper salts along the fracture planes. The gangue of the vein is mainly quartz, with some manganese-bearing carbonates. The ore minerals seen on the dump are pyrite and tennantite with some galena and sphalerite. Burchard[6] states that some high-grade gray copper ore had been taken from this prospect.

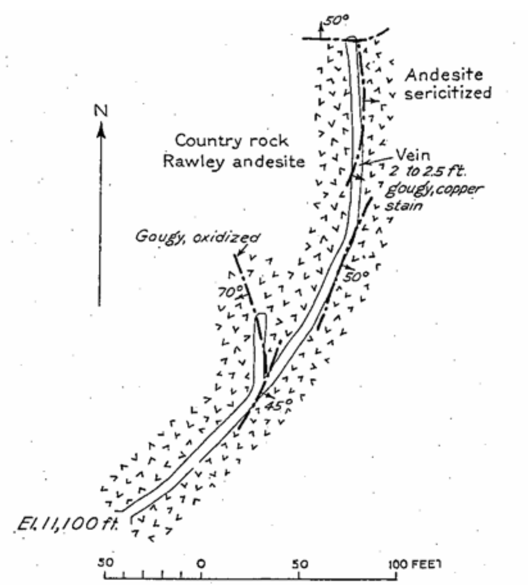

Figure 30. – Sketch map of the Gypsy Queen tunnel.

Vallejo—A sketch map of the accessible parts of the Vallejo workings (No. 80, pl. 1) is shown in Figure 31. The main vein prospected occurs in a fault fissure striking N. 70°-75° E. and dipping 45°-50° S. As the strike and dip of the Merrimac (May Queen) vein is not known, it cannot be positively stated that the Vallejo drift is on the same vein, but from the alignment of the claims this appears likely. There is a wide zone of bleached, decomposed andesite and gouge along the fissure, but where it could be seen the vein material is narrow and siliceous. Several cross fissures are cut by the workings, and nearly all of them show altered walls and small amounts of quartz, pyrite, and other sulphides. Most of the fissures appear to be of pre-mineral age.

Wisconsin—The Wisconsin adit (No. 87, pl. 1) is on the slope northeast of the mines in Sosthenes Gulch, at an altitude of 11,540 feet. The adit is apparently crosscut to the vein, which from surface indications appears to have a strike of about N. 20° E. The workings could not be entered, as the portal had caved. In contrast to the gangue of the Little Jennie and other veins near it, that of the Wisconsin vein, seen on the dump, is entirely quartz. The sulphides are mainly pyrite and sphalerite, with smaller amounts of galena and chalcopyrite. Quartz and pyrite were deposited early in the vein-forming stage and were followed by chalcopyrite and galena, deposited interstitially to the quartz. Under the microscope the sphalerite is seen to contain minute specks of chalcopyrite, which were apparently deposited with it. The later chalcopyrite has replaced pyrite to some extent. The texture of the siliceous ore is somewhat vuggy or banded, but none of the vugs were seen to contain carbonates.

[6] Burchard, H.C., op. cit. for 1882, p. 541, 1883.

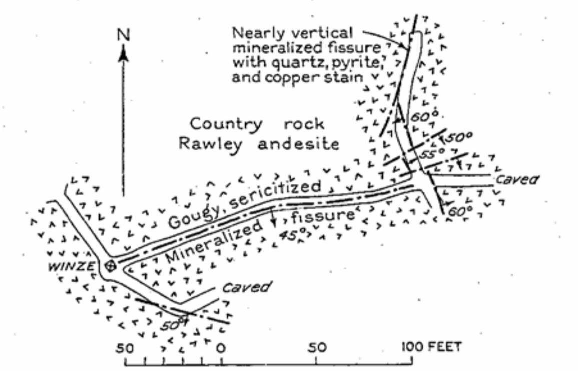

Figure 31. – Sketch map of the Vallejo tunnel.

ANTORO MINE

HISTORY AND PRODUCTION

The Antoro mine, owned by the Antoro Mines Co., lies north of Rawley Gulch adjacent to the property of the Rawley mine. The company controls 14 claims in the vicinity of the Antoro tunnel. Including the Antoro tunnel there are about 4,200 feet of drifts and crosscuts, with a shaft 550 feet in depth and a winze of 125 feet. Several veins are developed by the workings, including the Antoro vein proper.

The Antoro vein itself was discovered early in the history of the district. Burchard[7] states that in 1882 the Antoro vein was developed by four shafts from 20 to 60 feet in depth. Pockets in the walls of the vein near the surface are said to have been impregnated with native silver. The only year before 1900 for which data of the production are given is 1891.[8] During that year the Antoro produced $1,680 in silver and $522 in lead. In 1887 and 1888 the mine is reported as not producing. The early production was evidently intermittent, although Patton[9] gives an estimate of 1,000 tons of ore between 1881 and 1900. The production since 1900 has also been intermittent. The long Antoro adit was completed to the Antoro vein about 1910 or 1911 and was connected to the surface by an inclined raise. Between 1908 and 1927 about 1,400 tons of ore was produced from the several veins. There is some zinc-lead ore suitable for milling on the Antoro dump, which lies at the portal of the tunnel.

MINE DEVELOPMENT

The portal of the Antoro adit is at an altitude of 11,267 feet on the slope about 1,300 feet north of Rawley Gulch. There are about 4,000 feet of crosscuts and drifts on this adit level. (See pl. 31.) About 170 feet from the portal a winze 125 feet deep has been put down on a nearly vertical vein. At least three other veins and possibly several more smaller ones are cut by the workings. The Antoro vein, the Poverty vein, and the Zinc vein have received the most development. Another vein has been followed at a position about 400 feet from the portal. These workings have caved, but one drift is about in line with the Northeast vein developed by the winze. On the adit level the Poverty vein is the only one that has been stoped to any extent. The adit level is connected through to the surface by a 550-foot raise. (See fig. 32.) The Antoro vein is developed for about 500 feet on the adit level and for about 350 feet

[7] Burchard, H.C., op. cit. for 1882, p. 542, 1883.
[8] Smith, M.E., op. cit. for 1891, p. 184, 1892.
[9] Patton, H.B., op. cit. 68.

on the "114 level," which is about 114 feet above the adit level. The "200" level is 200 feet above the adit level and approximately 320 feet below the surface but has only about 30 to 40 feet of drifts.

GEOLOGIC FEATURES

All the workings of the Antoro mine are in the Rawley andesite, the upper levels and outcrop of the Antoro vein being in the upper latite member. The lava flows on the surface appear to have a strike somewhat west of north and a dip of 15°-20° W. The dips of the flows are much less steep here than 2,000 or 3,000 feet west of the mine. By allowing for the intervening lavas which have been eroded from above the vein outcrop but which overlay the andesite during the time of ore deposition, the present workings on the Antoro vein may be estimated as ranging within 200 to 600 feet below the base of the Bonanza latite.

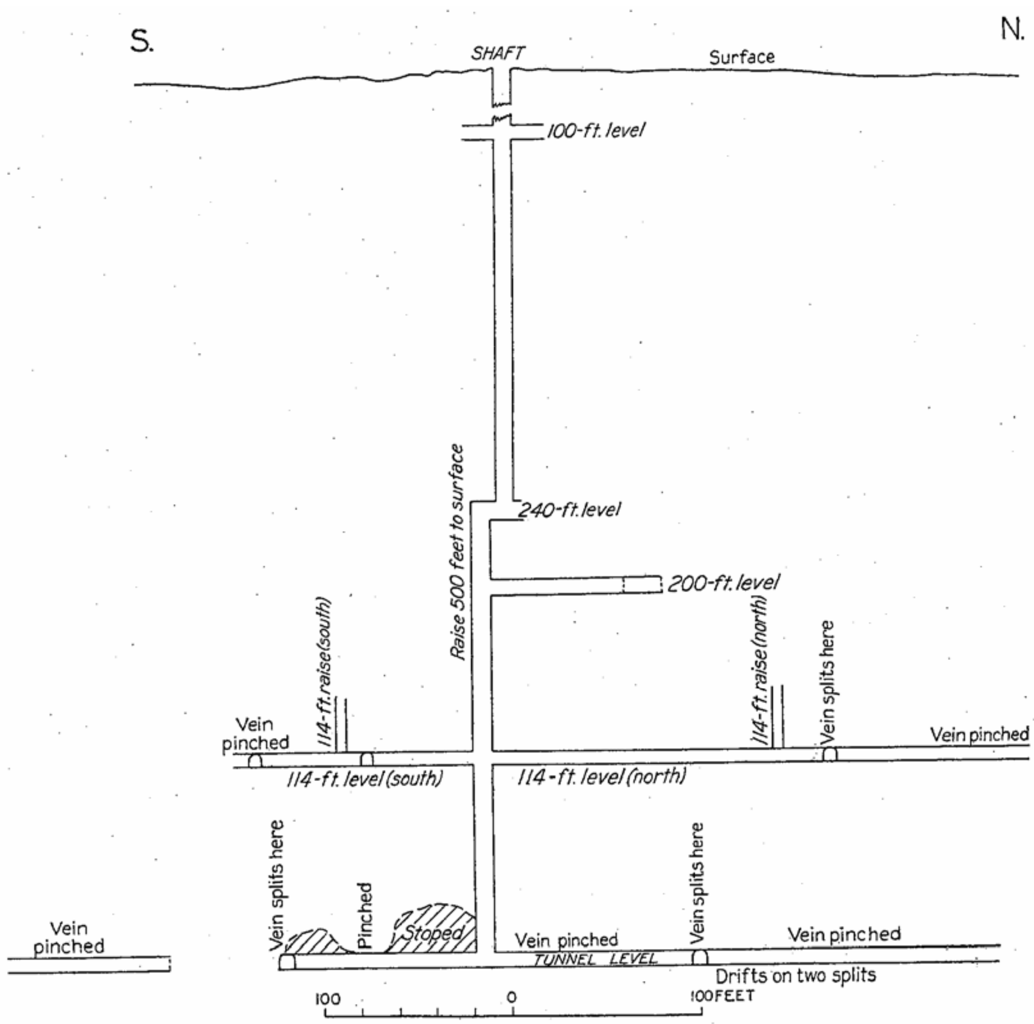

Figure 32. – Longitudinal section of drifts on the Antoro vein, Antoro mine.

On the main Antoro adit level the Rawley andesite is very much broken by faults, and it is in several of these fault fissures that the larger veins occur. Practically all the faults show some effects of mineralization, either by their altered gouge or by the presence of small amounts of sulphides, particularly pyrite or sphalerite. No postmineral faults of any consequence were found. The fault of greatest displacement is apparently the Poverty fault, in which the Poverty vein occurs. This fault has an average strike of N. 65° W., but the fault plane is somewhat curved and concave toward the north and dips 28°-35° N. The fault is accompanied by heavy gouge and some strong breccia zones, but, as is typical of all the low-angle faults in the district, the mineralization was very irregularly distributed.

The Antoro vein also occupies a fault fissure, as is shown by the different bodies of andesite that form the hanging wall and footwall at the south end of the "114 level." The Antoro fissure has an average strike of N. 25° W. and dips 65°-85° E. The average dip is probably 80°-85°, although the fault plane is warped irregularly, and both the strike and dip have a moderate range. At the surface near the Antoro shaft the vein crops out in the upper latite member of the Rawley andesite.

ANTORO VEIN

The Antoro vein proper is exposed at the north end of the mine workings. It strikes north and dips about 70° E. The gangue in the vein is largely quartz but is composed partly of barite and calcite. The sulphides that have been recognized in the ore are pyrite, sphalerite, galena, chalcopyrite, and tennantite. Some secondary chalcocite was present in the small vertical vein in the hanging wall near the adit level. This was probably of local distribution near some watercourse. The vein in the raises 25 feet above the "114 level" shows no evidence of alteration by surface water. Oxidized ore is said to extend from 75 to 120 feet below the outcrop of the vein.

For a distance of about 240 feet on the "114 level" the vein has an average width between 2 and 2.5 feet and carries about 5.5 ounces of silver to the ton, 8 percent of lead, and 8 percent of zinc, as indicated by mine assays. Copper is low, assays showing from a trace to 1.8 percent. The gold content of the vein is also low, ranging from negligible amounts to 0.02 ounce to the ton. In the 114 north raise the vein for about 25 feet above the drift level averages 3½ feet in width and as indicated by samples carries about 6.5 ounces of silver to the ton, 18 percent of lead, and 8.3 percent of zinc.

The vein has been followed by drifts for only about 60 feet on the 200 level north. It has an average width here of about 1.6 feet and carries 4 ounces of silver to the ton, about 9 percent of lead, 9 percent of zinc, and 0.5 percent of copper.

Along the main adit level the Antoro fissure is filled with a strongly sericitized gouge and is relatively tight and weakly mineralized. The vein could be examined for only about 100 feet north of the main raise, as the adit level was partly caved and filled with water. The Antoro vein is also exposed in a drift about 100 feet in length which branches north from the east-west drift on the Poverty fissure. The vein is also weakly mineralized in this drift and dips about 65° E. The relation between the Antoro fault and the Poverty fault could not be determined, as the Poverty fault passes into the south wall of the east-west drift where the two fissures meet.

About 100 feet south of the main raise, near the turn in the adit level, a small fracture in the hanging wall of the Antoro fissure has been explored. This fracture strikes N. 50° W. and dips 70° E. and presumably is a small transverse tension fracture formed in the hanging wall of the Antoro fissure. A narrow body of black sulphide ore has been stoped along this branch vein for about 20 feet upward. (See fig. 32.) The ore is partly enriched by secondary chalcocite.

On the "114 level" north of the main raise the Antoro fissure splits into two fissures, which appear to terminate against a premineral cross fault striking N. 40°–50° W. and dipping 75°–85° SW. Too little exploration has been done beyond this cross fault to determine whether this is the limit of the Antoro ore shoot. Conditions similar to those revealed on the main adit level north of the raise were probably found here but could not be examined because of a cave in the level. At the north end of the "114 level" the Antoro vein is better mineralized than on the main adit level but pinches down somewhat near the cross fault. Near the split the vein is about 18 inches in width and carries 8 ounces in silver to the ton, 15 percent of lead, and about 7.5 percent of zinc. About 150 feet north of the main Antoro raise there is a 30-foot raise on the vein which exposes about 30 inches of good-grade ore at the top. The vein in this raise is about 3 feet wide and has an altered gouge on its handling [hanging] wall. The structure of the vein in the raise is vuggy, with quartz and galena crystals lining the vugs. The gangue consists mainly of quartz but partly of barite and carbonate. About 30 inches of the vein at the top of the 30-foot raise shows a content of 22.5 percent of lead, 4.4 percent of zinc, and 9.5 ounces of silver to the ton. Both walls of the vein are much altered; sericitization is evident in both, but the footwall is the more strongly silicified. At the foot of the raise in the drift the vein matter is more massive and less vuggy, but there is about 1 to 1½ feet of loose altered gouge on the hanging wall. This gouge extends all along the north drift and has a tendency to slump into the drift, necessitating timbering most of the way.

In the "114 drift" south of the main raise the vein lies between pyritized walls and is well mineralized for a distance of 70 feet, to a small raise. The vein in the upper end of this raise appears similar in character to that in the north raise and is about 2 feet thick. Beyond this raise to the south the vein becomes nearly vertical and pinches to a narrow barren fissure filled with altered gouge. The fissure continues barren to the end of the south drift. There are several parallel fractures in both walls, but they are not mineralized.

As far as present developments show the ore body is about 240 feet in length, extending possibly 50 feet below the "114 level" and an undetermined distance above. How much of this body has been mined above the "114 level" is not known, as the old workings are not accessible, but the early production was small. Although the fissure is tight on the main adit level, the mineralogic character of the ore just above the level does not indicate that the bottom of mineralization has been reached. Should the vein widen below the adit level within the next few hundred feet, there might be additional bodies of zinc-lead ore or of copper-silver ore. The intersection with the Poverty fissure should also be reached within a vertical depth of 200 feet in the vicinity of the shaft, providing the two fissures hold their dip as exposed on the adit level. Although the ore body developed by the present workings is small, the amount of work done is insufficient to show its full extent. It is presumably limited, however, on the north and south by the cross fissures mentioned.

POVERTY VEIN

The Poverty vein occupies a low-angle fault dipping northeastward toward the Antoro fissure. The two veins intersect east of the main adit level, but the intersection is not exposed in the drift. Near the inter-section both veins are only weakly mineralized. The strongest mineralization in the Poverty fault occurred near the end of the west drift. A small body of high-grade lead-silver ore has been mined from the stope shown on the map. Shipments direct to the smelter amounting to 730 tons showed an average content of 32.3 percent of lead, 0.6 percent of copper, and 8.9 ounces of silver and 0.012 ounce of gold to the ton. The zinc is said to have averaged 4 percent or less in the ore that was shipped. The stope pinched at the east end but at the top showed 10 to 26 inches of ore which assayed from 3 to 7 ounces of silver to the ton, 8.5 to 25 percent of lead, 0.2 to 5.0 percent of copper, 2.4 to 6.0 percent of zinc, and 7 to 11 percent of iron. The data regarding the stope are based upon assay maps, as the stope could not be entered because of bad air. In the relatively high lead content and the low copper content this ore agrees with the ore of the Antoro vein as indicating that the bottom of the zone favorable to ore has not been reached. Ore bodies in flat veins such as the Poverty are likely to be very irregularly distributed, however.

ZINC VEIN

The Zinc vein is a north-south vein exposed by a crosscut east of the main adit level. It can be traced for about 160 feet in the drifts. It dips about 65° E., and the strike turns somewhat to the northeast in the north drift. It cannot be definitely stated whether or not this is the continuation of the Antoro vein until more development work has been done. The vein runs much higher in iron and zinc than either the Antoro or the Poverty vein, and this mineralogic difference, in conjunction with its strike in the north drift, suggests that it is not a direct continuation of the Antoro vein. It may, however, be another part of the Antoro fissure which has been displaced by pre-mineral movement on the Poverty fault. The vein is from 1 to 4 feet thick, averaging around 2 feet, and contains about 8 percent of lead, 13 percent of zinc, a trace of copper, and about 19 percent of iron. The silver assays range from less than 1 ounce to 9 ounces and average a little over 2 ounces to the ton.

At the south end of the drift the vein pinches and terminates against a fault plane striking N. 85° E. and dipping about 70° S. In the north drift the vein is only a foot or a little more thick and pinches near the breast of the drift. The gangue of the vein is siliceous, and it appears too narrow and too high in iron and zinc to encourage stoping.

NORTHEAST VEIN

About 170 feet from the portal of the main adit level a winze has been sunk 125 feet on a steep vein. The winze was filled with water, but from what could be seen near the adit level the vein strikes about N. 30° E. The winze is said to be nearly vertical. The gangue consists of hard, dense quartz containing pyrite and chalcopyrite,[10] and the vein matter is said to be 18 inches wide at the bottom of the winze. This vein is in line with and about 300 feet northeast of the split in the Rawley vein on the 300-foot north level of the Rawley mine. Mr. John E. Ashley, superintendent of the Antoro property, very reasonably considers the fissure in the winze to be a continuation of the east split of the Rawley fissure. According to him, the northeast vein carries about 2 percent of copper and has a good silver content. A vein of similar strike was apparently drifted on about 400 feet from the portal of the main adit, but these drifts were caved and could not be examined.

MICHIGAN AND PARAGON MINES

DEVELOPMENT AND PRODUCTION

The Michigan and Paragon properties (Nos. 54, 61, 62, and 63, pl. 1), which are owned by the Antoro Mines Co., have been developed on two veins on the north side of Rawley Gulch above the Rawley mine. The Paragon vein is in a fault that follows approximately the course of Rawley Gulch and is the large fault that is encountered in the Rawley mine. It has an average strike of N. 80°-85° E. and dips 55°-60° S. The Michigan vein has been found only north of the Paragon. It strikes N. 20°-25° E. and dips 45°-58° SE. The Michigan and Paragon veins intersect on the north side of Rawley Gulch, where the Michigan vein apparently terminates — at least it has never been recognized in the south or hanging wall of the Paragon fault.

The Michigan vein workings, which include a shaft on the vein at an altitude of 11,460 feet and two tunnels below the shaft, were operated during the early history of the district, and all are now inaccessible. The known extent of the Michigan tunnels is shown on Plate 1. It is estimated that about 700 tons of ore was taken from this vein.[11] In 1888[12] the Michigan produced $5,337 in silver and $8,253 in lead, and in 1890 $1,337 in silver and $2,471 in lead, making a total for these two years of $17,398. The production between 1881 and 1900 given by Patton[13] is $24,500. The production of $17,398 represents about 5,170 ounces of silver and

[10] Patton, H.B., op. cit., p. 89.
[11] Idem, p. 90.
[12] Munson, G.C., Report of the Director of the Mint upon the production of the precious metals in the United States, 1888, pp. 120, 121, 1889.
[13] Patton, H.B., op. cit., p. 68.

246,000 pounds of lead and would indicate on 500 to 700 tons of ore that the ore averaged from 8 to 10 ounces of silver to the ton and 20 to 25 percent of lead. The early shipping ore is said to have been oxidized and to have contained lead carbonate. There has been little or no production from the Michigan vein since 1900 except for a few tons of ore shipped from the vein where it is exposed in the Paragon No. 2 tunnel.

The Paragon vein was also developed to a slight extent in the early eighties. In 1884[14] the Paragon had shipped a small quantity of ore which was concentrated by hand jigs in use at the Empress Josephine. This ore was apparently unoxidized sulphide containing pyrite, sphalerite, and galena and was valued at $35 to $45 a ton. In 1887[15] the Paragon produced $625 in gold and $2,000 in silver, presumably from enriched ore. No other records of production prior to 1900 are known. There are also no records of production between 1900 and 1916, but from 1916 to 1927 about 500 tons of ore was taken from the Paragon tunnels in Rawley Gulch. About 30 tons of this ore came from the Michigan vein.

GEOLOGIC FEATURES

A geologic plan of the Paragon No. 2 tunnel giving the extent of development in October, 1926, is shown in Figure 33. The Paragon fault zone in the No. 2 tunnel consists of a series of mineralized fractures which have a general easterly strike and a southerly dip. Near the portal of the tunnel the Paragon fault zone consists of three nearly parallel fault planes with about 30 to 50 feet of broken and silicified or bleached andesite between them. They strike N. 50°-70° E. and dip 50°-55° SE. A small stope was being worked in the northwestern vein in 1926. The stope was up about 20 feet above the drift, on a narrow body of black sulphide ore containing some secondary copper sulphides. Altered gouge lay between the altered sulphide ore and the hanging wall. The hanging wall consisted of bleached and pyritized porphyritic andesite, which was partly crushed. There were also a small stope and two inaccessible winzes along the main Paragon fault in the drift. The crosscut southeast of the drift exposes an altered and broken zone beyond which there is a third fault plane. About 250 feet from the portal these fault planes appear to be displaced by an east-west fault dipping 55°-70° S. The east-west fissure is irregularly mineralized, but a few small lenses of tennantite (gray copper) ore have been uncovered. The drift continues on the east-west vein for about 150 feet from the intersection and then encounters a northeasterly fault which may be part of the Paragon fault. It appears that the east-west fissure has caused a horizontal displacement of about 150 feet. The N. 60° E. fissure contains an 8-foot vein mainly of quartz, manganocalcite, pyrite, and sphalerite just under the footwall of the east-west fault. The vein is not of high grade, however, and has a very low lead content. For the remainder of the tunnel the Paragon fissure is only weakly mineralized and turns into a nearly east-west strike.

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[14] Silver, Herman, Report of the Director of the Mint for 1884, p. 239, 1885
[15] Munson, G.C., idem for 1887, p. 181, 1888.

On the whole the mineralization in the Paragon fault zone was scattered, and only one small shoot has been stoped to any extent. The position and approximate limits of this stope, which was not accessible, are shown in the section, Figure 33. The Paragon vein where exposed for about 150 feet in the No. 2 adit shows a width ranging from 12 to 48 inches and averaging about 30 inches. Assays show from 1 to 6 percent of lead, 1 to 8 percent of copper, and 13 ounces of silver, and 0.05 ounce of gold to the ton. The assays average about 3 percent of copper and 2 percent of lead. Data on the zinc content are not available, but the vein, as a whole, probably contains at least one and one-half times as much zinc as lead. An average of about 375 tons of crude ore shipped from the Paragon mine gives 7.2 percent of lead, 2.3 percent of copper, and 12.2 ounces of silver and 0.08 ounce of gold to the ton. The N. 80° W. vein contains from 8 to 30 inches of vein matter in streaks. This assays about 1.0 percent of lead, 1.0 percent of copper, and 6.8 ounces of silver and 0.016 ounce of gold to the ton. Small pockets and streaks of ore from 8 to 12 inches in width containing considerable tennantite (gray copper) gave very high silver assays. This ore consists of pyrite, tennantite, and chalcopyrite with some quartz, galena, and sphalerite. The tennantite and chalcopyrite are in part very intimately intergrown, as shown by the microscope.

Small shipments of siliceous silver ores from the Paragon vein ran about 3 percent of lead, 1 percent of copper, and 18 ounces of silver and 0.20 ounce of gold to the ton. The iron content ranged from 8 to 18 percent and the silica from 48 to 60 percent.

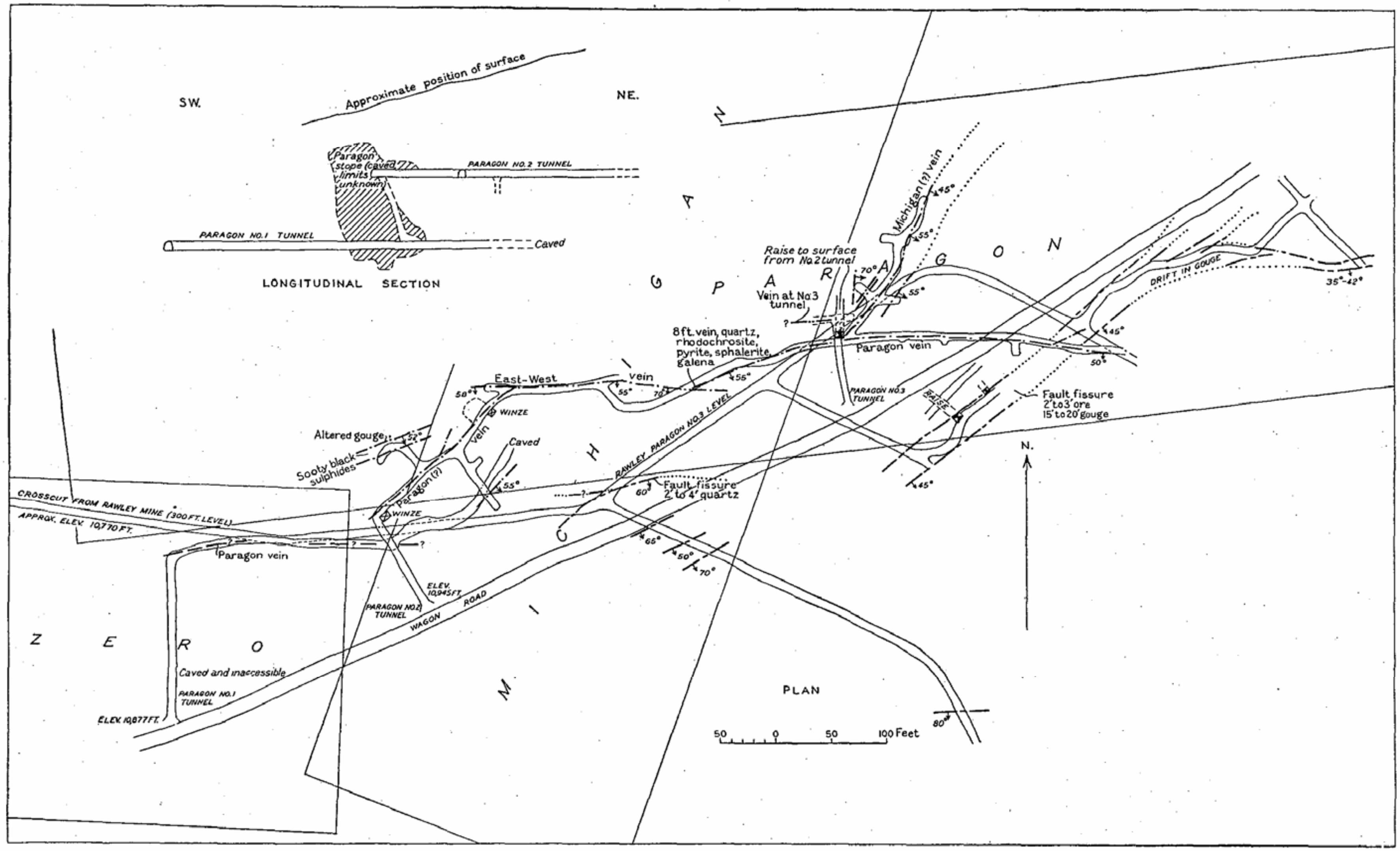

Figure 33. – Plan and longitudinal section of workings of the Paragon mine.

The Michigan vein is encountered in the footwall of the Paragon fault about 550 feet from the portal of the tunnel. It has been explored by a drift for about 150 feet. Near its intersection with the Paragon the Michigan vein is in a complex fissure zone 30 feet or more in width. Several parallel veins are shown by one crosscut. The gangue of the veins is made up of vuggy quartz, pinkish manganocalcite, and some jasper. The jaspery material is of earlier formation than the vein quartz and sulphides and represents a replacement of the original andesitic wall rock by silica. On the whole this part of the Michigan vein is essentially a zinc vein with a minor amount of lead. The sulphides recognized are pyrite, sphalerite, tennantite, and galena. There is an altered gouge on the hanging wall of part of the vein. At its intersection with the Paragon the mineralized part of the Michigan fissure turns sharply, paralleling the strike of the Paragon, but shows little evidence of being faulted by the movement on the Paragon fault. The evidence indicates that both fissures are of premineral age. The amount of displacement on the Paragon fault could not be accurately determined at any position along its outcrop, but about 2,000 feet west of the Rawley fissure, where it faults down a block of the Bonanza latite, the displacement down the fault plane (dip slip) is certainly in excess of 500 feet and may possibly be 1,000 feet. The displacement probably decreases toward the east, so that the movement on the fault plane has been in part one of rotation. The amount of displacement at the point where the Michigan vein joins the Paragon cannot be stated, but it is possibly less than 500 feet. Because of its dip the Michigan fissure, if it is present in the hanging wall, would probably have been displaced toward the west in the hanging wall of the Paragon, but it has not been definitely recognized in any of the workings. The deeper exploration of the Rawley mine also failed to find any vein corresponding to the Michigan in the hanging wall of the Paragon fault. Very little ore has been mined from this part of the Michigan vein, but one small shipment contained 8.9 percent of lead, 2.9 percent of copper, and 9.1 ounces of silver and 0.03 ounce of gold to the ton.

OTHER WORKINGS ON THE PARAGON VEIN

There are numerous other small workings and prospect tunnels on the Paragon vein, above the Paragon mine along Rawley Gulch. The largest of these are the Ashley tunnel, the Great Mogul tunnel, and the Rainbow tunnel. All the data that are available regarding the length and direction of these workings are shown in Plate 1 and Figure 34. The Ashley tunnel was driven on the Paragon fissure, but the first part of the Great Mogul tunnel is a crosscut. The two tunnels are connected by a winze, the position of which is not known, as neither tunnel was accessible. The Rainbow tunnel was open as far as the Paragon fissure, but the drift on this fissure was not accessible. There is said to be 450 feet of drift from this tunnel in a direction about N. 85° E. from the end of the crosscut. The fissure contains parallel, stringers of quartz and dips 60° S.[16]

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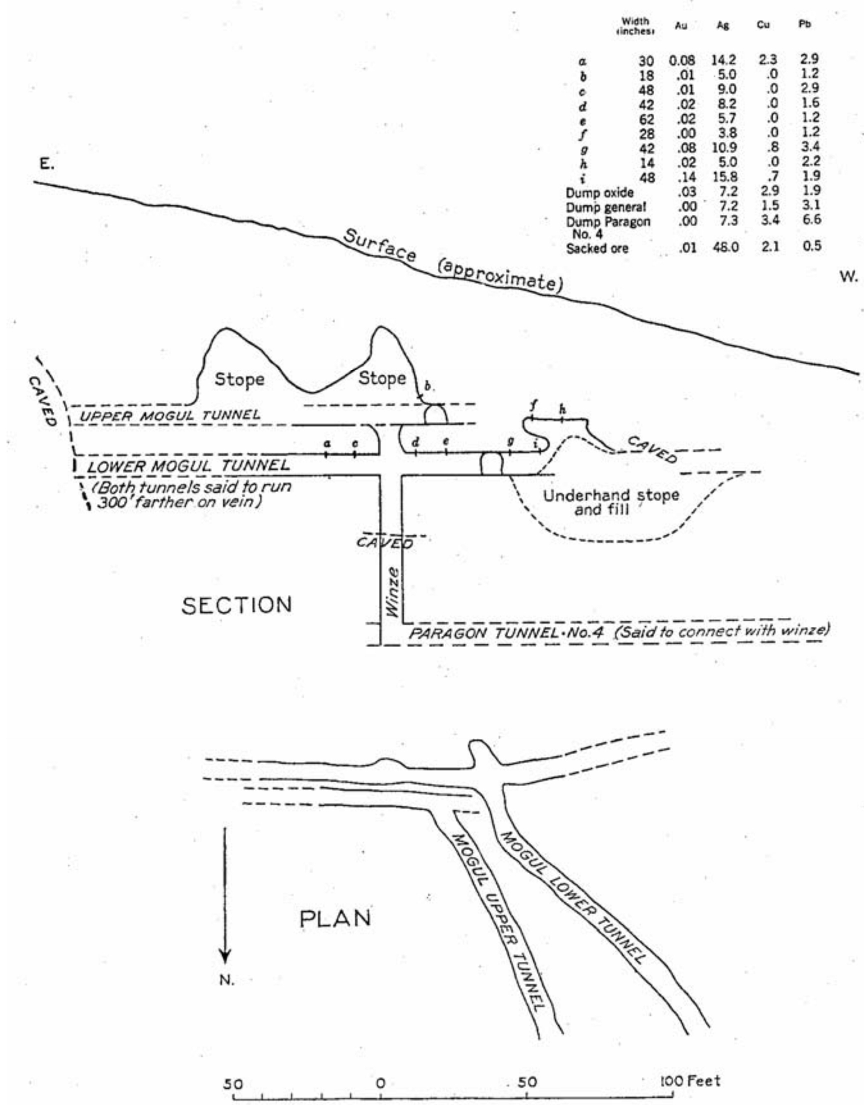
[16] Patton, H.B., op. cit., p. 92.



	Width (inches)	Au	Ag	Cu	Pb
a	30	0.08	14.2	2.3	2.9
b	18	.01	5.0	.0	1.2
c	48	.01	9.0	.0	2.9
d	42	.02	8.2	.0	1.6
e	62	.02	5.7	.0	1.2
f	28	.00	3.8	.0	1.2
g	42	.08	10.9	.8	3.4
h	14	.02	5.0	.0	2.2
i	48	.14	15.8	.7	1.9
Dump oxide		.03	7.2	2.9	1.9
Dump general		.00	7.2	1.5	3.1
Dump Paragon No. 4		.00	7.3	3.4	6.6
Sacked ore		.01	46.0	2.1	0.5

Figure 34. – Plan and longitudinal section of the Mogul tunnel levels.

According to Patton[17] there has been some slight production from the Great Mogul (First Chance), but there has been no production from the Rainbow so far as is known.

WHALE MINE

The Whale mine (No. 82, pl. 1) is on the slope south of Rawley Gulch nearly opposite the Rawley mine. The mine was worked through several adits and shafts, which were all inaccessible in 1926 and 1927.

The production for four years according to mint reports is shown in the accompanying table. The value of the ore during these years lay mainly in silver and

[17] Idem, p. 91.

copper. According to an estimate by Patton[18] the mine had produced 2,000 tons of $50 ore up to 1893, but authentic records of the total production are not now available. It is evident, however, that the production is considerably greater than that shown by the records of only four years given by the mint reports, as the mine was one of the larger early producers in the district. In his report for 1881[19] Burchard says: "The Whale has been a regular producer of ore, and the returns have been satisfactory to the owners." In the report for 1882[20] he says:

The Whale has been a large producer of ore. The shaft is down 100 feet and drifts run in both directions. The south drift is 35 feet, and the north 45 feet, and in this drift the mineral streak shows a body of ore 5 feet in width that has milled 149 ounces of silver and 10 percent copper. A tunnel is being run that when completed will cut the vein at a depth of 250 feet.

Partial record of value of metals produced at the Whale mine, 1887–1891[a]

Year	Gold	Silver	Lead	Copper	Total
1887	---------	$2,727	$678	----------	$3,405
1888	$100	3,233	-----------	$1,508	4,841
1890	---------	2,068	-----------	278	2,346
1891	---------	16,161	2, 175	3,300	21,636
	100	24,189	2, 853	5,086	32,228

[a] From reports of the Director of the Mint. No individual records of the production given for the district for 1889. Gold value, $20 an ounce; silver (coinage value), $1.29 an ounce; lead, $87 a ton; copper, $240 a ton.

The lowest adit to the Whale vein is about 10,900 feet above sea level and about 100 feet west of the old road from Rawley Gulch to the Superior-Erie mine. It was bulkheaded and filled with water at the time of examination and so could not be entered. Above it on the road is another caved adit which probably crosscuts about 300 feet to the vein. The Whale vein strikes a little east of north and is probably almost vertical. In the patent records on the Whale claim, No. 7228, the vein is said to have been stoped for about 300 feet north of a crosscut adit at the time the survey was made, in 1891, although the drift was then inaccessible. This old adit is said to have crosscut 151 feet to the vein, but its portal is now entirely caved in and covered. The discovery shaft was said to be 150 feet deep in 1891, but it is believed to have been connected later to the 300-foot level by a raise.

No data as to the average metal content of the Whale vein could be obtained. According to Patton,[21] most of the valuable ore was shipped from the upper

[18] Patton, H.B., op. cit., pp. 68, 92.
[19] Burchard, H.C., Report of the Director of the Mint upon the production of the precious metals in the United States, 1881, p. 427, 1882.
[20] Burchard, H.C., idem for 1882, p. 543, 1883.
[21] Patton, H.B., op. cit., p. 92.

workings, in which the metal content of the vein was mainly lead and silver. According to Mr. L. W. Sharpe, of Bonanza, the upper 50 to 100 feet of the Whale vein was an oxidized and enriched copper-silver ore, containing green copper carbonate. This ore assayed 100 to 140 ounces of silver to the ton and 8 to 12 percent of copper, with a little gold. Toward the north and on the lower levels (300 foot±) the vein split and became very wide. In these lower workings the metal content according to Mr. Sharpe was a complex zinc-copper-lead ore of low grade. It is not known how much stoping was done from the lower adit levels, but the output of 1888, 1890, and 1891 presumably came from the upper part of the vein, to judge from the relative values of lead and copper. Data as to the character and width of the vein in the lower workings are meager, but the vein appears to be worthy of consideration in explorations for additional bodies of low-grade ores in the district.

HANOVER MINE

The Hanover mine is west of the Whale, on the mountain slope south of Rawley Gulch. The Hanover vein is developed through an adit and an inclined shaft (Nos. 34 and 35, pl. 1). The Hanover property includes the Erie and Hanover claims, which are at present owned by Messrs. Buck & Sharpe, of Bonanza. In the mint report for 1891[22] the Hanover is credited with a production of $581 in silver and $696 in lead. Details of the production for other years are not known. A production of a few tons was made under lease in 1921. An estimate of 700 tons of ore produced prior to 1900 is given in the report by Patton.[23]

The Hanover tunnel is about 10,860 feet above sea level, and according to the patent survey made in 1900 runs due south for 250 feet. At a point 200 feet from the portal there is a winze sunk 140 feet to the east at a pitch of 35° and a 100-foot raise west of the tunnel and on the same pitch. There may have been a small amount of additional work in this tunnel since the patent survey was made. The Hanover vein apparently has a strike of south to S. 25° E. and a dip of 28°-35° E. The Hanover inclined shaft is about 300 feet south of the portal of the tunnel at an altitude of 10,880 feet. A plan of this incline taken from an assay map is shown in Figure 35. This plan perhaps does not represent the full extent of the workings, as the date of the map is not known.

[22] Smith, M.E., Report of the Director of the Mint upon the production of the precious metals in the United States, 1891, p. 184, 1892.
[23] Patton, H.B., op. cit., p. 93.

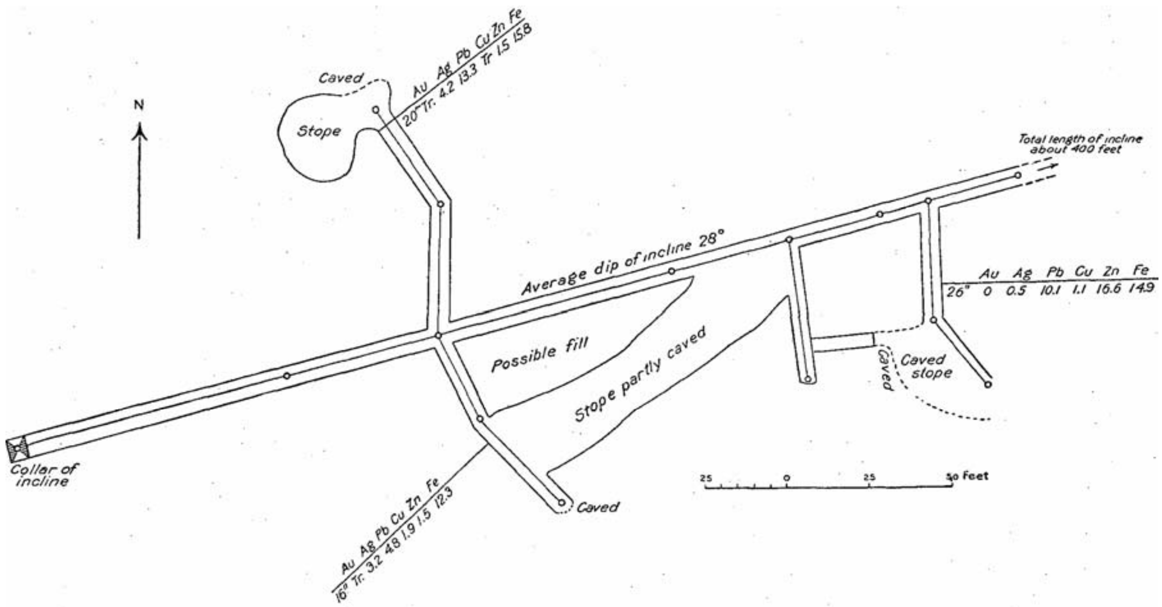


Figure 35. – Plan of the Hanover incline.

The country rock of the Hanover mine is entirely andesite. The ore consists of pyrite, sphalerite, galena, chalcopyrite, and tennantite in a gangue of quartz and barite. Copper is subordinate to zinc and lead in the ore seen on the dump. The formation of the vein was preceded, as in many other fissures in the district, by silicification of the wall rock. Red jasper is included in some of the vein material and is fractured and veined with quartz and sulphides and partly impregnated with pyrite. The jasper has replaced the andesite country rock, as microscopic examination reveals faint but unmistakable relicts of the original porphyritic texture.

The only record obtained of the metal content of the ores is on a small shipment of 17 tons, which showed a gross content of about 3 percent of lead and 15 ounces of silver and 0.018 ounce of gold to the ton. The zinc content was sufficiently high to be penalized. Several assays of the vein in the Hanover incline show a width of 16 to 26 inches, with 5 to 13 percent of lead, from a trace to 2 percent of copper, 1.5 to 16 percent of zinc, and 3 to 5 ounces of silver and a trace of gold to the ton. The iron content ranges from 12 to 16 percent.

ERIE AND SUPERIOR MINES

The Erie and Superior mines are on the same vein and have been developed jointly for a number of years. The Superior shaft is on a spur of the ridge south of Rawley Gulch at an altitude of 11,184 feet. There are several adits on the Erie claim below and west of the Superior shaft (Nos. 23 and 79, pl. 1). The mine is accessible by wagon road from Rawley Gulch. The Superior claim is not patented but is apparently excluded from the patent applications of several later conflicting claims. The Superior is an old property and in 1881[24] was being actively developed. In 1882[25]

[24] Burchard, H.C., op. cit. for 1881, p. 427, 1882.

the shaft had been sunk to a depth of 100 feet, disclosing a 7-foot vein with 3 feet of ore on the footwall. In this year some lead and copper ore were taken from the vein and treated at the Bonanza smelter. In 1883[26] levels driven at depths of 70 and 140 feet showed a 5-foot vein with 22 inches of ore containing galena, gray copper, and pyrite, running 20 to 60 ounces of silver to the ton. In 1890[27] the production of the Superior is given as $1,202 in silver and $522 in lead. There is no record of the production for other years prior to 1902. An estimate of 700 tons of $40 ore between 1881 and 1900 is given for the Erie and Superior together in Patton's report,[28] but most of this tonnage is credited to the Erie mine. Between 1902 and 1927, ore known to be produced from the Erie and Superior properties is given in the accompanying table.

Production of the Erie and Superior mines, 1902—1927[a]

Year	Ore mines (dry tons)	Concentrates produced (dry tons)	Gross content of concentrates and smelting ore				
			Gold (fine ounces)	Silver (fine ounces)	Lead (wet assay, pounds)	Copper (wet assay, pounds)	Zinc (pounds)
1902 …………	100	-----------	5.00	3,000	35,300	4,800	---------
1903 …………	80	-----------	----------	2,960	2,100	70	---------
1904 …………	60	-----------	3.00	2,400	21,200	2,800	21,200
1905 …………	(b)	-----------	----------	---------	---------	---------	----------
1912 …………	90	11	1.19	247	15,100	1,180	----------
1917 …………	114	-----------	2.57	1,473	22,095	1,348	----------
1918 …………	69	------------	1.26	843	9,685	1,203	----------
1924 …………	18	------------	0.36	110	2,508	----------	3,688
1927 …………	[c]10	------------	----------	59	1,308	----------	250

[a]No production in years omitted from table since 1902. See text for production prior to 1902. Compiled from mine records of U. S. Geological Survey and Bureau of Mines.
[b]May be some ore included in Rawley mine production.
[c]To Rawley mill, probably from dumps.

There are two main adit tunnels on the Erie — the lower Erie tunnel, at an altitude of 10,882 feet, and an upper tunnel, at an altitude of 11,000 feet. Both are drifts on the vein. Only part of the lower tunnel was accessible in 1926. A geologic sketch of this part based upon a compass and pacing survey is shown in Figure 36. The Superior shaft is said to be dry and to require no pumping. It is vertical for the first 20 to 25 feet and dips about 60° below. It could not be entered, as the air was bad. A plan of the workings on the Superior shaft is shown in Figure 37, taken from an undated assay map.

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[25] Idem for 1882, p. 543, 1883.
[26] Silver, Herman, op. cit. for 1883, p. 404, 1884.
[27] Smith, M.E., op. cit. for 1890, p. 139, 1891.
[28] Patton, H.B., op. cit., p. 68.

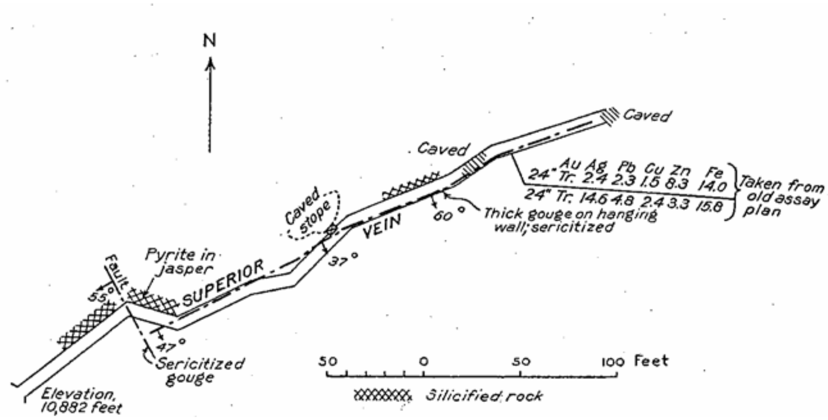

Figure 36. – Sketch map of the lower Superior tunnel.

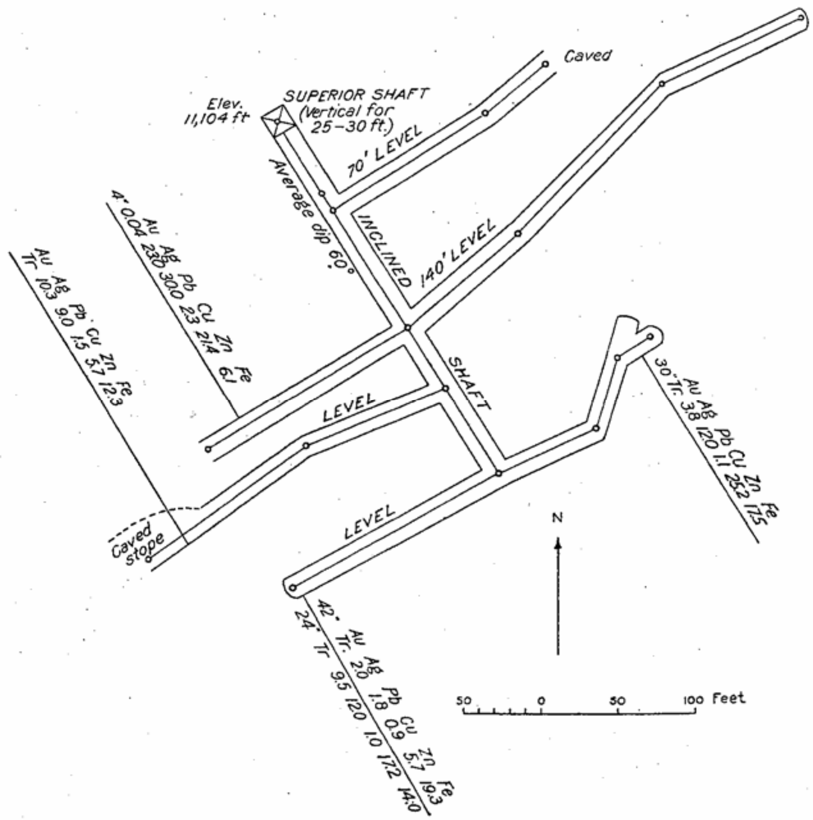

Figure 37. – Plan of the Superior-Erie mine.

The Erie and Superior vein lies entirely in Rawley andesite. The vein occupies a fault fissure that strikes about N. 60°-65° E. and dips 40°-60° S. and has brought the Superior member in the hanging wall opposite an amygdaloidal member in the footwall; but it is uncertain whether the fault is normal or reverse. Along parts of the lower tunnel the walls of the fissure have been intensely silicified and consist of reddish or white jaspery quartz partly impregnated with pyrite. The vein material is of later age than the silicification. An altered micaceous gouge occurs in places along the hanging wall, and next to this the hanging-wall andesite has been strongly decomposed and bleached to a whitish rock consisting of sericite, carbonates, chlorite, and quartz with some pyrite. Oxidation has affected the vein near the surface, and limonite and black manganese oxides have been deposited. In specimens of oxidized ore on the dump galena was the most abundant sulphide that remained partly unaltered, although it was largely altered to anglesite and cerusite. The primary ore minerals are pyrite, sphalerite, galena, chalcopyrite, and tennantite, which occur in a gangue of quartz, barite, and pinkish manganese-bearing carbonates.

Shipments of crude ore from the Erie and Superior show a gross content of 7 to 18 percent of lead, 0.6 to 3 percent of copper, 5 to 20 percent of zinc, and 5 to 40 ounces of silver and 0.017 to 0.05 ounce of gold to the ton. The average content was about 10 percent of lead, 1.5 percent of copper, and 21 ounces of silver and 0.025 ounce of gold to the ton. Mine samples of the vein show from 6 to 19 percent of iron, the average being about 15 percent.

MINES ON THE MINNIE LYNCH VEIN

The Minnie Lynch vein crops out on the ridge south of Rawley Gulch about a mile east of Kerber Creek. It is developed by three or four main tunnels and several shafts and cuts. The two upper adits at altitudes of 10,830 and 10,736 feet (No. 56, pl. 1) are on the Minnie Lynch property. The Paddy Doyle mine (No. 60, pl. 1), at an altitude of about 10,650 feet, is also on the Minnie Lynch vein but is a separate property. The production from this vein has been small.

The adits belonging to the Minnie Lynch mine were caved near the portals. The ore on the dumps is siliceous and contains considerable sphalerite. The other sulphides are pyrite, tennantite, and galena. Tennantite is fairly abundant and occurs in parts of the ore in a massive fine-grained aggregate of quartz, pyrite, and tennantite. Besides quartz the gangue contains some pinkish manganese-bearing carbonate. Very little of this, if any, contains sufficient manganese to be classed as rhodochrosite. According to Patton[29] the vein is from 3 to 5 feet wide, strikes N. 85° W., and dips 73° N. Small shipments of crude ore, from which the zincky material was apparently sorted out, to judge from the large proportion of sphalerite on the dump, showed a gross content of about 17 percent of lead, 1 percent of copper, and 0.091 ounce of gold and 33.8 ounces of silver to the ton.

A geologic sketch map of the Paddy Doyle adit on the Minnie Lynch vein is shown in Figure 38. The first 160 to 170 feet of the tunnel lies in broken Bonanza latite, which in this vicinity has an average northerly strike and a clip of 32°-40° W., which essentially coincides with the local surface of the hill slope. Underlying the latite in the tunnel are some breccias and fine-grained flows of the Rawley andesite. The contact between the andesite and the latite is practically a normal contact, as shown where the basal part of the latite is clearly exposed in the crosscut. The actual contact, however, has been slightly faulted by small breaks and is somewhat obscured by alteration. A. similar condition is encountered in several other small tunnels on the slope to the north and west, as the tunnels start in latite at the surface but soon penetrate the underlying andesite.

[29] Patton, H.B., op. cit., p. 93.

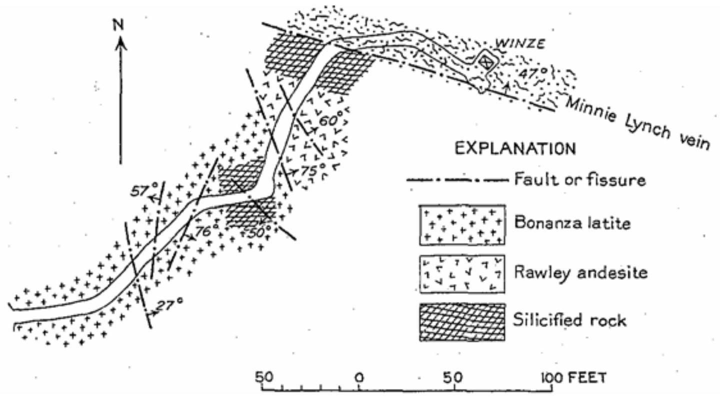

Figure 38. – Sketch map of the Paddy Doyle tunnel on the Minnie Lynch vein.

The Minnie Lynch vein is cut about 60 or 70 feet beyond the andesite-latite contact. In 1927 the vein was explored by a drift for about 90 feet, and a small winze was sunk 25 feet on the vein. Here the vein strikes N. 80° W. and dips about 45°-50° N. The character of the rock in the hanging wall could not be determined because of insufficient exploration and the decomposition of the wall rock near the fissure. The vein material occurs in a zone of shearing and alteration about 15 feet in width, which suggests that the fissure is a fault fissure. Mr. Dan Mahoney, who was working the property when it was examined, said that some assays of the vein material taken where the vein was first struck by the tunnel ran 100 to 150 ounces of silver to the ton. Where the winze was sunk the vein material was 2 feet wide, and the average content of the rock broken was about 8 ounces of silver to the ton. The silver is associated with gray copper (tennantite) ore. The volcanic rocks near the vein are altered to hard white silicified rocks or to a bleached greenish rock containing sericite, chlorite, and carbonates. Small shipments of crude ore from the Paddy Doyle show from 5 to 12 percent of lead and 9 to 30 ounces of silver and 0.02 ounce of gold to the ton. The copper content runs from 1 to 2 percent.

MINES ALONG COPPER GULCH

The mines along Copper Gulch (pl. 32) lie in a mineralized zone extending from the vicinity of the town of Bonanza northeastward for a little over 2 miles, although the greatest amount of development has been done in the lower part of the gulch. The veins of this area are similar mineralogically to those north of them, but several have a higher gold content than is common to other mines in the district, and in some of them small pockets of gold and silver tellurides have been found. The gold content of the ore shipped from the mines in this gulch averages from 0.02 to 1.2 ounces to the ton, but it is not at all consistent. The average gold content of the ores of the Bonanza district, not including those from Copper Gulch, is close to 0.01 ounce to the ton, as indicated by smelter recoveries since 1902.

Nearly all the workings in Copper Gulch are in andesite. For about a mile east of the town of Bonanza the andesite on both sides of the gulch is intensely silicified. Alteration of this type occurred commonly throughout the district but was particularly intense in this area, and in many places has made the determination of the character of the country rock a matter of some difficulty. Both reddish or brownish jaspers containing ferric oxide and white or gray jaspers are common. The jaspers are of earlier formation than the veins but are related in their distribution to the faults and fissures. Pyrite crystals are thickly embedded in some of the jaspers, but at the surface the pyrite has commonly been destroyed, leaving cavities in its place.

Most of the production from Copper Gulch has come from the Empress Josephine mine, although a small quantity of high-grade ore has been taken from the St. Louis mine. Other properties in this gulch are the Liberty, Glennbrook, Mariposa, Now What, Hortense, Cliff, and Queen City. Plate 1 shows the relative positions of some of the larger operations.

EMPRESS JOSEPHINE MINE
LOCATION

The Empress Josephine mine is on the north side of Copper Gulch a short distance northeast of the town of Bonanza, at an altitude of about 9,780 feet. It is accessible by a road up the gulch. The mine is owned by S. G. Everett, of Cleveland, Ohio. During 1926 and 1927 it was not being operated, and in the following discussion of the development and nature of the vein the writer has had to draw from the report of the Colorado Geological Survey and from information furnished by those familiar with the mine. The writer is especially indebted to Dr. R. D. George, of the State Geological Survey, and to Mr. Frank Leavitt, of Bonanza, for specimens of the telluride ores from this mine. Some data regarding the nature of the vein and the geologic occurrence of the tellurides were given by Mr. Leavitt and Mr. Dan Mahoney, of Bonanza.

HISTORY AND PRODUCTION

The Empress Josephine mine was developed early in the history of the district. Burchard[30] states that the Empress Josephine was perhaps the best developed mine in 1881. About 150 feet of levels had been run from the shaft, which was 180 feet deep. The daily output was 5 or 6 tons of ore, although no stoping had been done. Burchard states that the ore shipped yielded an average of $100 per ton. In his report for 1882,[31] he says:

*The Empress Josephine is one of the most valuable properties in the county. It is opened by a shaft of 210 feet in depth and three levels. The first level is now in 200 feet and is in a solid body of high-grade ore that will bear shipping without sorting. The second level is in 160 feet, also in high-grade ore. * * * Some of the richest ore yet encountered has been taken out of the 140-foot level, 100 feet east of the shaft. The ore in this level has shown a steady improvement, the streak on the footwall varying from 16 to 18 inches, consisting of galena of a high grade, with a 2-inch streak of antimonial silver on the hanging wall. Recently a marked change took place in the footwall streak, gray copper coming in with a 2-inch streak of silver glance, carrying native gold, which runs 36 ounces in gold and 22,000 ounces in silver per ton.*

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[30] Burchard, H.C., op. cit. for 1881, p. 426, 1882.
[31] Burchard, H.C., op. cit. for 1882, p. 540, 1883.

In 1883, according to Silver:[32]

The Empress Josephine mine is probably the largest producer in Saguache County. Machinery was erected during the summer, and the shaft, which is about 250 feet deep, will be sunk to a depth of 500 feet. From the shaft four levels run that aggregate 500 feet. The ore is a very high grade of gray copper and galena. The vein averages 10 feet wide; the pay streak 25 inches.

Up to 1884[33] the mine had produced more mineral than any other mine in the county. In the mint report for 1884[34] the following statements were made regarding the vein and the mine development:

*In the deep workings of the claim the ore is said to have changed from silver to gold bearing. The ore encountered was a form of telluride and was found near cross vein No. 2 in the second level. It lies in the casing immediately adjacent to the main pay streak and is 5 inches in thickness, associated with quartz. The telluride occurs in streaks through the quartz, varying from one-fourth to 1 inch in thickness, and is also scattered in pockets through the vein in crystallized form. The work now being done consists almost entirely in extending the east drifts at the different levels. * * **

Work has again been resumed in the first level. A streak of nearly 14 inches is exposed which carries large quantities of antimonial silver. The second level has reached a distance of 335 feet from the shaft. The rich telluride streak still continues, associated with 5 inches of quartz. In the third level the most favorable showing is at present disclosed. The pay streak, about 15 feet back from the breast, shows nearly 4 feet of ore, principally galena, associated with gray copper, assays of the best running from $150 to $300 per ton. The breast now carries a large streak of iron pyrites associated with brittle silver, yielding good returns.

The production for the three years for which data are given in the mint reports is shown in the accompanying table. Patton[35] estimates the production between the years 1881 and 1900 at 5,000 tons of $60 ore. Since 1909, 77 tons of ore has been shipped by lessees. (See table, p. 141, for some shipments of ore in 1908 and 1912.)

Value of metals produced at Empress Josephine mine, 1887, 1890, and 1891[a]

Year	Gold	Silver	Lead	Total
1887	$287	$2,181	--------	$2,469
1888	1,500	11,636	--------	13,136
1891	124	923	$71	1,118
	1,911	14, 740	71	16,723

[a]Value of gold, $20 an ounce; silver (coinage value), $1.29 an ounce; lead, $87 a ton; copper $240 a ton. No data on individual mines given for this district for 1889. Apparently no production in 1890.

[32] Silver, Herman, op. cit. for 1883, p. 404, 1884.
[33] Idem, pp. 238, 239.
[34] Idem for 1884, pp. 238, 239, 1885.
[35] Patton, H.B., op. cit., p. 68.

DEVELOPMENT

The Empress Josephine shaft is about 500 feet deep and follows the vein with a dip of about 85½° N. There are seven levels in the mine, but the length of drifts on some of them is not known. Regarding the condition of the upper levels in 1914 Patton[36] says:

*The first level has been apparently worked out and abandoned. Stopes from the second level have been broken through the floor of this level. * * **

The second level is developed east of the shaft only. It has not been completely worked out. A winze connects with the third level at about 270 feet from the shaft. At 350 feet the drift is blocked by a cave-in. At this point acid water enters the drift and attacks steel so vigorously as to require the laying of wooden rails. No timbering is required of the first two levels.

On the third level, which is developed on both sides of the shaft, some timbering is required. Stoping on this and on the fourth level has not been developed very systematically.

An incomplete stope map and section of the shaft and a plan of the third, fourth, fifth, and sixth levels is shown in Plate 33. Plans of the upper levels are not available. There has been no stoping on the third level beyond a point about 300 feet east of the shaft, where the Empress Josephine vein is sharply cut off by a fault.

GEOLOGIC FEATURES

Although the mine could not be entered, it is probable that the workings are largely, if not entirely, in the Rawley andesite. This is the rock which crops out in the vicinity of the shaft, and altered andesite flows and breccias are the only wall rocks that are found on the mine dump. A fault block of Bonanza latite crops out approximately along the strike of the vein about 200 to 250 feet west of the shaft, but this may not be reached by the west drifts.

The andesite and latite on the slopes bordering Copper Gulch in this vicinity are broken into a complicated series of block faults. Two predominating sets of faults can be recognized — a northeasterly set and a northwesterly set. A smaller number of faults strike nearly due east. Silicification and bleaching of the lavas along these fault planes have been very intense and in places have made the tracing of formation boundaries difficult. Because the jaspery rocks resist disintegration into soil the slopes bordering the gulch are strewn with their debris. Another type of decomposition of the lavas has resulted in soft bleached rock containing sericite and carbonates. As such altered rock disintegrates readily, the zones of sericitic alteration are in many places obscured by the heavy mantle of talus and soil on the slopes. The outcrops of andesite west and immediately east of the mine have been

[36] Patton, H.B., op. cit., p. 106.

intensely silicified and partly bleached. These types of alteration are described in a general way for the whole district on pages 20-34, where it is shown that the alteration which consisted in the formation of a soft rock containing sericite, chlorite, and carbonates was in most places, if not everywhere, later than that which produced the jaspery siliceous rock. The economic interest in these alterations lies in the fact that the siliceous type has preceded ore deposition, whereas the micaceous type has invariably accompanied it. As all the definitely recognized faults in the vicinity of this mine show one or both types of alteration, it is probable that the major faulting occurred either before or during the period of ore formation. It could not be determined from the distribution of rocks at the surface whether there had been any fault movement on the Empress Josephine fissure, but it seems very probable that the vein occupies one of the east-west series of fault fissures. The vein strikes about N. 75°-80° E. and dips about 85° N. According to Patton[37] the strike and dip of the vein have a considerable range in the workings. He states that the vein is cut by several faults, most of which are marked by a strong clay gouge, but that only one of these displaces the vein more than a few feet.

Although the writer has not seen these cross fissures in the Empress Josephine mine, the Now What and Hortense mines are both developed on similar east-west mineralized fissures. Most of the cross faults in the Now What mine cut obliquely across the Now What fissure and have displaced it a few feet at several crossings. The vein matter, however, has not been much disturbed by the formation of the cross fissures and at some crossings is noticeably wider, usually in the footwall of the cross fissure. The writer was informed by Mr. Leavitt that the Empress Josephine vein was richer in the vicinity of these cross faults, which cut across obliquely and displace the main fissure from a few feet to 15 or 20 feet. The vein was not only wider but yielded higher assays in the parts underlying the fault planes. Regarding the ore shoots Patton [37] says:

The ore values in the Josephine vein are very unevenly distributed. The ore occurs in shoots that are about 25 to 30 feet in breadth (in one case 100 feet) and that run from at or near the surface down to the 400-foot level and probably farther. These ore shoots have a pitch to the east, in conformity with a series of faults that also pitch to the east. The shoots are often bounded on one or both sides by these faults.

The relation of silicification to the fissuring in the Josephine mine is not known, but along the Now What fissure there was an early period of siliceous alteration, whereas most of the cross fissures are characterized by altered micaceous gouge and bleached wall rock. These relations may be interpreted to show that the east-west fissures, such as the Empress Josephine, Now What, and Hortense were first formed and that the earliest mineralizing solutions silicified their walls. Continued adjustments of the fault blocks during the period of alteration and mineralization caused these fissures to be displaced slightly by the formation of a series of oblique fractures. If these fault fractures were formed just before or even during the period of vein formation, they would undoubtedly have had an important control on the course

[37] Patton, H.B., op. cit., p. 107.

of the ore-depositing solutions that rose along the larger fissures. Those cross faults which happened to be formed during the deposition of ore would have sericitized and bleached walls rather than silicified walls as the solutions depositing the later sulphides were incapable of producing silicification of the jaspery type.

Regarding the eastward continuation of the Josephine vein Patton[39] says:

Only one of these faults displaces the vein more than a few feet. This is located several hundred feet east of the shaft on the third level. The fault plane has a strike of N. 10° W. and a dip of 50° E. It cuts the vein off sharply. Between the shaft and this fault the drift on the third level follows the vein, but beyond the fault no trace of the vein has been found. The drift was continued in the same general direction and at 450 feet east of the fault strikes the Hortense vein, which is a vein of the same general character as the Josephine vein, with about the same strike and dip, and is known to lie to the south of the Josephine vein. From this it would appear that the above-mentioned fault must throw the Josephine vein to the left—that is, to the north on the east side of the fault.

Patton makes no mention of the evidence upon which he bases the statement that the Hortense vein is known to lie south of the Josephine vein, but it appears very probable because of their same strike and the direction of fault displacements that the two veins occupy faulted portions of the same fissure.

CHARACTER OF THE ORES

The ore minerals of the Empress Josephine mine are galena, sphalerite, pyrite, chalcopyrite, tennantite, covellite, empressite, hessite, sylvanite (or krennerite), petzite, rickardite, altaite, and native tellurium. The gangue is mainly or almost entirely quartz but contains some barite and carbonates. Galena, sphalerite, and pyrite are by far the most abundant ore minerals. The tellurides were found only locally in small pockets. Limonite, cerusite, probably anglesite, native copper, and some basic hydrous aluminum phosphates of doubtful identity (p. 19) are of supergene or secondary origin. Native tellurium is perhaps secondary, but its geologic occurrence is not known, and the only specimen of it seen was not associated with other tellurides.

The vein quartz is massive and irregularly crystallized, either white or gray, and impregnated with finely divided sulphide. Some small cavities are present and are commonly lined with quartz crystals or small amounts of sulphides. Carbonates are uncommon but were seen in some cavities in ore on the dump. Some late veinlets of calcite were also seen. The ore is not appreciably crustified or banded except in relation to irregularly distributed cavities. The texture of the Josephine vein as a whole is not known, but to judge from material on the dump and from other veins in the vicinity, it is not at all different from the common type of siliceous veins in the district.

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[39] Patton, H.B., op. cit., p. 107.

The material on the dump contains some brick-red jasper in which pyrite crystals 2 to 4 millimeters in diameter are thickly embedded. It is not known from what part of the mine this came, but it is similar to jaspers that crop out along Copper Gulch above the mine. Some of the ore includes fragments of white or gray fine-grained siliceous material formed by the replacement of wall rock and containing very small grains of pyrite.

The ore shoots in the Empress Josephine vein pitch eastward, as is shown to some extent by the stope map. The ore is said to have been oxidized to a depth of 60 to 80 feet below the surface. In this oxidized ore the lead was present partly at least as cerusite and probably also as anglesite. Early shipments from the mine show the value of the ore to be mainly in silver and gold. How large the bodies of oxidized lead ore were is not known, but even complete oxidation to 60 or 80 feet could not account for a very large tonnage of ore of this type. The richest ore from the mine was obtained between the 70 and 140 levels east of the shaft.

The conditions on these levels in 1882 and 1884 are indicated by the quotations from the mint reports given above. The ore was apparently not oxidized, but there may have been a little enrichment in silver. A study of some polished sections of specimens from the telluride lenses (pl. 19, *C, D)* indicates that nearly all of these are primary or hypogene minerals, although the presence of native tellurium and some reported free gold suggests the possibility that some of the tellurides in the oxidized zone may have been decomposed, with the precipitation of free gold and some transportation of the tellurium to greater depth. Appreciable transportation of gold is not to be expected, however, as it is brought into solution with difficulty, except possibly in veins containing considerable manganese.

Regarding the decomposition of tellurides of gold Lindgren[40] says:

They decompose easily above the water level; the tellurium is in part carried away as soluble compounds, in part fixed as tellurite (TeO_2) or tellurates of iron like emmonsite and durdenite. The gold remains in minute brownish grains (mustard gold). In most cases there is little evidence of solution and transportation of this gold.

Under these conditions an apparent enrichment in gold might be expected in the oxidized ore, due largely, however, to the reduction in volume of the original ore and the carrying away of other constituents rather than to actual transportation of the gold itself. A zone of silver enrichment may have existed in the mine just below the oxidized ore, but unless the conditions were much different from those shown in other veins in the northern part of the district the zone was probably very shallow. The ground-water level in the mine probably stands at about the third level, but in scarcely any veins in the district, with the possible exception of some of the wide manganese veins in the southern part, does complete oxidation extend as deep as the water level.

[40] Lindgren, Waldemar, Mineral deposits, 3d ed., p. 965, New York, 1928.

The primary telluride ore which lay between the 70- and 140-foot levels is said to have been a lenslike body between faces of the normal lead-zinc ore. As only a few specimens of the telluride ore were available for microscopic examination, a comprehensive study of the paragenesis of these minerals could not be made. Some of the tellurides formed distinct crystals in the pockets in the ore, a mode of occurrence which shows them to be of late origin. Although considerable search was made for other lenses of telluride ore, only a few very small pockets were found. A similar condition occurs in the Hortense vein.

Microscopic study of a few sections shows the ordinary vein minerals to have the succession normal to the district. Silicification of the wall rock was the first process after the formation of the fissures. Barite was one of the earliest if not the earliest vein mineral. It is apparently not abundant, but one specimen taken from the dump shows platy white crystals of barite about which later pyrite and sphalerite are molded. Galena, tennantite, and a little chalcopyrite were later. The tellurides were distinctly later than the main deposition of galena, and between them and the galena there is in many places a narrow rim of lead telluride, altaite. (See pl. 19, *C, D.)* The tellurides themselves, such as hessite and empressite (AgTe), are intergrown irregularly, suggesting contemporaneous formation. Small amounts of altaite, sphalerite, galena, and chalcopyrite occur in microscopic particles distributed along certain zones or streaks in the hessite and empressite. Their presence in the tellurides suggests that the late solutions depositing the tellurides either dissolved and reprecipitated small amounts of copper, zinc, and lead, or that the late solutions originally contained small amounts of these metals. The gold tellurides, sylvanite (or krennerite) and petzite, in the specimens examined are not associated with the massive intergrowths of hessite and empressite but form small streaks in quartz containing some sphalerite, galena, and altaite. In the mint report for 1884 it is stated that these quartz veins containing gold telluride were 5 inches or so in thickness and lay immediately adjacent to the main lead-zinc ores. Quartz apparently continued deposition to a late stage in the Empress Josephine vein, as nearly all the small vugs in the siliceous lead-zinc ore are lined with small quartz crystals rather than with sulphides or carbonates.

The value of the ore taken from the mine is not known other than as given in the quotations from the mint reports. Because of the very irregular distribution of the gold and silver tellurides there was probably a wide range in the value of the early shipments. Small shipments of the normal type of lead-zinc and siliceous ores made since 1908 or 1909 show an average gross content of about 10 percent of lead, 1.1 percent of copper, and 38.4 ounces of silver and 0.66 ounce of gold to the ton. Assays and analyses of shipping ore taken from Patton's report[41] are shown in the following table.

[41] Patton, H.B., op. cit. p. 111.

Assays and analysis of ore shipped from the Empress Josephine mine

Date	Gross weight (pounds)	Gold (ounces per ton)	Silver (ounces per ton)	Lead (percent)	Copper (percent)	Zinc (percent)	Sulphur (percent)	Iron (percent)	Silica (percent)	Net value (per ton)	Cost of treatment (per ton)
April, 1908 ….	6,300	0.17	26.7	11.15	-------	9.2	23.5	15.5	34.5	$7.96	$12.00
Do ……….	18,040	1.67	12.6	-------	-------	4.5	8.1	6.1	73.0	26.10	13.00
Do ……….	4,720	.055	54. 6	23.9	0.7	4.0	29.1	22.7	15.6	29.49	9.00
Do ……….	305	2.0	21.6	3.8	-------	9.0	10.4	5.0	61.4	56.71	13.00
April, 1912 ….	3,257	1.225	46.9	25.4	-------	7.9	12.0	7.8	36.0	60.00	12.85

LIBERTY MINE

The Liberty mine is just east of the town of Bonanza and about 1,000 feet south of the Empress Josephine mine, on the south side of Copper Gulch. The portal of the adit is 9,619 feet above sea level. The Liberty vein strikes about N. 55°-60° W. and dips 70°-75° S. It is developed by an inclined shaft 125 feet in depth, the collar of which is in an adit about 70 feet from the portal. A compressor and hoist with electric power is installed at a station opposite the shaft on the adit level. The levels below the adit, except the 60-foot level, were under water at the time of examination.

Both walls of the vein to the 60-foot level were composed of Bonanza latite. A small amount of stoping has been done on the vein at the two upper levels. In a small stope below the adit level, which could be entered by a winze about 20 feet east of the shaft, a lenslike body of ore had been taken out. This stope was 6 to 8 feet wide in places, but the vein material remaining around its borders was from 6 to 18 inches wide. The latite has been bleached, sericitized, and partly silicified near the fissure. An altered micaceous gouge occurs on the hanging wall of parts of the vein. The gangue is mainly quartz with some barite and a little carbonate, probably calcite. The ore minerals found in specimens of the ore taken from the ore bins and from the small stope below the first level are pyrite, sphalerite, galena, tennantite, chalcopyrite, covellite, and probably stromeyerite. Mr. Theodore Eck, part owner of the property, states that some telluride ore was encountered in driving the adit level. The ore near the surface is partly oxidized and coated or stained with orange-yellow or yellowish-brown crusts. Chemical tests of this material show that it is probably a hydrated phosphate and sulphate of ferric iron (p. 19). It is associated with a soft fibrous mineral, possibly beidellite. In the less oxidized ore some of the cavities are filled with a pure-white soft mineral that resembles kaolin but proved to be a basic hydrous phosphate of aluminum. None of these products of oxidation could be definitely identified, however, without chemical analysis. They are commonly found throughout the northern part of the district in partly oxidized ores.

Small shipments of ore from this mine showed a gross content of 4 to 11 percent of lead, 4 percent or less of zinc, a trace to 0.25 percent of copper, and 55 to 145 ounces of silver and 0.01 to 0.03 ounce of gold to the ton. It is said by the owners that some of the oxidized ore ran $4 to $5 in gold to the ton. The production of the mine has been small.

NOW WHAT MINE

The Now What mine is on the opposite side of Copper Gulch from the Empress Josephine. The vein runs nearly due east and is developed by two adits—one near the bottom of the gulch at an altitude of about 9,690 feet and the other above on the slope at about 9,760 feet. A plan of the two tunnels is shown in Figure 39, taken from a map made by transit survey and furnished by Mr. William Burkhardt, owner of the property. The mine was under lease by the Bonanza Mining & Milling Co. when it was examined in June, 1927.

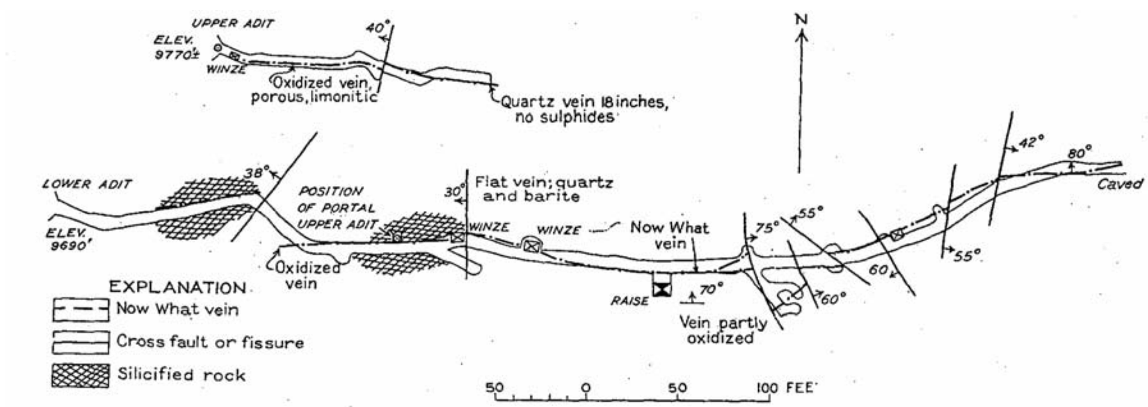

Figure 39. – Plan of the Now What mine.

The country rock of the mine is entirely Rawley andesite. The texture of the flows suggests that they belong to the middle part of the formation. The strike of the Now What vein ranges from due east to about N. 65° E. locally and the dip ranges from 75° N. to vertical. The fissure is displaced from a few feet to as much as 25 feet by five or six cross faults, which cut it somewhat obliquely or nearly at right angles. Some of the movement on these cross faults was post-mineral, but at several of the crossings nearer the face of the tunnel, 400 to 500 feet from the portal, the vein material is not noticeably disturbed by the faults but ends abruptly against them. At some of the cross faults the Now What vein is wider and has a higher sulphide content in the footwall of the fault. It is apparent that some of these faults have influenced and localized the ore deposition, and hence they must have been of premineral origin with movement continuing intermittently until post-mineral time. The cross faults contain an altered gouge, and some show a weak mineralization, although most of them are tight. The Now What vein ranges in width from 6 inches to a little over 3 feet but averages about 1½ feet.

The gangue of the vein is almost entirely quartz but includes a little barite and carbonates. The quartz is usually massive or jaspery, but some milky-white colloform quartz is present. The ore minerals are pyrite, sphalerite, galena, and small amounts of copper minerals.

Samples of the vein show an average content of about 5.1 percent of lead, 5.8 percent of zinc, 1.0 percent of copper, and 8.5 ounces of silver and 0.025 ounce of gold to the ton. About 46 tons of ore mined from the vein averaged a gross content of 5.5 percent of lead, 0.6 percent of copper, and 8 ounces of silver and 0.026 ounce of gold to the ton.

HORTENSE MINE

The Hortense mine is on the south side near the bottom of Copper Gulch, at an altitude of 9,807 feet. The vein has been developed by an adit and by a shaft on the hill slope above. In the adit the vein has been followed for about 500 feet. The shaft is probably about 100 feet in depth, but only short drifts have been run from it. The production of the mine has been small.

A plan of the Hortense tunnel showing its relation to the Empress Josephine workings is given in Plate 33. The vein strikes N. 70°-85° E. and dips 60°-90° N. The fissure is cut by several cross fissures, one of which is mineralized and has been explored in the adit level. The vein material in the upper 80 feet of the shaft is said to have been of low grade,[41] but the quality of the ore improved below this. In the adit the vein is narrow, ranging in width from 6 inches to 2 feet or a little more. There are several small stopes in the tunnel, both overhead and underhand. The fact that the vein contained small pockets of tellurides probably encouraged the development on it despite its narrowness. Its strike and dip are about the same as those of the Empress Josephine vein, and it very likely lies in a faulted portion of the same fissure. The country rock of the mine is entirely andesite.

The gangue of the vein is chiefly quartz, and the ore minerals include pyrite, sphalerite, galena, tennantite, and some tellurides. The tellurides are said to have contained both silver and gold and to have occurred in part as small cubic crystals. None of these were seen, and their identity is not known, but they are presumably of the same species that were found in the Empress Josephine vein. The average value of the ore from the mine is not known, but a shipment of several tons averaged in gross content about 21 percent of lead, 1 percent of copper, and 36.6 ounces of silver and 0.60 ounce of gold to the ton.

MARIPOSA TUNNEL

The Mariposa tunnel is on the north side of Copper Gulch at the east side of the town of Bonanza, at an altitude of about 9,660 feet. A geologic sketch map of that part of the workings which was accessible in 1927 is shown in Figure 40. The country rock includes andesite and Bonanza latite in fault contact and much broken and altered along a series of northeast and northwest fractures. In the part of the tunnel that was accessible two fissures have been followed by drifts, but they show only weak mineralization. Beyond the second fissure the tunnel is caved. The rocks have been bleached and silicified and contain some pyrite, and some of the fissures show siliceous vein material with a little sulphide.

[41] Burchard, H.C., op. cit. for 1882, p. 544, 1883.

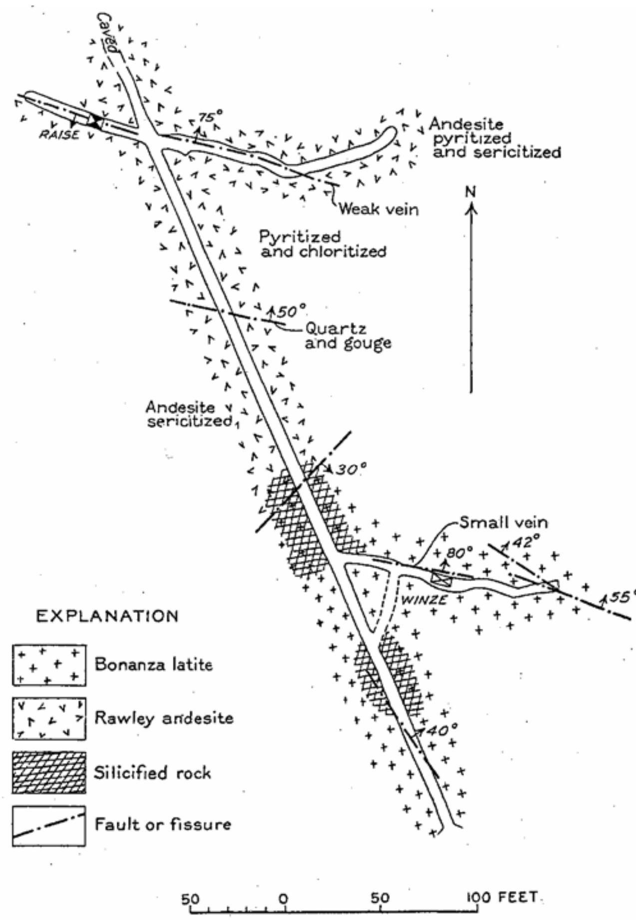

Figure 40. – Sketch map of the Mariposa tunnel.

As far as is known, there has been no production of any importance from this property.

ST. LOUIS MINE

The St. Louis mine is on the south side of Copper Gulch about a mile above the town of Bonanza. The shaft is at an altitude of 10,045 feet. The property is at present owned by the Antoro Mines Co.

In the mint report for 1890[43] the production of the St. Louis is given as $840 in gold, $679 in silver, and $183 in lead. In 1891[44] the production was $413 in gold, $646 in silver, and $174 in lead, making the total for these two years $2,935. The mine was reported as not producing in 1887 and 1888, but data on the production for other years prior to 1900 could not be obtained. An estimate of the production by J. M. Poole, of Bonanza,[45] credits the St. Louis with a total production of about $3,600 between 1881 and 1900. Between 1913 and 1926 the mine produced about 1,200 tons of ore, the content of which is shown in accompanying table.

[43] Smith, M.E., op. cit. for 1890, p. 139, 1891.
[44] Idem for 1891, p. 184, 1892.
[45] Patton, H.B., op. cit., p. 68.

Production of the St. Louis and other mines, 1914-1926 [a]

Year	Ore (dry tons)	Gross content of concentrates and smelting ore				
		Gold (fine ounces)	Silver (fine ounces)	Lead (wet assay, pounds)	Copper (wet assay, pounds)	Zinc (pounds)
1914	512	734.81	6,090	88,456	12,601	(b)
1915	228	230.05	3,649	48,047	6,035	----------
1916	66	253.36	1,314	12,402	1,445	----------
1917	336	268.24	6,670	35,028	21,311	----------
1923	[c]57	13.60	2,922	11,837	1,334	----------
1924	[d]22	0.94	322	7,071	----------	7,721
1925	[d]35	14.14	212	4,505	----------	6,450
1926 …..	22	1.10	480	3,517	483	----------

[a]No production in years omitted since 1902. Compiled from mine records of U.S. Geological Survey and Bureau of Mines.
[b]6 to 12 percent.
[c]Recorded as Rico and St. Louis mines.
[d]Possibly not St. Louis mine, but other mines of St. Louis group.

The geologic conditions in the vicinity of the mine are similar to those existing along the lower part of Copper Gulch. There are two major sets of fissures along this part of the gulch — one set striking northeast to nearly east and the other striking northwest. A definite age relation between the two sets could not be determined, but nearly everywhere on the slope southeast of the St. Louis the northwest set appears to be the younger. There probably was not, however, any great lapse of time between the different sets. Both sets are mineralized in places, but in general the northeasterly fissures are characterized by more intense silicification of the adjoining lavas. The St. Louis vein occupies a fissure or fault zone belonging to the northeasterly system. The country rock of the mine, so far as could be determined from observations in the adit level and at the surface, is entirely Rawley andesite, but the andesite flows and breccias in the vicinity do not lie stratigraphically much below the base of the Bonanza latite. Fault blocks of latite on the opposite side of the gulch have about the same altitude as the workings, and latite is exposed several hundred feet above the mine on the slope southeast of the shaft.

In proximity to faults and fissures on both sides of the gulch near the mine the lavas have been intensely silicified. Reddish-brown or white jaspery rocks form a large proportion of the debris on the slopes. Some of the dark-reddish jaspers are thickly crowded with crystals of pyrite.

The St. Louis shaft is about 340 feet in depth, and there are five main levels from it, mostly east of the shaft. At the 80-foot level there is a crosscut adit to the north which drains the upper part of the mine. Below this level the mine was filled with water in 1927. The following discussion is based upon information given to the writer by Mr. John Ashley, of Bonanza, who was in charge of the property, and upon information obtained from the map and an examination of the 80-foot level. A longitudinal section of the mine is shown in Figure 41. At and above the 80-foot level there are two nearly parallel fissures that strike N. 50°-70° E. and at the level are about 10 to 15 feet apart. The north fissure dips 75°-80° SE. and the south fissure 55°-60° NW., so that the two fissures converge in depth and are said to come together about 15 feet below the 80-foot level. This junction was under water, but the relations seen suggest that the south fissure is a split or hanging-wall fracture of the north fissure. The shaft follows approximately the course of the north vein to a point between the 180 and 230 foot levels, about 200 feet below the collar. At this point the vein is said to be cut off by a nearly horizontal fault, and in the rest of the shaft no vein is exposed. A drift east on the 230-foot level intersects the fault and vein about 120 to 150 feet from the shaft. Beyond this the vein is exposed in the drift. The ore shoot in the north vein has a pitch of about 50° E. and is apparently limited laterally both by cross fissures and by pinching of the fissure walls. Within the main shoot on the north vein there is a narrow shoot of ore of high gold content which grades laterally in each direction into lower-grade lead-zinc ore. Some local shoots or bodies of copper ore containing bornite are also found in the mine. The vein material ranges in width from less than 1 foot to 3 or 4 feet. In the south vein the stopes are less extensive and largely above the 80-foot level. The largest stope shows a tendency for the ore to pitch steeply toward the east. The south vein has about the same range in width at the 80-foot level as the north vein.

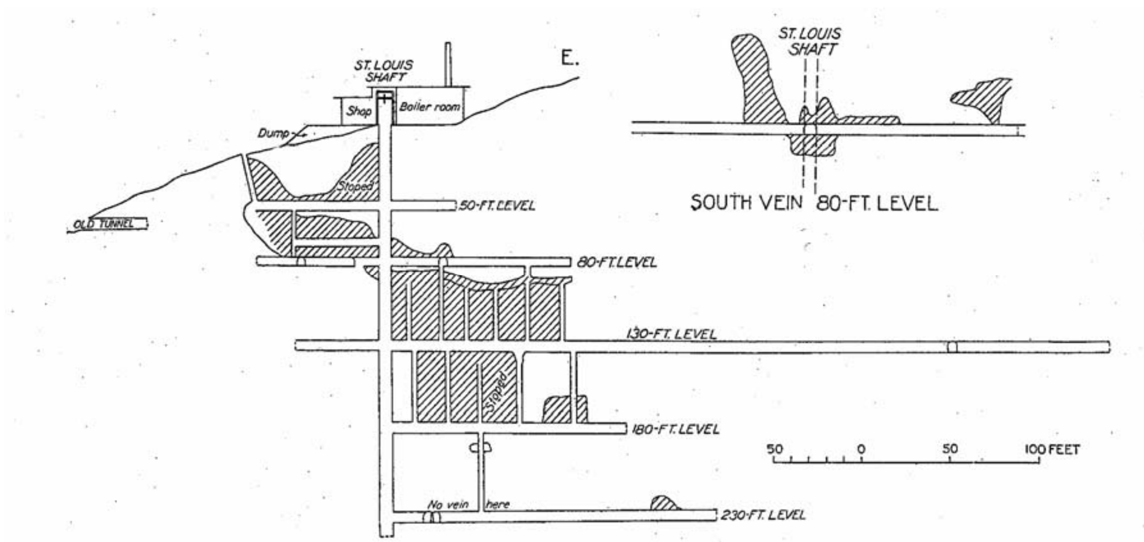

Figure 41. – Longitudinal section of the St. Louis mine.

The gangue is chiefly quartz, which is in part coarse grained and in part dense and jaspery. There has been a considerable silicification of the walls of the veins. The ore minerals include pyrite, sphalerite, galena, chalcopyrite, bornite, and tennantite. The form in which the gold occurs in the vein is not known, and apparently no tellurides have been recognized. It is said that even in the highest-grade ore, which the writer has not seen, no gold was visible.

Both veins are considerably oxidized on the 80-foot level, and the ore occurs in irregular streaks, of which the larger ones have apparently been stoped. The most thoroughly oxidized material is soft and crumbly and contains considerable limonite. This is said to have a high gold content, and some relative enrichment in gold might be accounted for by reduction in volume or specific gravity of this material during oxidation. In less oxidized portions of the veins the sulphides are partly altered to or coated with bluish-black secondary sooty chalcocite. Some enrichment of silver may have occurred in this material, as is common in the district. It is said that in the south vein the gold content was less consistent than in the north vein.

In the north vein the gold shoot, which extended from a position west of the shaft on the 50-foot level down to the 180 level, had an eastward pitch of about 58°. The stope length of this shoot ranged from about 15 to 30 feet, to judge from Mr. Ashley's indication of it on the map. The pitch length was about 160 to 180 feet. The gold content apparently decreased on each side of the axis of the shoot, which was bounded by lower-grade lead-zinc ore of the normal type. About 40 narrow-gage carload shipments of approximately 20 to 25 tons each, mined from this shoot and near its borders, had gold contents ranging from 0.03 to over 7 ounces to the ton and averaging between 1.3 and 1.4 ounces. Two small shipments of 4 or 5 tons each contained about 27 and 35 ounces of gold to the ton. The ore averaged 12 to 15 ounces of silver to the ton, 8 to 9 percent of lead, and 1.5 to 2 percent of copper and contained as much as 12 percent of zinc.

A small body of bornite ore was stoped on the 180-foot level between 85 and 110 feet east of the shaft, just east of the lower part of the gold shoot. One carload shipment from this shoot had a content of 7.55 percent of copper and 55.3 ounces of silver and 0.15 ounce of gold to the ton.

Some shipments of the normal type of lower-grade lead-zinc ore had gross contents of 6.5 to 16 percent of lead, from several percent to 12 percent of zinc, about 1 percent of copper, and 6 to 22 ounces of silver and 0.03 to 0.07 ounce of gold to the ton.

OTHER MINES AND PROSPECTS OF THE ST. LOUIS GROUP

Besides the St. Louis there are several other claims and prospects adjoining Copper Gulch which are the property of the owners of the St. Louis mine. These include the Boston, Philadelphia, Coin, St. Louis No. 2, Chicago, Cronje, Botha, Joubert, Kruger, Chief, Summit, Bay State, Cliff, and some other claims that have not been surveyed for patent. The most extensive workings on these are the Cliff and Cronje tunnels, shown in Plate 1. The Cronje tunnel was not examined. The Cliff tunnel (fig. 42) was examined only hastily, but it is of some interest, as it penetrates one of the strong northeasterly fault zones along which the Bonanza latite is faulted down toward the southeast. The Cliff tunnel runs in a direction averaging S. 65° E. for about 420 feet. Within this distance it intersects several cross faults striking N. 30°-50° E. and dipping 50°-60° SE. Although the tunnel starts in andesite it penetrates altered latite not far from the portal. The Cliff vein occupies one of the faults. It strikes about N. 50° E. and dips 60°-70° SE. In the hanging wall of the Cliff vein the country rock has been completely silicified for a distance of about 200 feet along the crosscut. Some pyrite is present in the jasper. Beyond the jasper zone another gougy fault plane is cut near the end of the tunnel. Most of the silicified rock is of a reddish-brown color and is much veined and impregnated with pyrite. The alteration has been so complete that the original character of the country rock has been largely destroyed; consequently the details of the geologic relations could be worked out only by careful examination and microscopic study of the altered rock.

The Cliff vein, which is from 1 foot to 4 or 5 feet in width, has a metal content consisting largely of iron and zinc. The writer was informed by Mr. Ashley that some shipments of zinc ore had been made from this vein, and also that several hundred tons of ore had been treated in the Bonanza mill. Some of the ore is said to have run 18 to 22 percent of zinc. The gold, silver, copper, and lead content of the vein is low. Assays of the vein taken from an assay map show from 0.7 to 8 ounces of silver and a trace to 0.2 ounce of gold to the ton, a trace to 1 percent of copper, and 0.5 to about 5 percent of lead.

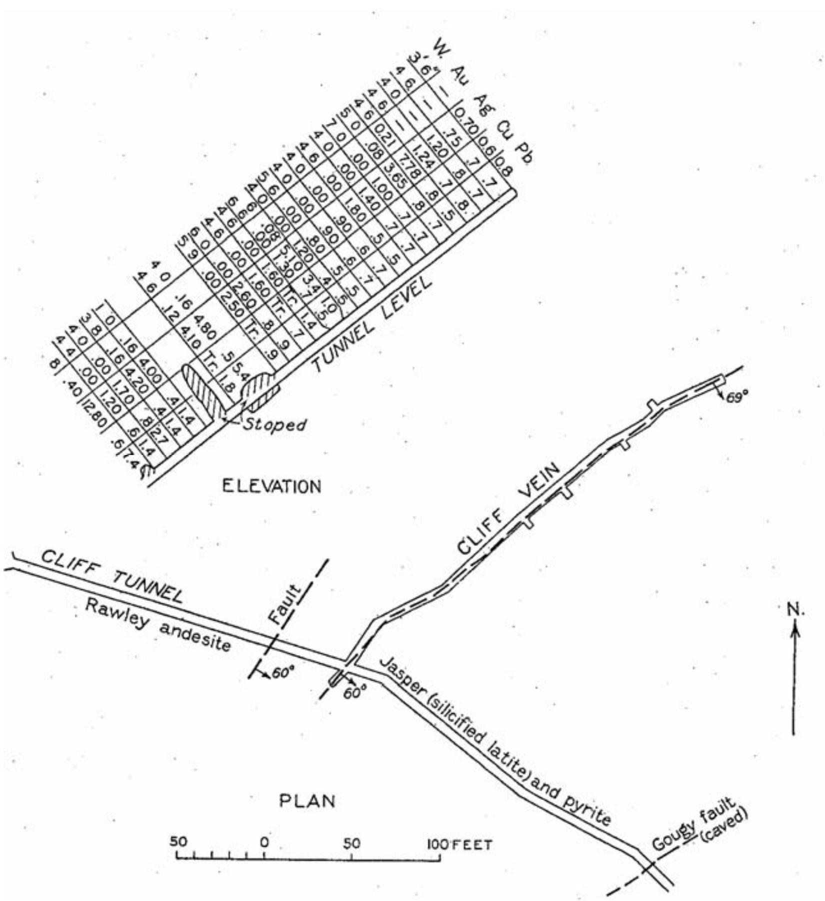

Figure 42. – Sketch map of the Cliff tunnel.

QUEEN CITY MINE

The Queen City mine is near the head of Copper Gulch, about 2 miles northeast of the town of Bonanza, at an altitude of 10,754 feet. Although apparently considerable work had been done on this prospect, to judge from the dump and mine buildings, most of it evidently was of an exploratory character. The dump consists largely of unaltered andesite and contains little vein material. A small pile of ore in the ore bin shows some galena intimately intergrown with quartz in a peculiar graphic manner. Superficially some of this material resembles steel galena, but microscopic examination shows that the separate grains of galena are in parallel crystallographic orientation with one another and are graphically intergrown with quartz and some sphalerite. The texture suggests contemporaneous deposition of galena, quartz, and sphalerite. There is a little manganiferous calcite in some of the cavities in the quartz. The production of this mine is not known, but it was probably small.

MINES ALONG KERBER CREEK

BALTIMORE MINE

The Baltimore mine is just below the Cocomongo mine on the west side of Kerber Creek, about 1¼ miles above the town of Bonanza. The collar of the shaft is a little over 100 feet west of the main road up Kerber Creek, at an altitude of about 9,685 feet. The mine was being operated in 1927, and a compressor and hoist had been installed. When it was examined only about 120 feet of drifting had been done on the 100-foot level of the main Baltimore vein and several small stopes 15 to 25 feet in height had been opened along the drift.

The country rock of the mine is Bonanza latite to the present depth of development. The Baltimore vein strikes from about N. 75° W. to nearly west and dips 65°-70° S. It apparently occupies a fault of small throw. A short crosscut to the south on the 100-foot level near the shaft reveals a parallel fissure about 25 feet away on the hanging-wall side of the Baltimore fissure. This crosscut had not been driven far enough to show whether or not the parallel fissure is mineralized, but the alteration became less intense in the crosscut away from the main vein. The latite is silicified near the Baltimore vein. The vein showed a tendency to pinch and swell owing to irregularities in the walls and a small horse of altered country rock occurs in the fissure about 100 feet from the shaft. Where it widens out the vein material is 3 to 4 feet in width, exclusive of the silicified and fractured country rock, but it pinches down to a foot or less in other places, where it is too narrow and of too low grade to stope. When examined the drifts were insufficient to indicate the promise of the vein, but at least it occupies a fairly strong and steep fracture. The shaft is said to have been in some ore practically all the way.

The new shaft is about 180 to 190 feet S. 80° E. of an old shaft believed to be on the Baltimore vein. The west drift had been started with the purpose of driving below or connecting with these old workings, the extent of which is not known. Several north-east faults crop out on the ridge 1,500 feet southwest of the Baltimore. Their strike indicates that they might intersect the Baltimore fissure near or somewhat west of the old shaft. It is not known whether the northeast fissures are mineralized, although in the saddle where they cross the ridge there has been some alteration of the latite near them. The Baltimore fissure is said to be traceable across Kerber Creek for some distance to the east, where there are some small prospects on it. It must, however, in its eastward extension intersect the northwestward-trending fault zone of the Bonanza and Cocomongo veins or of the Exchequer fault. Its age relations to these fault systems cannot be determined from surface indications, at least without considerable detailed work.

The gangue of the vein is chiefly quartz, usually somewhat massive, and the sulphides are mainly pyrite, galena, and sphalerite. There is a little copper in the vein, probably as chalcopyrite or tennantite or both. The ore that was stoped in 1927 averaged about 13 percent of lead, 0.3 percent of copper, and 6 to 7 ounces of silver and 0.01 to 0.02 ounce of gold to the ton. The iron content ranges from 8 to 12 percent, and the silica from 40 to 60 percent.

EXCHEQUER MINE

The Exchequer mine is on the east side of Kerber Creek a little over a mile above the town of Bonanza. The portal of the Exchequer adit is about 9,660 feet above sea level, at the side of the Kerber Creek road. Between 1881 and 1900 this mine produced considerable ore,[46] but since 1900 there has apparently been little production or development. In the mint report for 1882 it is stated that the mine was opened on an incline and that 3 to 10 feet of ore was exposed. In his report for 1883 Silver[47] states:

The Exchequer, near the town of Exchequer, possesses one of the largest ore bodies in the county. It is a true fissure from 25 to 30 feet in width, with a pay streak of from 2 to 8 feet wide. A great deal of the Exchequer ore is free milling, carrying from 50 to 90 ounces of silver. The development consists of an incline about 175 feet long.

Regarding the development and production in 1884, Silver[48] says:

*The Exchequer * * * began work in June, since which time shipments have been quite regular of large quantities of fine concentrating ore. The mineral is largely associated with gray copper.*

The only record of production is in the mint report for 1890,[49] which credits the Exchequer with a production of $724 in silver.

The mine was apparently worked mainly through an inclined shaft and a tunnel, shown in Plates 1 and 34. The inclined shaft is at present caved but is said to have been timbered and 400 feet in depth with a dip of 26° 30'. The tunnel trends northeast for 170 feet, and at 130 feet from the portal a crosscut extends east-northeast for 340 feet to the Exchequer fault (or vein). A drift follows the vein northward for more than 700 feet, but only the first 150 feet from the crosscut remained accessible.

The country rocks of the mine are andesite and Bonanza latite. The Exchequer vein, from which most of the ore was presumably mined, strikes about N. 10°-15° W. and dips 20°-30° E. The first part of the drift reveals a fault dipping at a very small angle and mostly filled with a soft altered gouge from 20 inches to 3 feet in thickness. (See pl. 7, *D*.) Although the latite and gouge have been very strongly altered, there is little or no vein material. About 100 feet north of the crosscut the drift apparently turns

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[46] Patton, H.B., op. cit., p. 68.
[47] Silver, Herman, op. cit. for 1883, p. 403, 1884.
[48] Idem, for 1884, p. 238, 1885.
[49] Smith, M.E., op. cit. for 1890, p. 139, 1891.

into the hanging wall, where the latite is broken by a series of steeper hanging-wall fractures striking north to N. 45° E. and dipping 45°-55° E. There is considerably less gouge in the larger fractures, and in joints in the rock parallel to them and to the flow planes of the latite there are small seams containing quartz, pyrite, some copper minerals, and a little rhodochrosite and calcite. Some of these seams show a delicate banding of the minerals in which quartz, pyrite, rhodochrosite, and calcite were deposited in order toward the middle of the seams. The main fault or vein could not be reached beyond this point, and nothing more could be determined concerning the character of the mineralization.

The early mint reports on the character of the vein material and silver content indicate that parts of the Exchequer fault contained bodies of gray copper ore similar to those found in parts of the Cocomongo fault. These two faults are alike in some respects, except that the Exchequer fault has a considerably flatter dip at the outcrop and is not as well mineralized where it can be seen. In the Cocomongo mine the fault displacement on the fissure zone was fairly large. It is possible that toward the south this displacement was taken up by movement on the Exchequer fault. That the displacement on the Exchequer fault was large is suggested by the intense fracturing and disturbance of the Bonanza latite in the immediate footwall of the fault. The flow planes dip very irregularly both toward the east and toward the west. This is one of very few places in the district where the Bonanza latite flow planes are seen to dip eastward. The dip ranges from horizontal to 55°. On the surface of the ridge above the mine the latite has a normal westward dip of 45° to 50°, so that the eastward dips would appear to be caused by the rotation of small blocks adjacent to the Exchequer fault plane.

The average grade of ore taken from this mine is not known, but probably some of the early shipments were of very good grade compared with ores from the district as a whole. The fissure probably has too gentle a dip to be of great promise for deeper exploration, as with increasing depth it is likely to become tighter and the ore bodies to be narrow and irregularly distributed. There may be some hanging-wall veins that were overlooked during the early development, but this appears unlikely.

MEMPHIS MINE

The Memphis mine is on the west side of Kerber Creek opposite the Exchequer tunnel, a little over a mile above the town of Bonanza. It is developed on a vein that was known in the early days of mining as the Arkansas vein. The location and extent of all the old Arkansas workings are not known, and some of them may have been on the east side of Kerber Creek. In the mint report for 1882 Burchard[50] says:

The Arkansas, below the Revenue and near the town of Exchequer, is developed by a tunnel 175 feet long, from which a shaft has been sunk 75 feet and a level run from the shaft for 25 feet. The vein is 7 feet wide, with a pay streak of galena and gray copper 26 inches in width, assaying 75 ounces of silver per ton.

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[50] Burchard, H.C., op. cit. for 1882, p. 541, 1883.

In 1883 there was no development on this property, but in his report for 1884 Silver[51] states:

Among the most promising prospects in this vicinity are the Bonanza, Revenue, Keystone, Rawley, Antoro, and Arkansas mines. The latter is being opened by an adit tunnel now 161 feet in length. A shaft 75 feet deep connects with a tunnel at a point where an incline has been commenced, which will be driven for 100 feet. The vein is 6 feet wide, showing an ore streak of 16 inches, composed of gray copper and copper pyrites, with an average value of $125 per ton. Irregular shipments were made during 1884.

For 1885 and 1886 there are no detailed records of the production and development of individual mines, but in 1887 and 1888 the Arkansas is reported as not producing. The mint report for 1890[52] credits it with a production of $840 in silver and $165 in lead. In 1914, when the district was examined by the State Geological Survey, the mine was being worked in a small way. In 1915 and 1916 there was no production from the mine, but in 1917 and 1918 development work was carried on and a small amount of ore was shipped.

The location of the Memphis mine and part of the drifts on the Arkansas vein are shown in Plate 34. In 1918, when the last work was done, the total development was reported as comprising a vertical shaft 135 feet in depth and 300 feet of drifts. There is an adit on the property 50 feet in length. According to Patton[53] there were levels at 20 feet and 100 feet from the collar in 1914. In 1918 it was reported that 40 feet of stoping had been done on the first and second levels.

The main shaft was entirely caved near the collar in 1927, but a short part of an inclined winze or raise along the strike of the vein was accessible from the bottom of a shallow shaft about 40 feet east of the main shaft. In these shallow workings two fissures had been developed—one striking about N. 70° E. and the other about N. 80° W. These fissures are nearly vertical and close together and probably are caused by a splitting of the Arkansas fissure. The N. 80° W. fissure contained some small lenses a foot or so in width of siliceous ore containing pyrite, sphalerite, galena, and tennantite. The N. 70° E. fissure was tight and poorly mineralized. The country rock is Bonanza latite, which strikes about north and dips 30°-35° W. Regarding the workings from the main shaft in 1914 Patton[53] says:

The mine was worked through a shaft 100 feet deep. There are two levels—one at 20 feet, from which most of the ore has come, and inaccessible at the time the mine was visited, and one at 100 feet depth. In the second level is a vein with east and west strike and dip 80° N. The ore is mostly galena and sphalerite in a quartz gangue. The vein appears to be a replacement of the country rock along a line of

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[51] Silver, Herman, op. cit. for 1884, p. 238, 1885.
[52] Smith, M.E., op. cit. for 1890, p. 139, 1891.
[53] Patton, H.B., op. cit., p. 104.

brecciation. The mine is said to have produced ore to the value of $5,000, but the values are very irregularly distributed.

The ore mined since 1914 has showed a gross content ranging from 5.5 to 13 percent of lead, 1 to 4 percent of copper, and 19 to 31 ounces of silver and 0.025 to 0.044 ounce of gold to the ton. The average content, based upon total shipments of less than 200 tons, is about 12.7 percent of lead, 1.2 percent of copper, and 30 ounces of silver and 0.034 ounce of gold to the ton.

WHEEL OF FORTUNE MINE

The Wheel of Fortune tunnel is just above the town of Bonanza on the east side of Kerber Creek near the valley bottom, at an altitude of about 9,525 feet. The old Wheel of Fortune shaft, which was sunk on the Wheel of Fortune vein proper, is on the ridge northeast of the town at an altitude of a little over 9,900 feet. The vein developed by the shaft appears to strike northwest, but workings on the vein were inaccessible. The lower adit was apparently driven to intersect the vein at a lower level, but a blind vein striking about N. 80° E. was intersected and drifted on, and the old Wheel of Fortune vein does not appear to have been cut by the tunnel.

The development work in the adit (fig. 43) is in Bonanza latite except for a porphyry dike crossed near the portal. The vein has an average strike of about N. 80° E. and dips 50°-60° N. A heavy gouge from 2 to 3 feet thick is present in parts of the vein, and the ore is in part contained within this gouge in local shoots. A small shipment of ore containing considerable gougy vein material ran about 12 percent of lead, 0.7 percent of copper, and 22 ounces of silver to the ton. Zinc is present in the vein, but the proportion of this metal is not known.

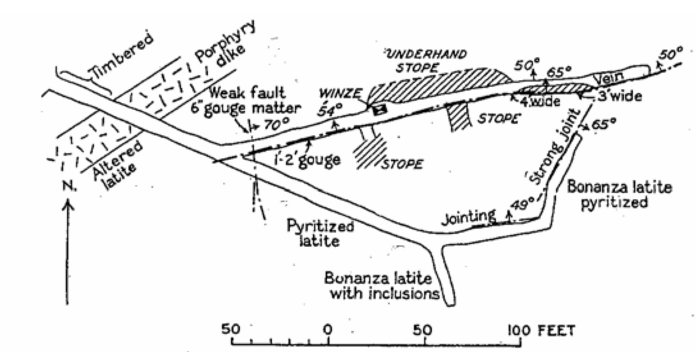

Figure 43. – Sketch map of the wheel of Fortune tunnel.

The Wheel of Fortune vein, which is developed by a shaft about 100 feet in depth (see pl. 1, No. 84), strikes about N. 60° W., as nearly as can be determined by the outcrops. The country rock is the Bonanza latite. The vein material on the shaft dump contains pyrite, sphalerite, galena, chalcopyrite, and tennantite (gray copper) in a gangue consisting mainly of quartz with some calcite. Fine granular intergrowths of sphalerite and galena were noted, and in most of the material on the dump zinc is in excess of lead, partly perhaps owing to the discarding of zinc at the time of operation. The total production of this property is not known, although it was probably not large. An estimate made by J. P. Poole[55] gives a production of 100 tons of silver-lead ore from this property from 1881 to 1900.

[55] Patton, H.B., op. cit., p. 68.

Since 1900 about 140 tons of ore produced from the district is credited to the Wheel of Fortune.

ST. JOSEPH MINE

The St. Joseph property is on the east side of Kerber Creek about half a mile above the town of Bonanza. The vein has been worked through two adits, and there are some shafts and pits on it at the surface. The portal of the lower adit is at an altitude of about 9,560 feet. The underground workings were not examined by the writer, but the outcrop of the vein can be traced and has a trend of about N. 78° W. In this vicinity, as along the lower part of Copper Gulch, there appear to be two sets of fissures, a northeast and a northwest set. The dip of the vein is not known. Patton[56] states that the ore carries lead, zinc, and silver and in certain parts of the vein has a gold content as high as 1 ounce to the ton. The lower adit is said to be over 560 feet in length and is probably entirely in andesite.

MINES OF THE SOUTHERN PART OF THE DISTRICT

EAGLE MINE

HISTORY AND PRODUCTION

The Eagle mine is in the southern part of the Bonanza district, in Eagle Gulch, about three-quarters of a mile east of Kerber Creek. It is the only mine in the district from which there has been appreciable production from a vein of the rhodochrosite-fluorite type. The underground workings were not accessible in 1926 and 1927, and the following discussion of this property is based upon information furnished to the writer by Mr. C. N. Glascow, upon published accounts of the mine,[57] and upon microscopic examination of specimens obtained from the dump and other sources. The writer is especially indebted to Mr. Glascow, who furnished specimens of ore from the 600-foot level and gave other information concerning the character of the vein. A part of the following description is drawn from the published report of Wuensch.

Regarding the early history of the property Wuensch[58] says:

It was discovered in the fall of 1882, but little more than assessment work was done on the property for a number of years. A prominent lens of quartz containing an abundance of manganese oxides outcropped, but its silver and gold content were practically nil. At a depth of about 40 feet a small pocket of native and horn silver ore was found which netted $1,200 from approximately 1,200 pounds. This stimulated development, and at a depth of 90 feet the water level was reached without finding

[56] Idem, p. 105.
[57] Idem, pp. 114-117. Wuensch, C.E., Secondary enrichment at the Eagle mine, Bonanza, Colo.: Am. Inst. Min. and Met. Eng. Trans., vol. 69, pp. 96-109, 1923.
[58] Wuensch, C.E., op. cit., pp. 96, 97.

any more ore. Desultory operations were conducted by various lessees for several years, and on the 134-foot level a few small "bunches" of residual primary ore, which had escaped leaching, were found; because of their low grade (average 12 ounces silver and 0.02 ounce gold) operations proved unprofitable. In 1898 the owner, a local merchant, sank a shaft to a depth of 200 feet, where the top of the zone of secondary enrichment was encountered. The rich sulphide streaks were carefully sorted out and the low-grade vein material used to fill the stopes. The ore shipped averaged about 130 ounces of silver and 0.30 ounce in gold. Occasionally the gold content was as high as 2 to 3 ounces.

The production for the years 1902–1926 is shown in the accompanying table.

Production of the Eagle mine, 1902-1926 [a]

Year	Ore (dry tons)	Concen-trates produced (dry tons)	Gross content of concentrates and smelting ore			
			Gold (fine ounces)	silver (fine ounces)	Lead (wet pounds)	Copper (wet assay, pounds)
1902	20	-----------	5.00	2,000	----------	--------
1903	90	-----------	21.77	8,189	----------	--------
1904	224	-----------	56.00	44,800	----------	--------
1915	50	6	.60	385	60	--------
1917	[b]117	-----------	2.11	1,735	1,576	133
1920	[c]4,000	102	44.50	16,620	4,957	212
1921	[d]4,500	98	17.68	22,805	8,446	141
	175	-----------	21.00	34,908	14,717	354
1922	[e]9,200	184	18.50	31,564	11,183	238
	5	-----------	.30	1,208	401	--------

[a]No production in years omitted from table since 1902. See text for production prior to 1902. Compiled from mine records of U. S. Geological Survey and Bureau of Mines.
[b] Includes 7 tons from Eagle dump.
[c] Ore from Eagle dump.
[d]Largely old fillings from stopes between 400 and 500 foot levels.
[e]Ore from 500 and 600 foot levels.

Between 1904 and 1916 the mine was not worked, but in 1916 and 1917 some small shipments of ore were made. About 1917 the operation of the mine was undertaken on a larger scale by the Saguache-Eagle Mining Co. A 50-ton flotation mill was erected, and from 1920 to 1922 it treated 17,700 tons of ore. Smelting ore amounting to 180 tons was also shipped to the smelter.

The mill was closed in June, 1922, as the primary ore of the lower levels with the mining methods employed had proved of too low average grade to treat profitably. Up to 1930 it had not been operated since that time. The total production of the Eagle mine is not known, as there are no detailed accounts of production prior to 1902.

DEVELOPMENT

The Eagle property embraces two abutting patented claims, the Eagle and the Hawk, and three other unpatented claims known as the West Eagle, South Eagle, and East Eagle. A shaft 650 feet in depth has been sunk near the common end line of the Hawk and Eagle claims at an altitude of about 9,620 feet. The drifts and stopes at the time when the mine was last closed are shown in Plate 35. An adit known as the Hawk tunnel has been driven on the south side of Eagle Gulch opposite to the shaft at an altitude of about 9,535 feet. The Eagle shaft follows the west or Eagle vein to a point between the 134 and 200-foot levels, but below this it is in the footwall of the veins and connected to the drifts by crosscuts. In all there is nearly 4,000 feet of drifts and crosscuts, including the Hawk tunnel.

GEOLOGIC FEATURES

The Eagle vein so far as is known lies entirely in the Eagle Gulch latite, an intrusive volcanic rock. The veins in the Eagle mine occupy a system of nearly parallel branching fissures which strike N. 12°-37° W. and dip 75°-90° E. In the upper levels the fissured zone is 60 to 70 feet wide and three principal veins are developed — the Eagle vein, the intermediate vein, and the east vein. Their relative positions are shown on the vertical cross section of the shaft in Plate 35. Regarding the structural features of these veins Wuensch[59] says:

The first, the Eagle, outcrops prominently in two places and contains an abundance of manganese oxides in a quartz gangue; small amounts of limonite and fluorite are also present. The outcrops of the other two, the intermediate and east veins, are scarcely discernible. The outcrop of the east vein consists of a mixture of barren quartz, silicified, and kaolinized porphyry with only a slight manganese stain. The intermediate vein does not seem to outcrop; only a small manganese-stained fracture is found on the surface.

The oxidized ore is very porous; the sulphide zone not so much, but both are of such an open texture as to permit rapid and deep circulation of the surface waters.
The Eagle and east veins are well defined. They vary from 2.5 to 17 feet in width, with an average of 4 to 5 feet. The intermediate vein is very erratic; it pinches and swells both laterally and vertically. Numerous other small feeders and fractures extend into the hanging wall, and some into the footwall. These terminate in relatively short distances and join either of the two major veins. The veins occupy well-defined fracture planes, as well as erratic fractures suggestive of shearing. The footwall is especially well developed in all the veins, the hanging wall not so well.

Between the fifth and sixth levels a false footwall is found in addition to the real footwall. This has proved most disastrous to the mining of the ore body by the shrinkage system between these levels. It was wholly unexpected because, except for two small lenses of latite found lying along the footwall of the vein in the upper

[59] Wuensch, C.E., op. cit., p. 98.

parts of the mine, the walls were very firm and well adapted to this system of mining. However, this false footwall material, which is from 2 to 8 feet in width (with an average of perhaps 3 feet), is uniformly present between these levels, and because of its highly altered and propylitic condition it sloughed off and seriously diluted the grade of the ore. The false footwall appears to be the downward extension of the footwall of the Eagle vein, whereas the real footwall is the downward extension of the east vein. In general, the wall rock is comparatively fresh and unaltered, except for a few feet next to the vein, where it frequently is partly silicified and pyritized.

The intersection of the Eagle (west) vein and the east vein is exposed on the 350 and 400-foot levels. This intersection pitches to the south, as indicated on the longitudinal section of the vein given in Plate 35. The intermediate vein branches off from the east vein somewhat higher. The writer was informed by Mr. Glascow that the intermediate vein is not much more than 6 inches wide in places but contained some small bodies of good ore. Most of the older workings of the upper levels are on the Eagle vein. Below the 400-foot level and the junction of the east and Eagle veins only one main vein is known to be present. Between the 500 and 600 foot levels this vein averages about 4½ feet in width, and there is a definite slip or fault plane along the footwall. The hanging wall is indefinite, grading into altered and silicified country rock. The vein has a tendency to widen in depth, and at the 600-foot level there is a broken fissured zone about 17 feet in width. Below the 600-foot level the vein material is in a wide, much broken fissure zone. On the lower levels there are in both walls small branch veinlets which run very high in silver, particularly those in the footwall.

On the 350-foot level the east vein has been developed by a drift south beneath Eagle Gulch. Below the center of the gulch the vein changes in strike. According to Mr. Glascow the vein walls at this position are broken and there is no definite footwall slip, such as is found along the vein north of the gulch. Farther south, both in the Hawk tunnel and on the 350-foot level, the east vein is displaced slightly by an east-west post-mineral fault. At the extreme south end of the drift on the Hawk tunnel level the east vein is accompanied by a series of diverging mineralized fault fractures which form the footwall of the vein and against which it appears to terminate, at least locally. Explorations have not been continued beyond the intersection with these fractures because of the lean character of the mineralization in this part of the mine.

ORES

The unoxidized vein material consists largely of quartz, rhodochrosite, and fluorite with relatively small amounts of sulphides — an association that appears to be characteristic of the mineralization as a whole in the southern part of the district. (See pl. 21*, B.)* In the great bulk of the vein material left on the dump the sulphides occur in very scattered grains in the gangue and consist largely of sphalerite, pyrite, and galena, with smaller amounts of chalcopyrite and tennantite. In the lower levels of the mine, where the primary silver minerals are found, the ore is not of uniform grade, but the silver-bearing ores are said to occur in a series of high-grade lenses or chimneylike shoots separated by stretches of nearly barren gangue. These silver shoots occupy a series of late fissures which lie in and along the early low-grade vein matter and which are both oblique and parallel to the original vein walls. In a specimen of ore from one of these shoots on the 600-foot level given to the writer by Mr. Glascow the sulphides consist of pyrite, sphalerite, galena, chalcopyrite, pyrargyrite, and an unknown mineral, possibly pearceite. The gangue consists of rhodochrosite, fluorite, and manganocalcite. In this ore pyrite and sphalerite are the minerals of earliest formation and were followed by galena intimately intergrown with manganese-bearing carbonate. (See pl. 19, *B.)* The pyrargyrite and the pearceite (?) are found in smooth rounded areas in galena, suggesting that they were in the earlier stages deposited together with the galena and so of primary or hypogene origin. Pyrargyrite and chalcopyrite of a still later stage replace galena and occur intergrown with carbonate and in well-crystallized form lining and projecting into small cavities in the ore. (See pl. 22, *A, B.)* In one cavity associated with pyrargyrite there were also a few small crystals of a lead-gray soft mineral of high metallic luster and irregular fracture, containing bismuth. This mineral could not be definitely identified, and none of it was seen in a number of polished sections made of the ore. It contains no silver nor copper, so far as could be determined by microchemical tests, and may possibly be a rare sulphobismuthite of lead. The small cavities in the ore contain many small prismatic crystals of scarlet ruby silver perched on rhodochrosite, manganocalcite, or other earlier sulphides. Small greenish-yellow crystals of chalcopyrite have a similar mode of occurrence. The bases of the larger crystals are partly intergrown with carbonates. The early pyrargyrite occurring in galena is without much doubt of primary or hypogene origin, but the origin of the later pyrargyrite is more problematic. Because these minerals are in part intergrown with carbonates and earlier sulphides and because of their association with the bismuth-bearing mineral they probably represent a late stage of primary or hypogene silver enrichment. The low sulphide content of the vein as a whole and the occurrence of the silver ore in small shoots appear to be unfavorable to a deep or pronounced zone of supergene sulphide enrichment.

In vein material obtained from the Eagle dump in which no ruby silver was found the order of mineral formation was quartz, pyrite, sphalerite, galena, and chalcopyrite, followed by an intergrowth of tennantite and carbonates. The carbonate overlapped the galena slightly but not to the extent shown in the specimen containing pyrargyrite from the 600-foot level. Fluorite is an early mineral that was formed largely before the manganese-bearing carbonates and rhodochrosite. (See pl. 21, *B*.) It was partly deposited with and partly replaced early vein quartz. The later rhodochrosite replaced early quartz extensively in some parts of the vein and produced a fine-grained tough rock of pale pinkish color which resembles some intergrowths of quartz, rhodonite, and rhodochrosite seen in other veins in the district. Microscopic examination shows this material to consist almost entirely of quartz and rhodochrosite with traces of fluorite. (See pl. 21, *A*.)

As is common throughout the district, a period of silicification of the wall rock preceded the deposition of vein material. The underground relations were not seen by the writer, but surface relations and fragments of silicified rock seen in the ore confirm this conclusion as to the general relations. Regarding the condition of the wall rock Wuensch[60] says, "In general, the wall rock is comparatively fresh and unaltered, except for a few feet next to the vein, where it frequently is partly silicified and pyritized."

The writer selected some of the freshest-appearing wall rock that could be obtained from the dump. Microscopic examination shows it to be considerably altered, however, with the formation of carbonates, sericite, and pyrite. Wuensch[61] says:

In certain parts of the vein brecciated and partly silicified fragments of country rock (latite) are found. In these instances the vein is invariably nonproductive and rhodochrosite conspicuously lacking or present in very small quantity.

On the same page, in summarizing his views of the general order of mineralization, he says:

Two distinct periods of mineralization are evident. The first is characterized by an abundance of barren quartz with subordinate amounts of fluorite containing a small amount of pyrite. Later, along the same lines of fracturing, or roughly parallel fractures, the second period of mineralization is found. This was characterized by an abundance of quartz, rhodochrosite, and subordinate amounts of fluorite; the amounts vary considerably in different parts of the vein. It was with these mineralizing solutions that the argentiferous sulphides were introduced into the vein by ascending solutions. Invariably these sulphides are absent if there is no rhodochrosite, although in parts of the vein where rhodochrosite predominates but little or no sulphides are found.

The microscopic study of the ore confirms the close association of the silver sulphides with manganese-bearing carbonates. Although pyrite and sphalerite appear to have formed earlier than the vein carbonates, the carbonates in several specimens are intimately intergrown with galena, tennantite, and polybasite in such a way as to suggest their essentially contemporaneous formation.

The results of oxidation and enrichment could not be studied at first hand, and no specimens of the enriched sulphide ore of the intermediate levels of the mine could be obtained. With regard to these features Wuensch[62] states:

Roughly, the upper 100 feet of the various veins are completely oxidized, although local oxidation may extend to between 250 and 300 feet. The vein material consists of quartz, psilomelane, wad, limonite, and fluorite. The fluorite usually is completely decolorized or has a black to purplish-black tint—a decided difference from the deep

[60] Wuensch, C.E., op. cit., pp. 98, 99.
[61] Idem, p. 100.
[62] Idem, p. 99.

*green in the primary ore. Even though quartz predominates, the vein is so thoroughly stained by the manganese oxides as to give the appearance that it is the most abundant mineral. This part of the vein is practically devoid of precious metal content. It contains from a trace to 0.01 ounce gold and from 0.3 to 6 ounces silver. The higher content is found only in small residual portions where sulphides are sparingly disseminated. In these instances the rhodochrosite can usually be observed in the last stages of alteration to psilomelane. * * * In the upper part of the sulphide zone argentite coats the sphalerite and to a less extent the galena. This is unusual, because galena is usually the more effective precipitant of silver from secondary solutions. There is some evidence that chalcopyrite, which is visible in intimate association with the sphalerite, may account for this irregularity. The sphalerite is mostly of the resinous variety, although some marmatite is found. Most of the sphalerite, however, has the appearance of being of the blackjack variety, because of the sooty coating of secondary argentite. In places native silver is found in the form of delicate wires in vug holes perched on the base sulphides. Doctor Patton says wire silver is the predominating ore mineral in the Eagle. This is not the case, however. At the time of his visit to the district the mine was full of water, so that he probably derived his information from sources other than observation. Below this argentite zone the ruby silver minerals, proustite and pyrargyrite, are found in association with the other sulphides. The former appears to be slightly in excess of the latter. Occasional crystals of polybasite are found.*

The zone of secondary black or sooty sulphides mentioned by Wuensch is found in many veins in all parts of the district. In the northern part of the district it has a very short vertical range, however, compared with that in the Eagle mine. The black sooty coating commonly found on sphalerite is not believed to consist entirely of argentite, as is implied by Wuensch's description. This coating, which in some places is hardly more than a film, consists primarily of chalcocite or covellite, but the somewhat enriched silver content of some black friable ore of this nature indicates that silver is also present in some invisible secondary form. This coating of secondary copper and silver sulphides is said to have been found in the ore at least to the depth of the 350-foot level and perhaps is present to some extent on the 400-foot level. On the 600-foot level at least, as mentioned above, there is no convincing evidence of extensive supergene enrichment, and sooty coatings or films are absent. Wuensch[63] further states:

Because the original ore shoot increased in length with each successive level in depth, the volume of vein material leached must have been small compared with the volume of material subjected to enrichment; hence though the enrichment was important in increasing the grade of the secondary ore, the secondary ore was not enriched as much as is usual in such enrichments.

LIMITS OF THE ORE SHOOT

As brought out in the preceding description, the ore shoot in the upper levels was

[63] Wuensch, C.E., op. cit., p. 103.

narrow and consisted apparently of local bodies of enriched or partly leached ore. At the north end of the mine there is a gradual transition from the normal rhodochrosite-fluorite-quartz vein material into barren quartz with small amounts of fluorite and scarcely any rhodochrosite. The wall rock is partly silicified in this portion of the mine. The northern limit of the shoot is indicated on Plate 35, and in the lower levels pitches about 45° N. The southern limit of the shoot is nearly vertical, however, and is bounded by a zone of barren, bleached rhodochrosite in which, except for a few scattered bodies, the sulphides are entirely absent. This change to barren altered rhodochrosite is said to be abrupt and occurs on all levels at about the limit indicated by the nearly vertical line in Plate 35. In this barren part of the vein the rhodochrosite is soft and bleached and is partly replaced by a claylike earthy material resembling kaolin. From a commercial analysis of a mixture of rhodochrosite and this claylike mineral Wuensch[64] concluded that this mineral is nontronite, a hydrated ferric silicate of variable composition but similar to kaolin in that the alumina of kaolin is replaced in nontronite by ferric iron. Wuensch's conclusion appears to be supported by the very low alumina content of the material analyzed. A number of specimens of yellowish-white bleached material which the writer obtained from the Eagle dump were examined microscopically for the purpose of determining the occurrence of this mineral. Most of this material was found, however, to consist of a mixture of granular iron-manganese-calcium carbonate, quartz grains, and kaolinite, named in the order of abundance. The kaolinite occurs as minute colorless fibers or scales with a moderately large extinction angle ranging between 10° and 20°. The birefringence of this mineral is low, and the indices of refraction lie entirely between 1.56 and 1.57. The mineral shows no color or pleochroism such as is characteristic of the varieties of nontronite listed by Larsen.[65]

This mineral is undoubtedly kaolinite, and no minerals corresponding to nontronite were identified in specimens which the writer obtained. This statement is not intended to imply, however, that nontronite may not be present in parts of the vein, as described by Wuensch, for only a few specimens were examined by the writer. The quartz in the recrystallized carbonate consists of small irregular grains and many minute terminated crystals. The kaolinite also occurs in nearly pure-white form, filling small pockets in the carbonate and quartz. Whether or not this claylike material in the southern part of the vein is largely nontronite or kaolinite, the particular interest attached to it lies in the fact that where it is present in the vein the sulphides are practically absent. Wuensch concluded that this absence was caused by the action of surface waters which had leached the primary sulphides from the vein, and therefore he suggested that an enriched zone might be encountered at greater depths. Regarding the condition encountered on the 350-foot level south he says:[66]

Out of about 500 feet of drifting on the vein only three or four daily face samples

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[64] Idem, pp. 104-106.
[65] Larsen, E.S., Microscopic determination of the nonopaque minerals: U.S. Geol. Survey Bull. 679, pp. 217, 251, 252, 255, 258, and 259, 1921.
[66] Wuensch, C.E., op. cit., p. 105.

contained more than 2 ounces of silver and a trace in gold, although the gold content of these was much higher in all samples than from the same grade of silver ore from other parts of the mine. The average of the whole vein would not contain as much as did the average on the Hawk tunnel level, 220 feet vertically above.

Where the cross vein joins the east vein rhodochrosite containing a few disseminated crystals of the sulphide minerals characteristic of the deposit is found. The rhodochrosite shows various stages of the conversion into nontronite. The sulphide particles are rather sooty and give the appearance that they too are in the incipient stages of solution. This seems to indicate that a selective solution may have taken place—that is, that the character of the downward-circulating waters was such as to have affected the solution of the sulphides before the rhodochrosite. If this is so, there is a possibility of finding an important secondary enrichment in depth. On the other hand, there is the contradictory evidence that no important amounts of sulphides were ever present. In a few isolated parts of the veins small areas of rather fresh rhodochrosite, with an abundance of quartz and some fluorite, are found in which little or no nontronite is present, but the sulphides are absent.

It has recently come to be recognized that the formation of kaolin in nature requires a certain limited range in the acidity of the solutions causing its formation. Boydell[67] has emphasized the importance of this feature with regard to the enrichment of disseminated copper deposits. He says:

At Tyrone, N. Mex., in an ore body which occurs entirely in monzonite, the ore is comparatively hard and silicified, whilst outside the ore body, where concentration has been slight, the altered rock is highly kaolinized, soft, and only slightly silicified. The contrast is very pronounced; examination of the ore shows that it contains much unaltered pyrite largely as residual kernels, as evidence that the primary mineralization was strong. Outside the ore body, in the soft kaolinized rock, pyrite is sparsely disseminated, showing that the primary mineralization was weak.

This difference is attributed by Boyden to the more acid condition of the downward percolating waters in the neighborhood of the ore body because of the oxidation of the abundant pyrite there. In such solutions the acidity was too high for the formation of kaolin. Solutions percolating through a relatively barren gangue, as in the rhodochrosite and quartz lying south of the Eagle ore shoot, would have a low acidity, and conditions might be favorable for the formation of kaolin. The formation of nontronite is not so well understood as that of kaolin, but it is evidently, at least in some occurrences, a product of weakly acid surface solutions. Although the vein could not be studied underground at the Eagle mine, the possibility that the portion lying south of the main ore shoot was originally barren is an alternative hypothesis that appears to have support both from the general character of the veins of the southern part of the district and from consideration of the conditions under which kaolin may form.

[67] Boydell, H.C., Operative causes in ore deposition: Inst. Mining and Metallurgy Bull., pp. 64-66, 1927.

GRADE OF THE ORE

The accompanying table, taken from Wuensch's paper, gives a series of assays from different levels of the mine. Wuensch[68] says of these samples:

These samples are quite representative of the vein material on the respective levels, with the exception of the 200 foot, 300 foot, and 400 foot, which were so largely stoped out that an average could not be obtained, although the samples give an average of what remains. Samples from the 500-foot and 600-foot levels were obtained from the floors of the respective levels, samples being taken every 10 feet. If the samples of the residual lens of primary ore are omitted from the samples taken on the 134-foot level, the average silver content will be about the same as on the 90-foot level.

Shipping ore that was mined and sorted from the upper levels of the mine between 1902 and 1904 showed a content ranging between 90 and 200 ounces of silver and about 0.25 ounce of gold to the ton. The ore that was treated in the mill between 1920 and 1922 failed to show the average silver content that had been expected from the dump and mine samples. The occurrence of the rich ore in narrow shoots rendered accurate sampling of the mine very difficult and required more careful selection of stoping ground than was practiced under the mining methods actually used. The average recovery from the 17,700 tons of ore treated in the mill was between 4 and 5 ounces of silver and less than 0.1 ounce of gold to the ton. The lead content was near 0.01 percent, and the copper content practically negligible. The sources of this ore are indicated in the table on page 155. The mill recovery is said to have averaged about 72 percent, and dilution of the ore in the shrinkage stopes ranged between 10 and 15 percent.

Assays of ore from different levels of the Eagle mine[a]

Level	Au	Ag	Mn	Fe	Pb
90-foot	0.01	2.4	9.6	3.4	0.15
134-foot	0.01	[b] 9.8	4.8	2.4	0.09
200-foot	------	7.0	-------	2.0	0.10
300-foot	-------	22.7	-------	-------	-------
400-foot	-------	15.2	-------	-------	-------
500-foot.	0.02	15.5	7.6	3.1	0.50
600-foot	0.02	10.6	13.6	3.0	0.10

Level	Zn	SiO_2	Al_2O_3	S	CO_2
90-foot	Tr.	62.4	-------	0.4	-------
134-foot	0.10	-------	-------	-------	-------
200-foot	0.09	-------	-------	-------	-------
500-foot	0.20	46.6	1.7	1.7	-------
600-foot	0.20	48.8	1.2	1.1	15.5

[a]Wuensch, C. E. op. cit., p. 101.
[b]2.5 ounces excluding lens of residual primary ore.

[68] Wuensch, C.E., op. cit., p. 102.

OREGON VEIN

Near the upper end of Eagle Gulch, about 4,000 feet northeast of the Eagle mine, there is a group of claims with several exploratory tunnels and shafts known as the Oregon group. The main Oregon tunnel and shaft are at an altitude of about 10,200 feet on the north side of the gulch. (See pl. 1 and fig. 44.) The vein has also been prospected by a shaft and several tunnels on the south side of the gulch.

The Oregon vein occupies a fault zone having a strike of about N. 55° W. and a nearly vertical or steep northeasterly dip. The oxidized vein matter and altered rock crop out from a point near the crest of the ridge south of Eagle Gulch in a northwesterly direction across the gulch for a distance of 1,000 to 1,500 feet. The country rock along the outcrop consists of a complex of Rawley andesite, Hayden Peak latite, and intrusive Eagle Gulch latite, with several latitic dikes. The structural relations between these different rocks are necessarily much generalized on Plate 1.

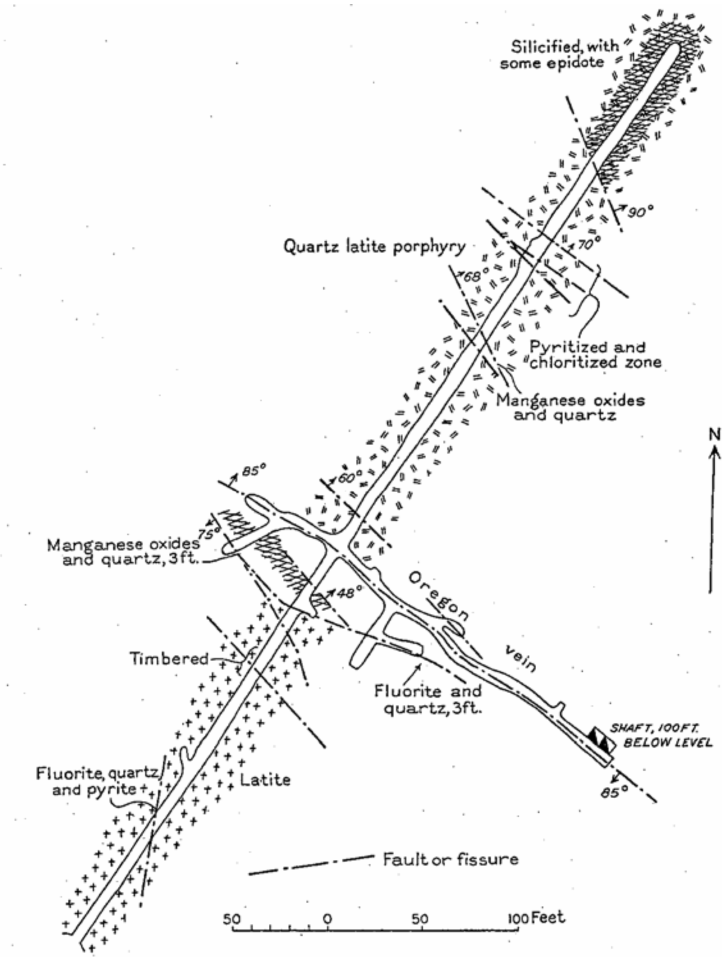


Figure 44. – Sketch map of the Oregon tunnel.

Where exposed in the Oregon tunnel the vein matter occupies a fissured zone having a width of 60 to 65 feet, but this width includes much altered rock, and the mineralization has formed parallel veins that range from a few inches to 5 feet in width. The principal vein minerals are quartz, fluorite, a little barite, and manganese and iron oxides (psilomelane and wad). The walls and rock bodies included within the vein zone are silicified and sericitized, and away from the oxidized fissures they contain pyrite. The country rock exposed in the Oregon tunnel crosscut consists of latite and quartz latite porphyry. The rocks are considerably fissured on both the north and south sides of the Oregon vein and are silicified and sericitized near the other fissures intersected by the tunnel. Other alteration products are chlorite, epidote, and pyrite. A shaft 195 feet deep has been sunk from the surface to a depth of 100 feet below the level of the southeast drift. (See fig. 44.) According to Mr. Emil Keserich, part owner, this shaft was sunk by lessees and did not expose the vein fully at depth, owing to the position of the shaft bottom in the wall of the main vein.

The assays of the vein given below were obtained from reports by C. E. Wuensch and J. H. Farrel and from the description of the vein given by Patton.[69] In a number of assays from several different sources the silver content ranges from 0.3 to 3 ounces and the gold from 0.005 to 0.02 ounce to the ton. The manganese content ranges from several to 19 percent. An average sample across 50 feet of the vein at the Oregon tunnel level assayed 3.2 percent of manganese, 0.15 percent of lead, a trace of zinc, and 0.3 ounce of silver and 0.005 ounce of gold to the ton. Massive streaks of ore from veins 2 to 8 feet in width assayed 0.005 ounce of gold and 1.1 ounces of silver to the ton, 0.09 percent of lead, 0.13 percent of zinc, 10.2 percent of manganese, 1.03 percent of sulphur, 3.1 percent of calcium oxide, and 3 percent of iron. The silica content of the vein in several samples ranged between 40 and 80 percent. A sample of 6 feet of vein material from the 100-foot shaft on the ridge southeast of Eagle Gulch assayed 19.1 percent of manganese, 10.1 percent of iron, and 3.2 ounces of silver and 0.01 ounce of gold to the ton. The low grade and oxidized nature of the vein near the surface are characteristic of the veins in this part of the district. In the description of the Eagle mine (p. 159) attention is called to the fact that the richer silver ores have been found only where the vein contained considerable rhodochrosite, but that the presence of rhodochrosite does not always indicate silver shoots. Present explorations on the Oregon vein fail to indicate definitely the position of possible rhodochrosite-silver shoots, but the work done is too shallow and does not include sufficient drifting along the exposed length of the vein to be conclusive.

VEINS OF CHLORIDE AND GREENBACK GULCHES

In Chloride and Greenback Gulches, which parallel Eagle Gulch on the southeast, there are many small prospect shafts and tunnels, but production from this area has been negligible. Along Chloride Gulch the only prospecting work of interest is that of the Chloride group, and among those tributary to Greenback Gulch are the Whitney group (No. 85, pl. 1), the Enterprise, the Crown Point (No. 19, pl. 1), the Exchange, and the Mount Hayden and Schoville groups of unpatented claims (Nos. 37 and 74, pl. 1), but this list is far from complete.

The most extensive work done in this area is that on the Chloride group of patented claims, about half a mile above the mouth of Chloride Gulch. These claims lie along the continuation of the strike of the Eagle and Hawk veins, but it is not certain that they belong to the same vein system because of intervening faults and splitting of the fissures. The principal development tunnel of the Chloride group is at an altitude of about 9,375 feet on, the south side of Chloride Gulch. This is chiefly a crosscut tunnel, but there are several drifts and winzes on the veins intersected. The tunnel has a direction of S. 88° E. for at least 440 feet, but when examined in 1927 it could

[69] Patton, H.B., op. cit., pp. 117, 118.

be entered for only 240 feet because of caved ground. At about 200 feet from the portal the tunnel intersects a northwesterly fissure on which a winze had been sunk, but the nature of the ore in place could not be seen. Other veins are said to have been cut near the breast of the tunnel and a winze sunk on one of them. One of the winzes is said to have been continued to a depth of 100 feet below the tunnel level. Vein material from the dump at the portal of the tunnel shows the gangue to consist of early quartz and fluorite, with later quartz and adularia, and a final stage of rhodochrosite. A shaft on the ridge about 900 feet southeast of the tunnel at an altitude of 9,714 feet is 240 feet in depth, and from this about 280 feet of drifting has been done, probably on a N. 45° W. vein. Vein matter from the shaft dump contains pyrite, chalcopyrite, sphalerite, and galena in a gangue of quartz, fluorite, adularia, and altered carbonate. (See pl. 20, *A*.) There are also some chalcocite, covellite, limonite, manganese oxides, and kaolin due to superficial alteration. The material of these veins, to judge from the dumps, consists chiefly of gangue. No data were obtained on the metal content of the veins, nor on the production of this group, but it is probable that no production of consequence was made.

The other veins of Chloride and Greenback Gulches consist chiefly of quartz with small amounts of carbonates, other gangue minerals, and sulphides. The extreme alteration of the volcanic rocks in this area is described on pages 25-26. Evidences of silicification, pyritization, and sericitization are common in the vein walls, but the concentration of sulphides in the vein matter of later age has been very weak. Figures on the average gold and silver content of the different veins were not obtainable, but the relative concentration of these metals is presumably comparable to that shown by such veins as the Eagle, Oregon, Express, and Pershing (pp. 168-170). According to Mr. Schoville, of Bonanza, some of the veins of the Mount Hayden and Schoville groups assay near the surface about $1 in gold and from several to 10 ounces of silver to the ton. These veins occur along the upper parts of Greenback and Schoville Gulches (Nos. 37 and 74, pl. 1) and are just outside of the area of most intense solfataric alteration that centers near the lower part of Greenback Gulch.

EXPRESS MINE

The Express mine is on the northwest side of Express Gulch about 4,000 feet northeast of the junction of Express and Kerber Creeks and is accessible by a road up Express Gulch. The Express shaft is at an altitude of 9,275 feet and is 240 feet in depth; levels are driven 96, 150, and 224 feet below the collar. The drifts were not completely accessible on all levels because of caves, but a sketch of part of the 224-foot level is shown in Figure 45. There are about 150 feet of drifts on the 96-foot level and 300 feet on the 224-foot level.

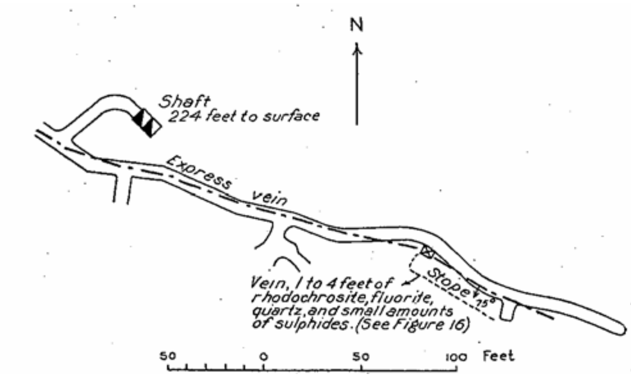


Figure 45. – Sketch map of the 224-foot level of the Express mine.

The Express vein strikes N. 50°-80° W., with an average of about N. 70° W., and dips 75° SW. on the upper level and as much as 75° NE. on the 224-foot level. To the depth explored the average dip of the vein is nearly vertical. The country rock of the mine consists of altered latite breccia, andesite, and latite or quartz latite porphyry. On the 224-foot level most of the wall rock is altered latite breccia, probably a part of the large volcanic neck on the edge of which the mine is situated: (See pl. 2.) A small block of andesite is cut on the 224-foot level on the south side of the drift about 100 feet east of the crosscut from the shaft. Owing to the intense alteration near the vein the relations of this body could not be determined during the short examination that was made. This body is locally referred to as a "basalt dike," although it is possibly a fault block of one of the andesite flows of the Rawley formation. At the bottom of the shaft a conspicuous porphyry is present, presumably an intrusive body associated with the latite breccias of the volcanic neck. The structural relations of the different wall rocks are probably complex, as is typical of the relations seen at the surface in this vicinity, but the wall rocks including the porphyry have been silicified and sericitized along the fissure, and hence all are older than the mineralization.

The Express vein ranges from 1 to 4 feet in width and has a conspicuous banded texture (fig. 13) of a type practically absent in the veins of the northern part of the district. This texture is one more typical of low-temperature (epithermal) veins, and the mineralogy of the vein further supports the classification of this vein, along with others in the southern part of the district, as of a lower-temperature type than those of the northern part. The ore minerals, which are in small proportion to the gangue, are chiefly pyrite, sphalerite, galena, and chalcopyrite, with small amounts of enargite, tennantite, pyrargyrite, covellite, and possibly bornite and stromeyerite. The gangue consists of quartz and fluorite, with some rhodochrosite and calcite. In addition to the pyrargyrite, which occurs in small blebs in the galena in a manner similar to its occurrence in the Eagle vein (pp. 157-158), there are also closely associated with it small amounts of an unidentified gray mineral, possibly another silver mineral. A similar mineral is seen inter-grown with pyrargyrite in the Eagle vein (pp. 157-158). Minute amounts of a brownish-gray mineral associated with tennantite and resembling stromeyerite, a copper-silver sulphide, which is common in the ores of the district, was seen under the microscope in a specimen taken from the dump. Although to judge from the specimens collected by the writer, pyrargyrite is not as common in the developed parts of the Express vein as in the Eagle vein, Mr. John McKenzie, owner of the property, reports the occurrence of shoots in which the silver content is high.

The mineralization in the vein, as judged from the banded texture shown in Figure 13 and from the microscopic study of sections of the ore, began with the deposition of quartz with only small amounts of fluorite. Pyrite, chalcopyrite, sphalerite, and galena, with small amounts of silver minerals, accompanied the quartz filling, but chalcopyrite is the most common mineral in the quartz. A fluorite-quartz stage appears to have followed the early quartz, carrying only very small amounts of sulphides, largely sphalerite and galena. Rhodochrosite in the main followed the major deposition of fluorite, and barren calcite was last. The metal sulphide content of the vein, like that of the Eagle vein, is very low, and the only metals occurring in sufficient amount to be of value are silver and traces of gold. The silver content of the vein as a whole is low, however, the richer ore lying in small shoots, as in the Eagle vein.

There has been no production from the Express vein, all the work up to 1928 being done for the purpose of development. Ore shoots of sufficient size or grade for mining had not up to that time been developed. Although the more extensive explorations of the Eagle vein and other properties in the southern part of the district have not yet yielded large bodies of primary ore, the amount of development work done in this part of the district does not completely exclude the possibility of finding such bodies. The oxidized and enriched tops of such ore shoots, as at the Eagle, have proved of some value, but the primary ores below have not yet been profitably mined. Exploration should be confined to the upper parts of these veins until enriched shoots of sufficient size and silver content have been discovered. The primary ore below can probably be expected to hold its average tenor to depths greater than any present explorations in this part of the district. In the Express vein exploration eastward in the andesite would probably be in more favorable country than westward toward the center of volcanic activity, where silicification and kaolinization were the dominant and usually barren types of alteration. A bleaching and softening of the rhodochrosite similar to that found in the Eagle vein is seen in the Express vein. This is usually erroneously interpreted as an indication that the metal content of the vein has been leached. This alteration was of a weak nature and was due to the formation of small amounts of kaolinite in the relatively barren gangue; the adjacent sulphide grains appear to be entirely unaffected. Whether this alteration was caused by a late circulation of warm waters of hot springs or by descending cold meteoric waters is problematic, but the second alternative is more likely. The Express vein is partly oxidized on the 96-foot level, indicating strong action of surface waters to at least this depth. On the 224-foot level there is little or no indication of oxidation, but the rhodochrosite has been bleached and softened.

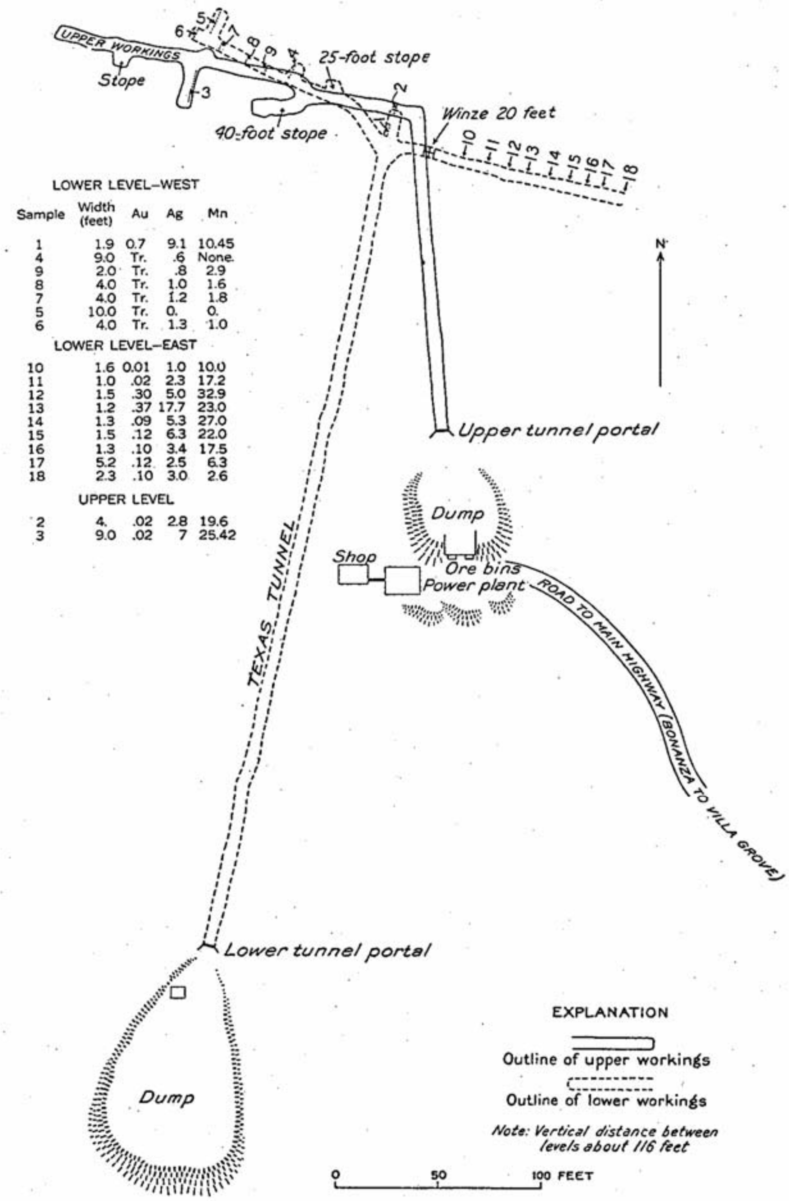
PERSHING MINE

The Pershing mine is near the head of Manganese Gulch, a short gulch paralleling Express Gulch and about 1,000 to 1,400 feet southeast of it. Development work on the vein was first done during the World War for the purpose of obtaining manganese ore, but this work was of minor extent. In 1927 and 1928, the property, which is owned by the Express-Headlight Mining & Development Co., was under lease to the Texas-Colorado Mining Co.

The Pershing or Headlight vein strikes nearly west to N. 80° W. and has a nearly vertical dip. It is developed by two crosscut tunnels and a few hundred feet of drifts. (See fig. 46.) The upper tunnel is at an altitude of 9,625 feet, and a lower tunnel, called the Texas tunnel, was driven in 1927 and 1928 and intersects the vein about 116 feet below the upper workings.

The principal country rock is the Rawley andesite, but it is much shattered and fissured and is intruded by a complicated network of rhyolite and quartz latite dikes. A large part of the rock penetrated in the Texas tunnel consists of rhyolite intrusions, the shapes of which are not definitely known because of debris on the surface which obscures their outcrop in this vicinity. The Texas tunnel was driven about 75 feet before bedrock was encountered, indicating a thickness of 30 feet or more of soil and slumped rock. The vein where cut by the upper tunnel is 3 to 4 feet in width, but it widens rapidly westward along the drift, and a shoot of manganese oxides approximately 100 feet in length and 10 to 25 feet in width had been developed in 1928. The ore in this shoot consists of mixed manganese oxides, quartz, and fragments of altered country rock.

Pyrolusite and psilomelane are the principal manganese oxides, with some admixed earthy and siliceous material and limonite. The pyrolusite occurs in massive form, in sheaflike groups of prisms, and as striated crystals lining cavities in the more siliceous ore. It may possibly represent a pseudomorphic replacement of manganite, although no unaltered manganite was recognized in the upper level. The psilomelane is in part intimately associated with the pyrolusite but in part appears to have been deposited later. In the siliceous ore the quartz is intimately associated with the oxides, preventing easy mechanical separation. Some late quartz veinlets cut through the pyrolusite, and quartz crystals incrust some of the prismatic growths of pyrolusite. The limonite is usually intergrown with the psilomelane or earthy manganese oxides. A few large and small masses of vein quartz were encountered in developing the upper tunnel, which contained a little pyrite, chalcopyrite, and sphalerite. Mr. William Heim, manager of the property, reported that some of this vein matter ran from 4 to 10 ounces in silver to the ton. Texturally and mineralogically it resembles the siliceous vein material from the Express and Eagle veins.



Sample	Width (feet)	Au	Ag	Mn
LOWER LEVEL–WEST				
1	1.9	0.7	9.1	10.45
4	9.0	Tr.	.6	None.
9	2.0	Tr.	.8	2.9
8	4.0	Tr.	1.0	1.6
7	4.0	Tr.	1.2	1.8
5	10.0	Tr.	0.	0.
6	4.0	Tr.	1.3	1.0
LOWER LEVEL–EAST				
10	1.6	0.01	1.0	10.0
11	1.0	.02	2.3	17.2
12	1.5	.30	5.0	32.9
13	1.2	.37	17.7	23.0
14	1.3	.09	5.3	27.0
15	1.5	.12	6.3	22.0
16	1.3	.10	3.4	17.5
17	5.2	.12	2.5	6.3
18	2.3	.10	3.0	2.6
UPPER LEVEL				
2	4.	.02	2.8	19.6
3	9.0	.02	7	25.42

Figure 46. – Map of the Pershing mine.

The vein is in part siliceous, and as the silica is intimately intergrown with the oxides good mechanical concentration would require rather fine crushing. There are, however, narrow shoots of practically clean pyrolusite, ranging from small veinlets up to some 1.5 feet in width. The fissured zone where cut in the lower tunnel is about 10 feet in width and consists of a series of small parallel veins with quartz and pyrolusite. According to Mr. Heim a sample across the vein at this point assayed for 8 feet 0.25 ounce of gold and 9 ounces of silver to the ton and for the additional 2 feet about $2.50 in gold and 27½ ounces of silver to the ton. The west drift from the lower tunnel failed to expose an oxide ore shoot comparable to that in the tunnel above, probably showing that these bodies are of lenticular shape. The gulch in the vicinity of the property is very dry, and attempts to obtain water in the gulch bottom below the mine were not successful. For this reason it is possible that oxidized ore may extend several hundred feet below the outcrop. The manganese oxides are presumably derived largely if not entirely from rhodochrosite.

The small amount of iron in the oxidized vein probably indicates a low percentage of primary pyrite, and in the manganese oxide shoots the complete loss of the original structure of the vein indicates a small amount of original vein quartz. The vein presumably was a quartz-rhodochrosite vein, with lenses or shoots of purer rhodochrosite, and with a comparatively low average content of sulphides.

Over 600,000 pounds of ore shipped in 1926 and 1927, which consisted largely of lumps or coarse material, roughly hand sorted as it was mined, contained from 39.7 to 44 percent of manganese, 14 to 19 percent of silica, about 8 percent of water, and 0.03 percent of phosphorus. The iron content was low, being 6 percent in the largest shipment, and there was no sulphur. Sample assays of the siliceous vein in the drifts are given in Figure 46.

MINES OF ALDER CREEK

The Alder Creek district adjoins the Bonanza district on the northeast, across the high divide between Round Mountain and Manitou Mountain. Alder Creek drains the district northeastward into the San Luis Valley. The nearest town in the San Luis Valley is Alder, on the narrow-gage branch of the Denver & Rio Grande Western Railroad. (See fig. 1.) The region adjoining the upper part of Alder Creek and shown on Plate 1 is one of steep northward or eastward-facing slopes, many of which are heavily covered with timber. Access to the mines of the upper part of Alder Creek is gained by wagon road along the creek from Alder, a distance of 4 to 5 miles. This road formerly afforded a connection with the Kerber Creek mines by way of the Colorado Belle mine and along the east and south slope of Round Mountain. In 1927 the road was passable by automobile for about 2½ miles west of Alder, but it has since been opened to permit the shipment of ore from the Joe Wheeler mine. When the road has been in good condition automobiles have also been driven almost to the end of the road, in the bottom of the valley near the head of the creek.

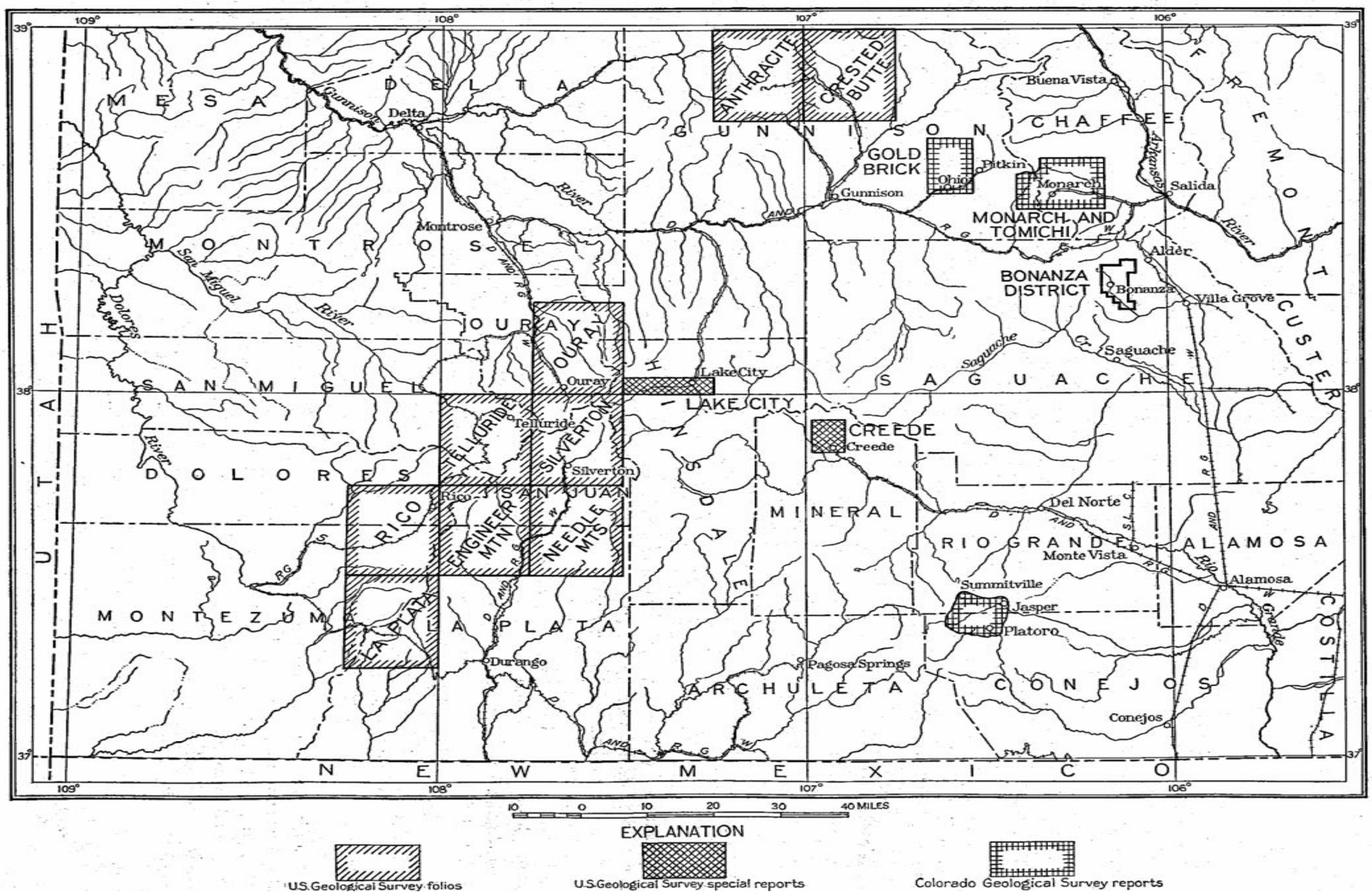


Figure 1. – Map of southwestern Colorado, showing location of Bonanza mining district and other districts.

The general relation between the geologic features and mineralization in the Alder Creek area is discussed on pages 71-72. The production from the mines of this area has undoubtedly been small, and the activity has not revived much since the earliest discoveries and prospecting. Of recent years there has been intermittent production by lessees from the Golden Wave (Joe Wheeler) and Silver Queen claims and possibly a few others. There are also several prospects that lie east of the area mapped and were not examined.

JOE WHEELER MINE

The Joe Wheeler mine (No. 39, pl. 1) is on the slope north of Alder Creek at an altitude of 10,700 feet. It consists of several tunnels and shafts, the present main working tunnel being on the Golden Wave claim (unpatented). The property is owned by the Joe Wheeler Mining & Milling Co. The Joe Wheeler vein where exposed in the main tunnel (fig. 47) has a strike of N. 10°-15° W. and a nearly vertical dip. When examined in 1927 the vein had been opened for a length of about 50 feet by a manway and stope from 30 to 35 feet above the tunnel level. In the northern and upper part of this stope the vein had a dip of 70° W., but in the lower 20 feet the vein reversed its dip to 73°-75° E. The vein occupies a fault zone about 6 to 8 feet in width but consisted where exposed of two parts — a lenticular body of ore from 1 to 4 feet wide against the east wall of the fault, and another vein 1 to 2 feet wide against the west wall — separated by a horse of altered rock and low-grade vein matter. The hanging or east branch of the vein consisted of a quartz-barite gangue carrying chalcopyrite, bornite, and gray copper, with some pyrite, sphalerite, and galena. The mineralized rock on the west wall contained a higher proportion of galena, and the writer was told that it was of lower silver content. At the north the Joe Wheeler vein is cut off by a N. 10°-20° E. gougy fault, which contained lenses of ore consisting chiefly of sphalerite and galena. A small stope 3 to 4 feet in width had been mined out above the tunnel level on this fault. The tunnel also crosscut through the fault, but it was caved, and whether a vein corresponding in strike to the Joe Wheeler had been discovered in the west wall could not be determined. The only country rock exposed adjacent to the Joe Wheeler vein and in other parts of the tunnel was the Rawley andesite, which is considerably sericitized and pyritized near the fissures and veins and locally replaced by quartz.

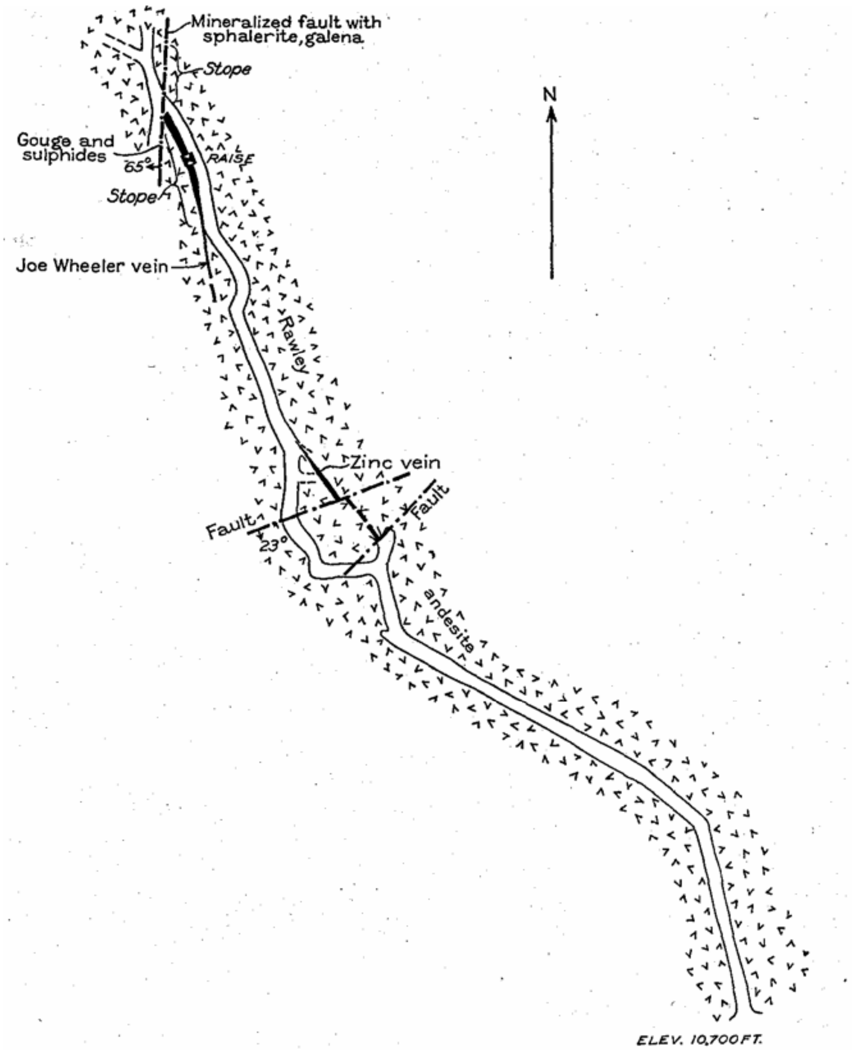


Figure 47. – Sketch map of the Joe Wheeler tunnel. Scale 1 inch = 100 feet.

There are several other tunnels and shafts on the hill above the Joe Wheeler tunnel, and these extend in a northwesterly direction to the saddle on the ridge about 375 feet higher than the tunnel. (See pl. 1.) The dump material and leached vein from the surface show that mineralization along this zone above the tunnel consisted chiefly in the formation of quartz, barite, rhodochrosite, sphalerite, and galena, with some pyrite and other sulphides. On the other hand, tunnels farther down the gulch in line with and below the Joe Wheeler vein show chiefly quartz, barite, chalcopyrite, and pyrite, with lesser amounts of galena and sphalerite. It would appear, therefore, that there was a pronounced decrease in lead content of the veins of this fissure system in depth.

The mineralogy of the Joe Wheeler vein is not greatly different from that of the veins in the Kerber Creek mines, except that barite is more abundant than in the greater number of the veins in Rawley Gulch. The order of crystallization in any particular piece of vein matter is essentially quartz, barite, pyrite, sphalerite, and an intergrowth of galena, bornite, chalcopyrite, and tennantite. The relations of galena and the copper minerals are variable. Chalcopyrite occurs in microscopic particles in sphalerite, and bornite and chalcopyrite of an early stage have replaced crackled grains of pyrite, but the deposition of chalcopyrite seems to have continued intermittently until most of the galena was deposited. Photomicrographs of the ores showing relations of the common minerals of the Joe Wheeler vein are reproduced in Plates 14, A, *B,* and 16, *D.* In addition to the more common minerals mentioned above there are small amounts of an unidentified lead and bismuth bearing mineral, probably a sulphobismuthite of lead such as cosalite, and some chalcocite, covellite, and stromeyerite. Chalcocite and stromeyerite are late minerals but may belong to a late period of the primary (hypogene) mineralization. The lead-bismuth mineral is clearly primary and where seen is associated with galena and stromeyerite. (See pl. 17, *C, D.)*

Shipments of crude smelting ore made from the Golden Wave claim in 1917, 1919, 1926, 1927, and 1928 amounted to a total of 138 tons. The gross metal content was 0.35 ounce of gold, 1,210 ounces of silver, 39,653 pounds of lead, 840 pounds of copper, and some zinc of which the records are incomplete. One shipment of 23 tons of lead-zinc ore assayed 8.4 percent of lead and 5.7 percent of zinc. Another shipment of 16.4 tons, which is said to have been broken for the full width of the vein without sorting, assayed 6.9 ounces of silver to the ton, 11.7 percent of lead, 9.7 percent of zinc, 55.9 percent of insoluble matter, and 11.4 percent of sulphur.

COLORADO BELLE MINE

The Colorado Belle (No. 14, pl. 1), located as the Belle of Colorado, is one of the very old claims of the district, having been located in 1881 and patented in 1887. The workings are near the first saddle of the ridge extending northeastward from Round Mountain, at an altitude of about 10,290 feet. In 1883 the Director of the Mint[70] made the following statement:

On the opposite side of Round Mountain at the Alder Gulch are situated a number of fine prospects of which the Belle of Colorado is the principal. Near the surface the ore was galena, but as depth was attained the mineral gave out, and nothing was uncovered until the shaft was down about 80 feet, when the vein was found, and at the bottom of the shaft, 90 feet in depth, nearly 3 feet of mineral is exposed. The large percentage of gray copper which the ore carries in the lower workings renders it of a much higher grade than that encountered near the surface.

When the patent survey was made in 1884 the depth of the shaft was given as 130 feet. It is not known whether there was any production from this property.

The Colorado Belle shaft was entirely inaccessible when examined in 1927, and the vein could not be studied underground. Surface exposures, although poor, indicate that the vein has a roughly east-west and a southerly dip, possibly as low as 60°. Vein material on the dump has a gangue of quartz, barite, and a manganese-bearing carbonate of salmon-pink color, and the sulphides consist chiefly of pyrite, sphalerite, and galena. Rock of the dump shows that silicification of the wall rock occurred before mineralization. The rocks exposed in the vicinity of the mine comprise flows in the Bonanza latite and Rawley andesite. (See pl. 1.)

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[70] Burchard, H.C., Report of the Director of the Mint upon the production of the precious metals in the United States, 1882, p. 540, 1883.

OTHER MINES AND PROSPECTS

There are many other prospect tunnels and shafts on the slopes of the gulches tributary to the head of Alder Creek, some of which are shown on Plate 1. Sufficient accurate data on these openings were not obtained to permit their individual description without the possibility of giving misleading impressions. Many of the larger prospecting tunnels were driven early in the mining history of the region and therefore are now inaccessible, but attention may be called to two of them.

One of these older active properties is the Manitou, comprising a group of claims developed largely by a common improvement tunnel on the Green Bay claim (No. 49, pl. 1) and situated at an altitude of 11,519 feet on the steep northeasterly slope of the divide between Alder and Rawley Gulches. In 1883[71] the Manitou is reported as continuing development work, a crosscut tunnel 650 feet in length having been driven to intersect the Little Manitou vein. In this same year the Big Manitou is reported to have shipped a small amount of ore.

In 1888[72] the Emma, possibly the Emma lode of the Manitou group, is credited with a production of $9,381.40, consisting of $40 in gold, $7,757.40 in silver (at $1.29 an ounce), and $1,584 in lead (at $87 a ton). Another of the larger common development tunnels is that on the Great Depth claim (No. 30, pl. 1), but this tunnel was inaccessible in 1927.

[71] Burchard, H.C., Report of the Director of the Mint upon the production of the precious metals in the United States, 1883, p. 404, 1884.
[72] Munson, G.C. (agent for Colorado), in Kimball, J.P., Report of the Director of the Mint upon the production of the precious metals in the United States, 1888, p. 121, 1889.

SURVEYED MINING CLAIMS, GIVING LAND OFFICE SURVEY NUMBER

(In alphabetical order)

Name	Number	Sec.	T.N.	R.E.
Ajax	1332	8, 17	47	8
Alice	16861(1)	24	47	7
American Eagle	1388	17	47	8
Antoro	937	18	47	8
Arctic	14183(10)	18	47	8
Ashley	20125(2)	17, 18	47	8
Atlantic	7820	19	47	8
Aurora	1459	24	47	7
Backus	13598(1)	25 30	47 47	7 8
Baltimore	15099(1)	24	47	7
Baltimore No. 2	15099(2)	24	47	7
Bay State	14672(3)	30. 31	47	8
Beaver	1154	25	47	7
Belle of Colorado	2128	8	47	8
Bernice	6011	9	47	8
Big Manitou	1321	17	47	8
Black Bess	19582 Am.	24	47	7
Black Bess No. 2	19863	24 19	47 47	7 8
Blue Bell	20365	17	47	8
Bob Burdette	1052	17, 20	47	8
Bonanza	614	24	47	7
Bonanza No. 1	18775(1)	24	47	7
Bonapart	13598(2)	30	47	8
Boston	2291	23	47	7
Boston	14672(4)	30	47	8
Boston No. 1	19975(2)	23, 24	47	7
Botha	14845(1)	30	47	8
Brighton	16744(1)	7, 18	47	8
Brooklyn	18824	7	47	8
Buffalo	18803	17	47	8
Burlington	19552(1)	17	47	8
Burnes	19033(1)	18, 19	47	8
Cabin	17834	18, 19	47	8
Camp Bird	1624	18	47	8
Carrie Eugene	965	7	47	8
Chicago	8524(2)	30	47	8
Chicago No. 2	18392(4)	16	47	8
Chicago No. 8	18392(1)	17	47	8
Chicago No. 11	18392(2)	16, 17	47	8
Chicago No. 14	18392(3)	16	47	8
Chicago Nc. 16	18392(5)	16	47	8
Chief	14672(1)	30, 31	47	8
Chloride	19056(1)	6, 7	46	8
Chloride No. 2	19056(2)	6, 7	46	8
Chloride No. 3	19056(3)	6, 7	46	8
Chloride No. 4	19056(4)	6	46	8
Cincinnati	2267	24	47	7
Cliff	13597(1)	30	47	8
Cobalt	19144(1)	24	47	7
Cocomongo	18775(2)	24	47	7
Coin	13597(3)	30	47	8
Columbine	20366(1)	17	47	8
Columbus	1348	17	47	8
Columbus	13598(3)	30	47	8
Continental	19611(2)	17, 18	47	8
Cora	6014	18	47	8
Cornucopia	20012	24	47	7
Coronet	7515(2)	18	47	8
Cracker Jack	19611(4)	8, 17	47	8
Crain Boy	1502	19, 30	47	8
Crescent	19144(5)	24	47	7
Crescent No. 2	19144(6)	24	47	7
Cretone	19144(3)	24	47	7
Crevet	19144(2)	24	47	7
Cronje	14845(2)	30	47	8
Cross	19552(2)	17	47	8
Crown Point	1786	7, 18	47	8
Daisy	20366(3)	17	47	8
Dallas C. No. 1	19056(6)	7, 8	46	8
Dallas C. No. 2	19056(5)	7, 8	46	8
Dandy	19611(5)	8	47	8
Defiance	591	25	47	7
Demming	1016	18	47	8
Denver	20364(4)	8	47	8
De Soto	1024	25	47	7
Divide	19611(1)	18	47	8
Durango	1221	17	47	8
Eagle	9176(1)	6	46	8
Emma	1319	17	47	8
Empress Josephine	625	30	47	8
Enness F.	14347(1)	17, 18, 19	47	8
Enterprise	14700(2)	7, 8	46	8
Equalizer	14347(2)	17, 18, 19	47	8
Erie	13580	19	47	8
Esther	15541(1)	18	47	8
Ethelyn	19033(2)	19	47	8
Evening Star	1692	7	47	8
Excelsior	7283	25	47	7
Exchequer	6424	24	47	7
Express	16850	8	46	8
Fairplay	5358	7	47	8
Forest	20364(8)	8	47	8
59er	1391	23, 24	47	7
Foster	15513	18, 19	47	8
Four Per Cent	927	7	47	8
Gem City	7699	17	47	8
General Hancock	6016	18	47	8
Gypsy Queen	15541(3)	18	47	8
Glennbrook	2190	30	47	8
Glennevis	16744(3)	7, 18	47	8
Golden Age	18825(1)	7, 8	47	8
Golden Blow Out	14700(3)	8	46	8
Golden Fleece	1931	19	47	8
Grand View	1320	17	47	8
Grant	20364(9)	8	47	8
Great Depth	19611(6)	8	47	8
Great Depths No. 2	19611(7)	8	47	8
Great Eastern	2304	24	47	7
Great Mogul	14347(3)	17	47	8
Green Bay	1349	8, 17	47	8
Grover Cleveland	17738	24 19	47 47	7 8
Hanover	14348	19	47	8
Hawk	9176(2)	6	46	8
Headlight	19198	8	46	8
Helen Segar	7515(1)	18	47	8
Horace	1025	25	47	7
Hortense	909	30	47	8
Huron	1932	19	47	8
Hyde	15499	18	47	8
Idaho	20286(1)	19	47	8
Ignacio	14183(8)	18	47	8
Illinois	945	30	47	8
Independence	14183(1)	18	47	8
Iroquois	7152	7	47	8
Itasca	1350	8	47	8
Jack Pot	14697(2)	6	46	8
Jackson	20364(3)	8, 17	47	8
Japan	19552(3)	17	47	8
Joubert	14845(3)	30	47	8
June	1364	18	47	8
Jupiter	17251	18	47	8
Juretta	16861(2)	24	47	7
Katie	6036	8	47	8
Keystone	666	24 19	47 47	7 8
Kruger	14845(4)	30	47	8
Larkspur	20366(2)	17	47	8
Last Chance	1583	19, 20	47	8
Lawrence	966	19	47	8
Lee	20364(5)	8	47	8
Legal Tender	6013	7	47	8
Lincoln	19532(1)	18	47	8
Little Jennie	771	18	47	8
Little Jersey	2265	13, 24	47	7
Little Manitou	1351 A	17	47	8
Little Manitou (M.S.)	1351 B	17	47	8
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Number	Name
[illegible]	[illegible]
15541(3)	Gypsy Queen
15719	Midget
15951(1)	Portland
15951(2)	Ophir
16306(1)	Senator
16306(2)	Senator No. 2
16568	Saint Joseph
16744(1)	Brighton
16744(2)	Mount Joy
16744(3)	Glennevis
16850	Express
16861(1)	Alice
16861(2)	Juretta
17148	Minnie Lynch
17177	Pocahontas 2d
17178	Memphis
17251	Jupiter
17462	Lost Wonder
17738	Grover Cleveland
17834	Cabin
17850(1)	Pueblo
17850(2)	Pueblo No. 2
18392(1)	Chicago No. 8
18392(2)	Chicago No. 11
18392(3)	Chicago No. 14
18392(4)	Chicago No 2
18392(5)	Chicago No. 16
18611	Uintah
18775(1)	Bonanza No. 1
18775(2)	Cocomongo
18791(1)	Simonds
18791(2)	Wainwright
18792	West Rawley No. 1
18803	Buffalo
18824	Brooklyn
18825(1)	Golden Age
18825(2)	President
18825(3)	Vice President
18825(4)	Veni Vidi Vici
19033(1)	Burnes
19033(2)	Ethelyn
19056(1)	Chloride
19056(2)	Chloride No. 2
19056(3)	Chloride No. 3
19056(4)	Chloride No. 4
19056(5)	Dallas C. No. 2
19056(6)	Dallas C. No. 1
19144(1)	Cobalt
19144(2)	Crevet
19144(3)	Cretone
19144(4)	Lone Star
19144(5)	Crescent
19144(6)	Crescent No. 2
19198	Headlight
19532(1)	Lincoln
19532(2)	Washington
19535	Minnesota
19552(1)	Burlington
19552(2)	Cross
19552(3)	Japan
19582 Am.	Black Bess
19601	Middle
19611(1)	Divide
19611(2)	Continental
19611(3)	Timberline
19611(4)	Cracker Jack
19611(5)	Dandy
19611(6)	Great Depth
19611(7)	Great Depths No. 2
19863	Black Bess No. 2
19899(1)	Mary Jane
19899(2)	Mary Jane No. 1
19899(3)	Mary Jane No. 2
19975(1)	New York No. 1
19975(2)	Boston No. 1
19975(3)	New York No. 2
19975(4)	New York No. 3
19975(5)	New York No. 4
19975(6)	New York No. 5
20012	Cornucopia
20049	U. S. Grant
20089(1)	Mary McGinnis
20089(2)	Paddy Doyle
20089(3)	~~Pelican~~
20089(4)	Ubique
20125(1)	Weaver
20125(2)	Ashley
20125(3)	Weems
20125(4)	Sanders
20127	Sylvester
20286(1)	Idaho
20286(2)	Navajo
20364(1)	Salida
20364(2)	Sheridan
20364(3)	Jackson
20364(4)	Denver
20364(5)	Lee
20364(6)	Pemberton
20364(7)	Sherman
20364(8)	Forest
20364(9)	Grant
20364(10)	Meade
20365	Blue Bell
20366(1)	Columbine
20366(2)	Larkspur
20366(3)	Daisy

MINE AND PROSPECT WORKINGS

Name	Location Sec.	T.N.	R.E.
1. Antoro shaft	18	47	8
2. Antoro tunnel	18	47	8
3. Ashley tunnel	17	47	8
4. Baltimore	24	47	7
5. Bernice	9	47	8
6. Black Bess	24	47	7
7. Bonanza shaft	24	47	7
8. Broadbury group	12	47	7
9. Buffalo	17	47	7
10. Chloride shaft	6	46	8
11. Chloride No. 4 tunnel	6	46	8
12. Cliff No. 1 tunnel	30	47	8
13. Cocomongo shaft	24	47	7
14. Colorado Belle shaft	8	47	8
15. Cora shaft	18	47	8
16. Cornucopia	24	47	7
17. Cronje tunnel	30	47	8
18. Cross	17	47	8
19. Crown Point shaft	8	46	8
20. E. D. shaft	17	46	8
21. Eagle shaft	6	46	8
22. Empress Josephine shaft	30	47	8
23. Erie	19	47	8
24. Essie and Little Jeff	17	47	8
25. Evening Star	7	47	8
26. Exchequer	24	47	7
27. Express	8	46	8
28. Gladstone shaft	17	47	8
29. Glennbrook	30	47	8
30. Great Depth	8	47	8
31. Great Mogul	17	47	8
32. Green Bay	17	47	8
33. Gypsy Queen	18	47	8
34. Hanover tunnel	19	47	8
35. Hanover inclined shaft	19	47	8
36. Hawk tunnel	6	46	8
37. Hayden Mountain No. 2	5	46	8
38. Hortense	30	47	8
39. Joe Wheeler	5	47	8
40. Jupiter	18	47	8
41. Juretta tunnel	24	47	7
42. Katie	8	47	8
43. Legal Tender mine	7	47	8
44. Liberty	30	47	8
45. Little Jennie adit	18	47	8
46. Little Pittsburg	24	47	7
47. Little Thelma	6	46	8
48. Lone Star	24	47	7
49. Manitou Sunlight	9	47	8
50. Mariposa adit	30	47	8
51. Maybelle tunnel	7	47	8
52. May Queen	18	47	8
53. Memphis shaft	24	47	7
54. Michigan shaft and adits	18	47	8
55. Minnesota	17	47	8
56. Minnie Lynch	19	47	8
57. New York shaft	24	47	7
58. Now What	30	47	8
59. Oregon tunnel	5	46	8
60. Paddy Doyle	19	47	8
61. Paragon No. 1	18	47	8
62. Paragon No. 2	18	47	8
63. Paragon No. 3	18	47	8
64. Payson	18	47	8
65. Pershing mine	8	46	8
66. Queen City tunnel	20	47	8
67. Radcliff	18	47	8
68. Rainbow	17	47	8
69. Rawley drainage tunnel portal	24	47	7
70. Red Buck	25	47	7
71. Rico	7	47	8
72. Saint Joseph	25	47	7
73. Saint Louis	30	47	8
74. Schoville group	8	46	8
75. Senator	19	47	8
76. Shawmut tunnel	7	47	8
77. Sosthenis	18	47	8
78. Stem Winder	20	47	8
79. Superior	19	47	8
80. Vallejo	18	47	8
81. Vienna	7	47	8
82. Whale	19	47	8
83. Wheel of Fortune tunnel	25	47	7
84. Wheel of Fortune shaft	25	47	7
85. Whitney group	7	46	8
86. Wide Awake	25	47	7
87. Wisconsin	18	47	8

Topography by C. A. Ecklund and J. E. Blackburn
Surveyed in 1926

WILLIAMS & HEINTZ CO. WASH. D.C.

Geology by W. S. Burbank
Surveyed mining claims compiled from General Land Office records by W. S. Burbank

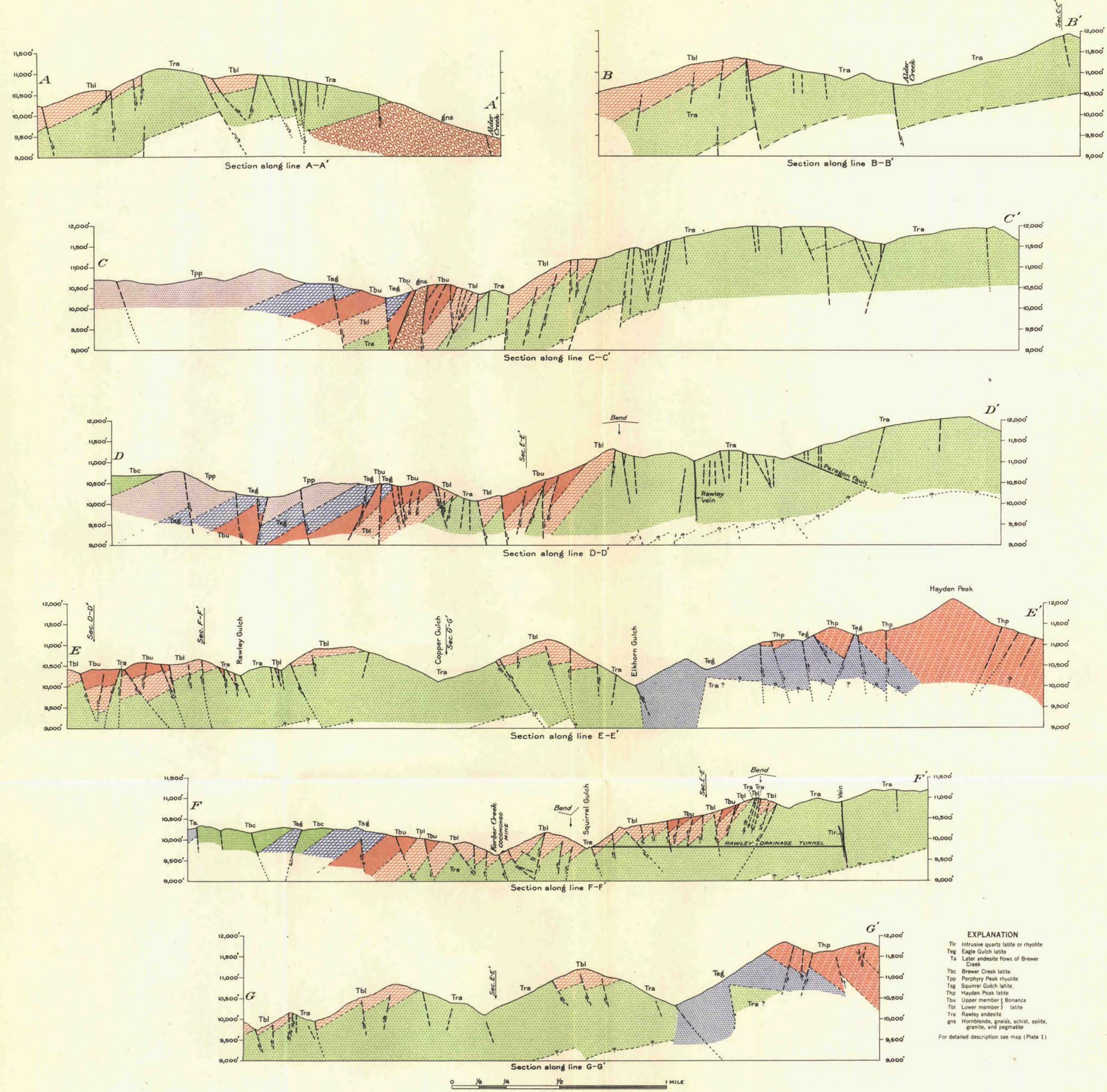
GEOLOGIC AND TOPOGRAPHIC MAP SHOWING SURVEYED MINING CLAIMS AND UNDERGROUND DEVELOPMENT IN THE BONANZA DISTRICT, SAGUACHE COUNTY, COLORADO

Scale $\frac{1}{12,000}$

0 ½ 1 Mile

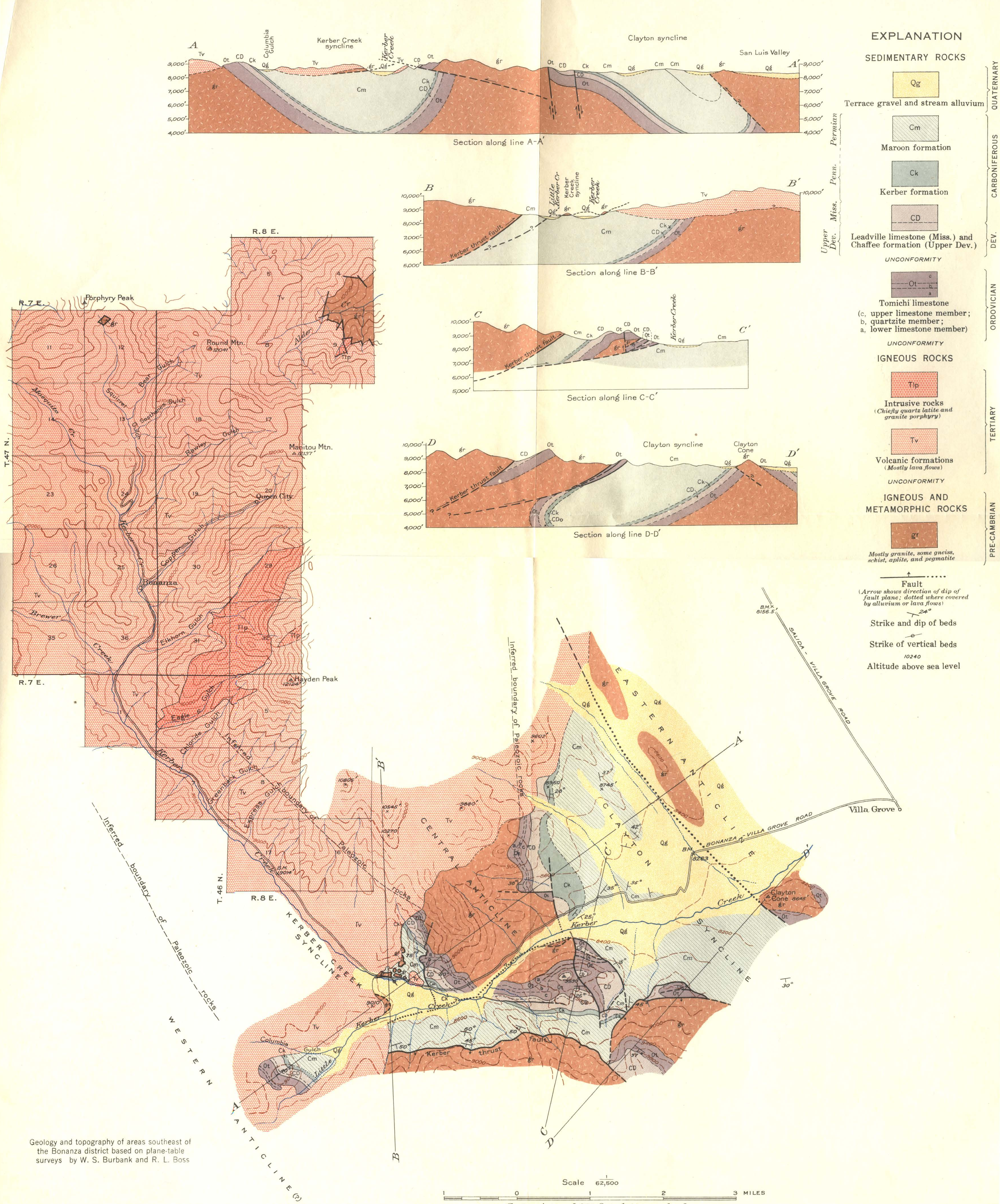
Contour interval 20 feet
Datum is mean sea level

1931



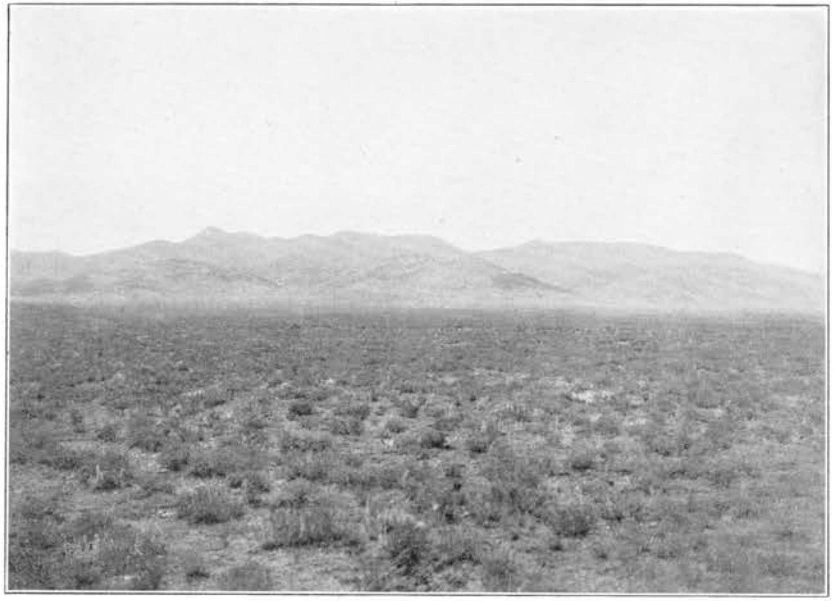
GEOLOGIC SECTIONS ACROSS THE BONANZA DISTRICT, COLO.

1931



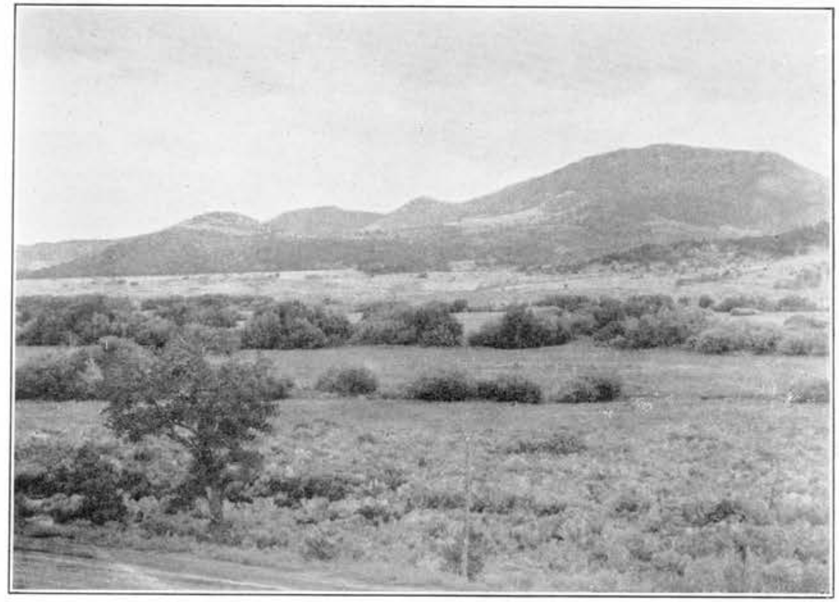
GEOLOGIC RECONNAISSANCE MAP AND SECTIONS OF THE KERBER CREEK REGION, SAGUACHE COUNTY, COLO.

1931



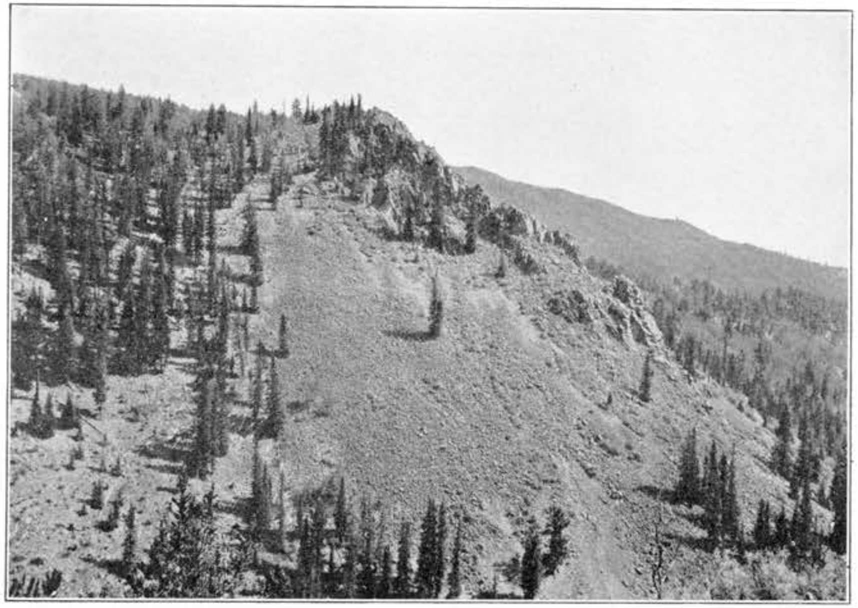
A. THE EASTERN RANGE OF THE BONANZA DISTRICT VIEWED FROM THE EDGE OF THE SAN LUIS VALLEY

Looking northwestward. The conical peak at the left is Hayden Peak, and the high, flat summit at the extreme right of the view is Manitou Mountain.



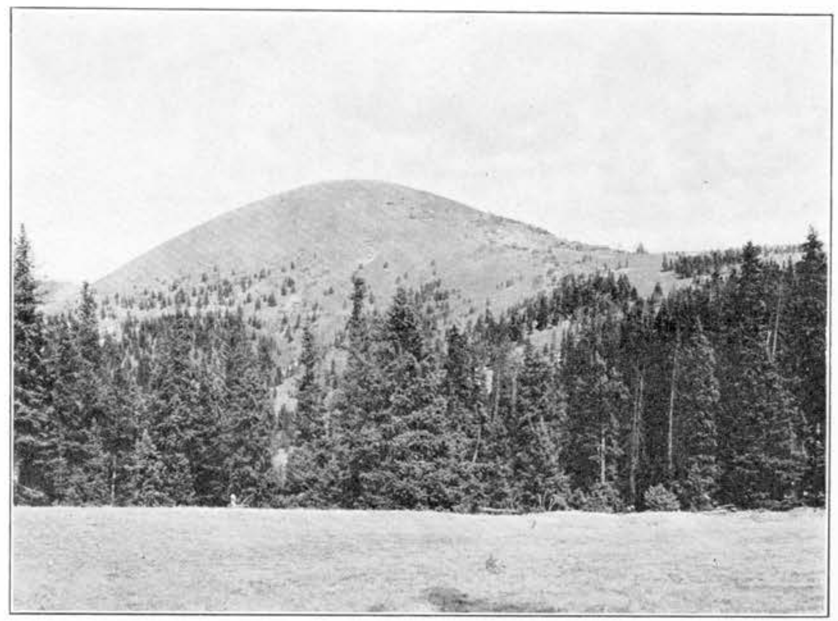
B. VIEW SOUTH ACROSS KERBER CREEK FROM THE BONANZA-VILLA GROVE ROAD TOWARD THE SAGUACHE HILLS

The hills consist of westward-dipping thrust blocks of Paleozoic limestones and pre-Cambrian granite, and the lower, flatter areas are largely underlain by the Maroon formation. (See pl. 3 and text, p. 40.)



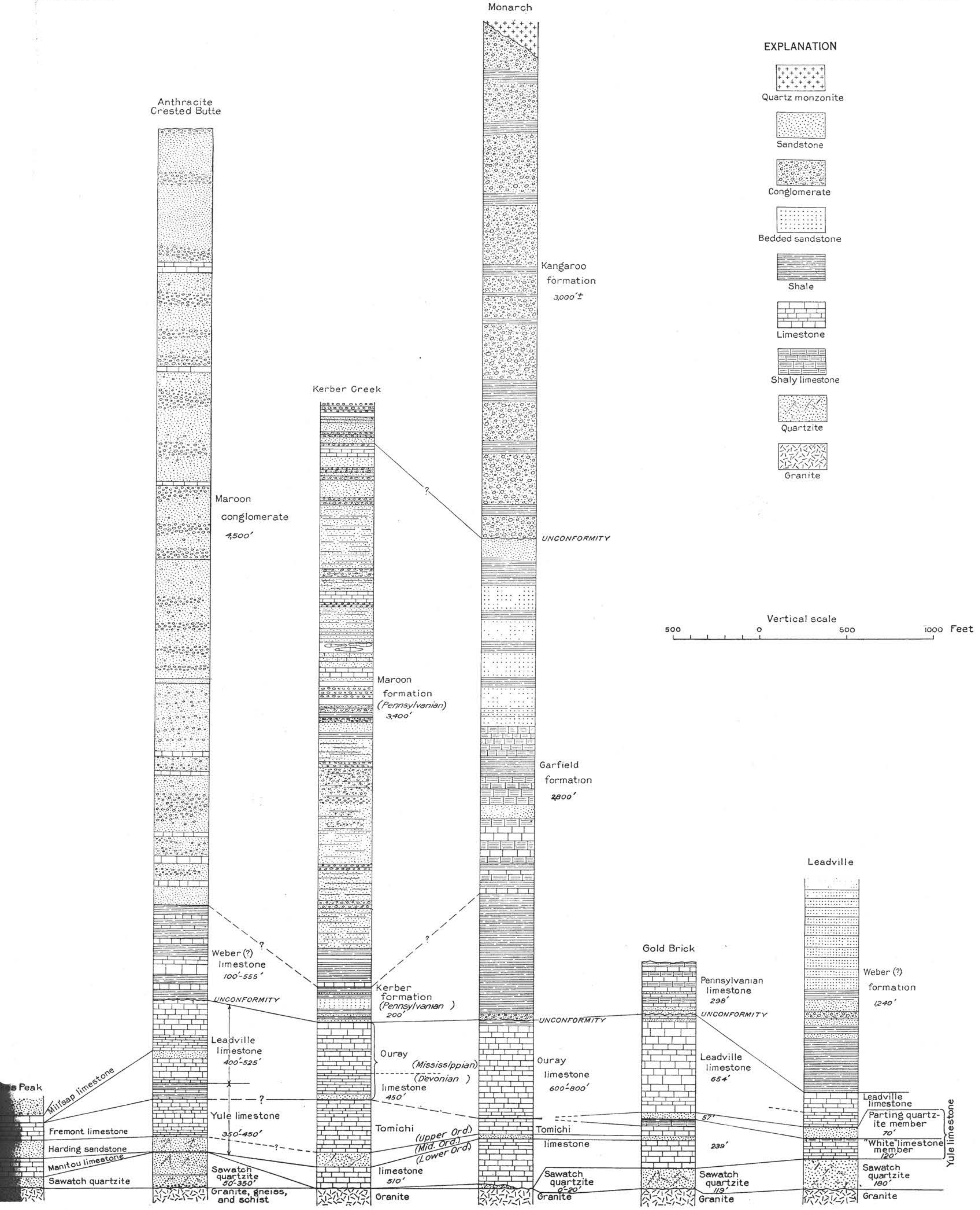
C. A WESTWARD-TILTED FAULT BLOCK OF BONANZA LATITE, ABOVE THE RAWLEY CAMP, SQUIRREL GULCH

Looking southwest. Characteristic of the outcrop of the lava flow and its talus slopes.



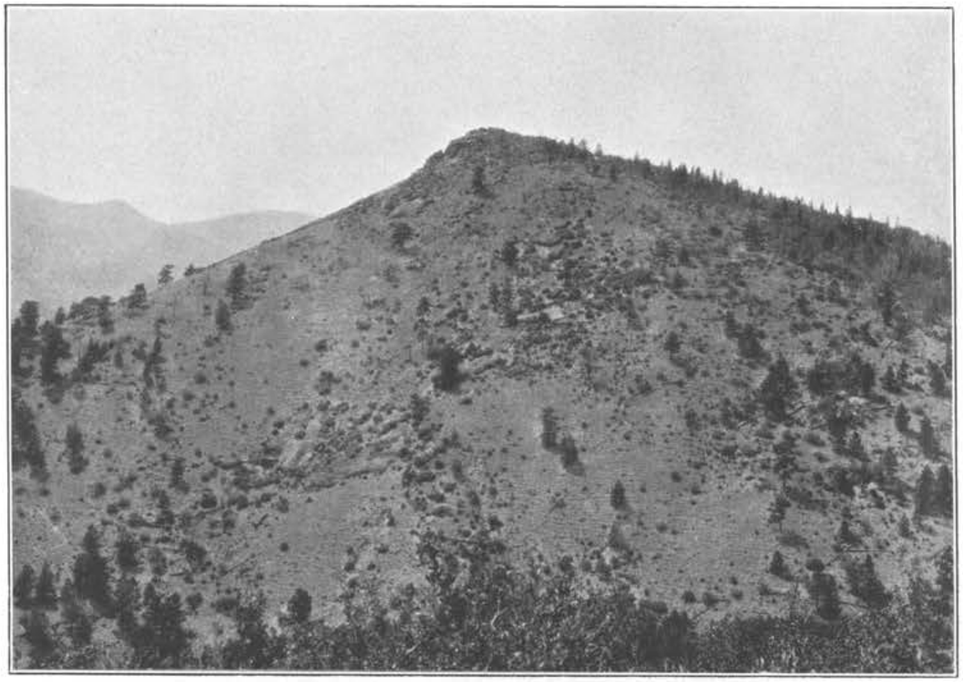
D. ROUND MOUNTAIN FROM THE SOUTHWEST

The Shawmut mine in distance on south side of mountain. Typical of barren smooth tops of range and heavily timbered sides of gulches in northern part of district.



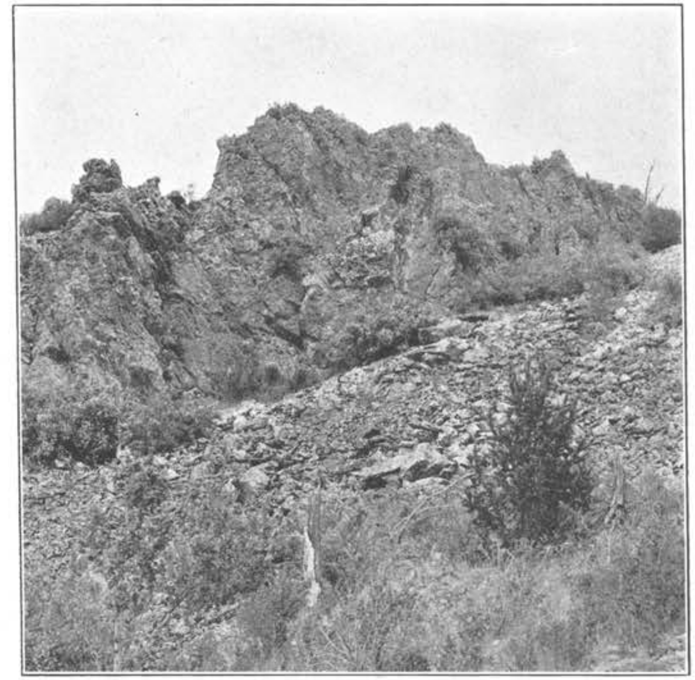
COMPARATIVE STRATIGRAPHIC COLUMNS OF SEDIMENTARY ROCKS OF KERBER CREEK AND OTHER DISTRICTS IN SOUTHWESTERN COLORADO

Note.—In the Anthracite-Crested Butte section part of the upper Sawatch and thee quivalents of the Manitou, the Harding, the Fremont, and a part of the overlying Devonian are included in the Yule limestone as defined by Eldridge in Folio 9. The Manitou is shown as not represented in the above columnar section, but its equivalent is in the lower part of the beds correlated with the Harding. In the Kerber Creek section the Devonian(?) part of what is called Ouray limestone, including the basal sandstone, is the Chaffee formation of the text of this report, and the Mississippian part is the Leadville limestone. The Maroon formation is now classified as Permian and Pennsylvanian (?) and the Kerber formation as Pennsylvanian. In the Leadville district the "White" limestone is now considered of Manitou age, while the Parting quartzite member of the Yule limestone and the part of the overlying Leadville limestone up to the dashed line on left of column is included in the Chaffee formation as defined by Kirk (see text). Leadville limestone is now restricted to the beds above the broken dashed line.



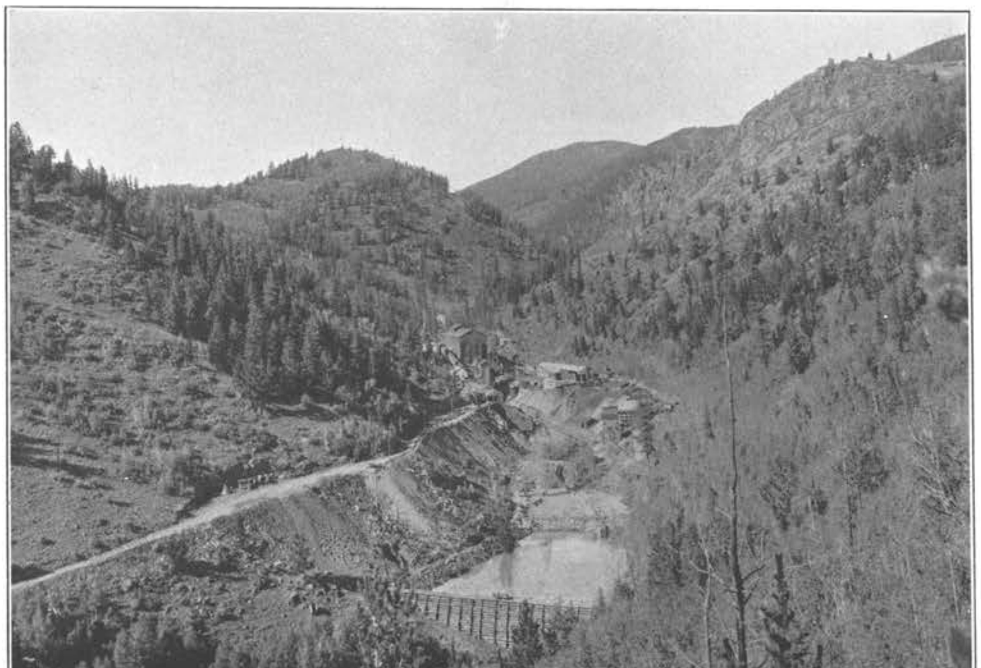
A. CONICAL HILL JUST EAST OF KERBER CREEK BETWEEN GREENBACK AND CHLORIDE GULCHES

Viewed from the southeast. This hill is composed largely of the altered rocks of the Greenback Gulch volcanic neck and is capped by a large mass of silicified rock formed by solfataric action.



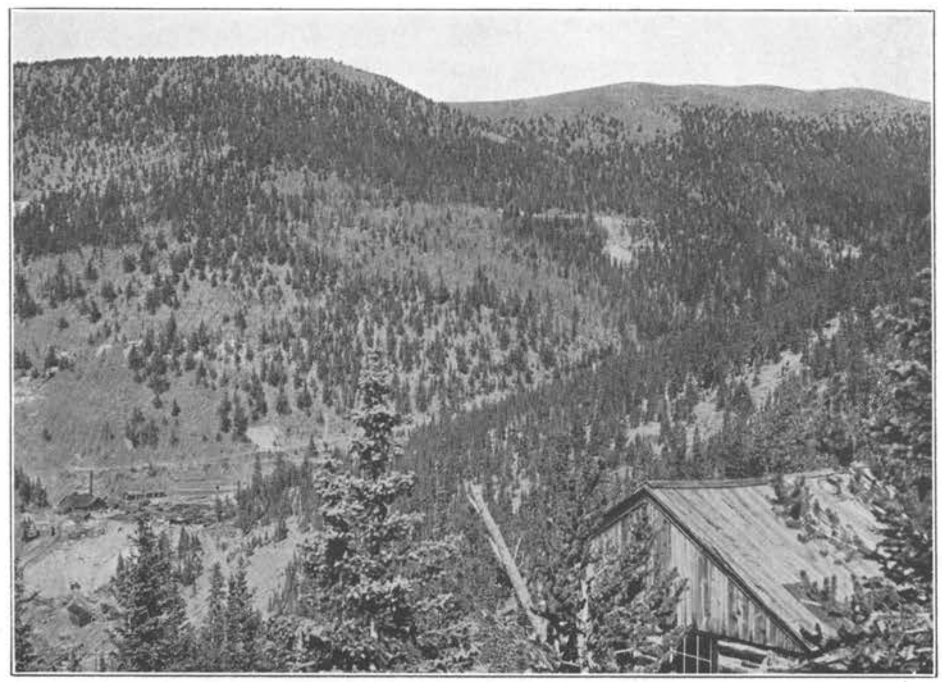
B. CLOSE VIEW OF ONE OF THE SILICIFIED ROCK MASSES FORMING A SHARP RIDGE ON THE SOUTH SIDE OF GREENBACK GULCH

Plate 10, *A*, *B*, shows the nature of part of the rock forming this ridge.



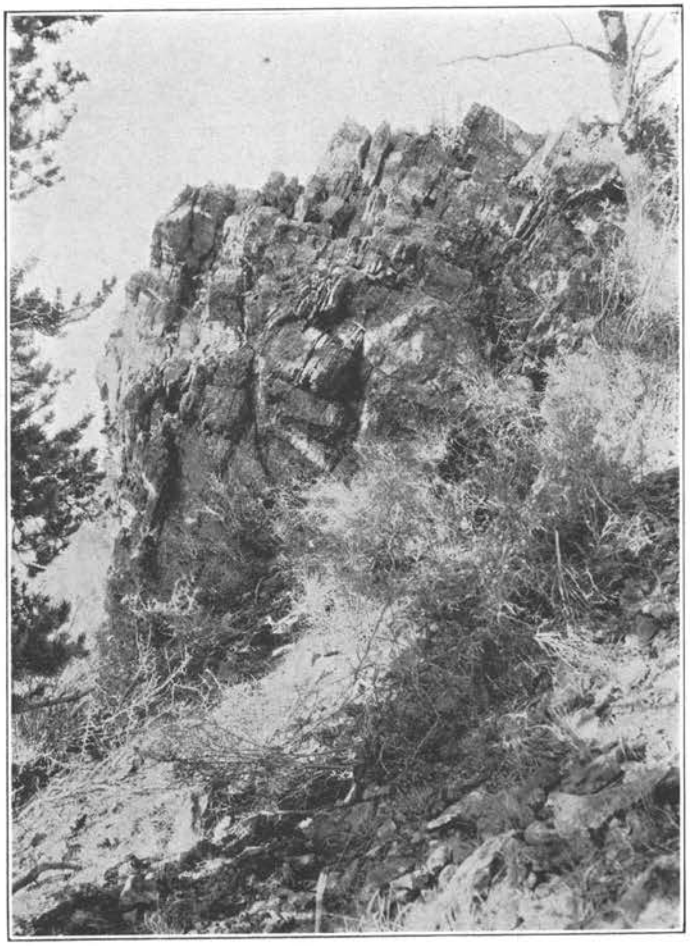
C. VIEW LOOKING NORTH UP SQUIRREL GULCH

Shows Rawley mill at portal of Rawley drainage tunnel. All the ridges in view are formed of westward-tilted Bonanza latite, repeated by faulting.



D. VIEW FROM POINT NEAR HANOVER MINE LOOKING NORTH ACROSS RAWLEY GULCH

The portal of the Rawley 300 level adit is in the bottom of the gulch. Halfway up the slope on the extreme left is the portal of the Antoro tunnel and in the central part the dumps of the Michigan tunnels.



A. DETAIL OF OUTCROP OF STEEPLY TILTED BONANZA LATITE SHOWN IN *B*

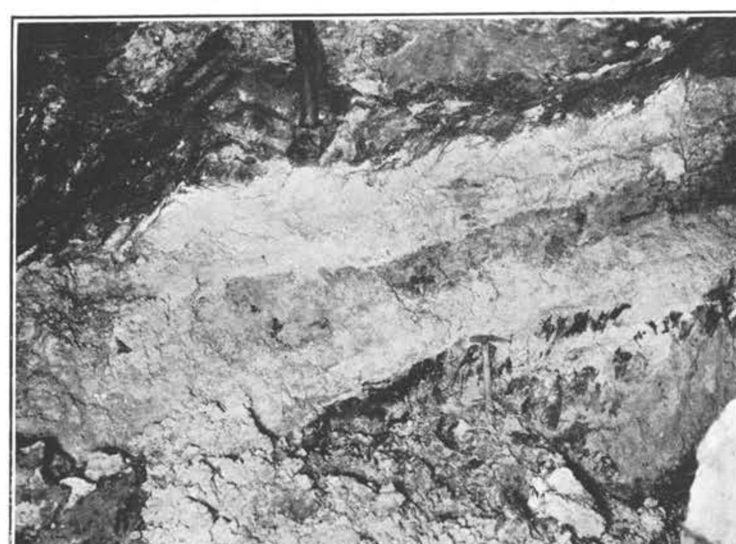
The sheeted structure parallels the flow lines, although several of the shearing planes cut across this structure at a small angle.

C. PARTLY ALTERED BONANZA LATITE, COCOMONGO MINE

Differential alteration has accentuated the flow structure.

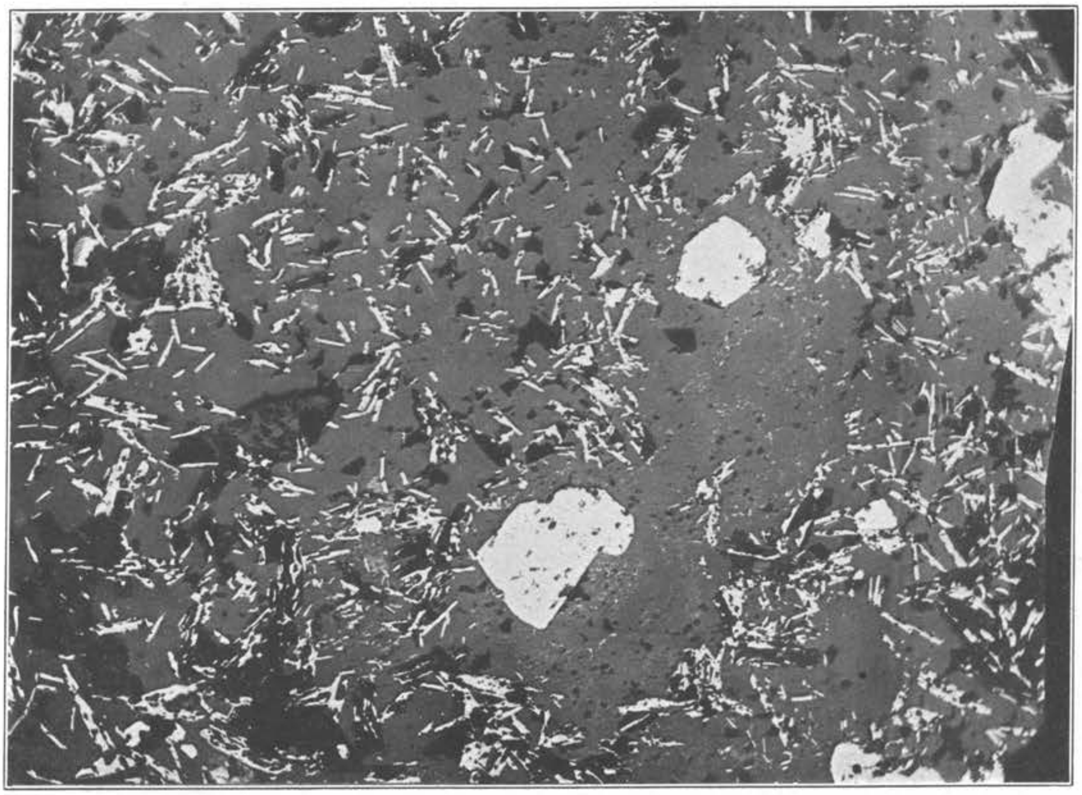
B. SQUIRREL GULCH FROM POINT ABOVE THE RAWLEY CAMP

An outcrop of a tilted fault block of Bonanza latite is seen at the right center. The high peaks near the head of the gulch consist of the Porphyry Peak rhyolite.



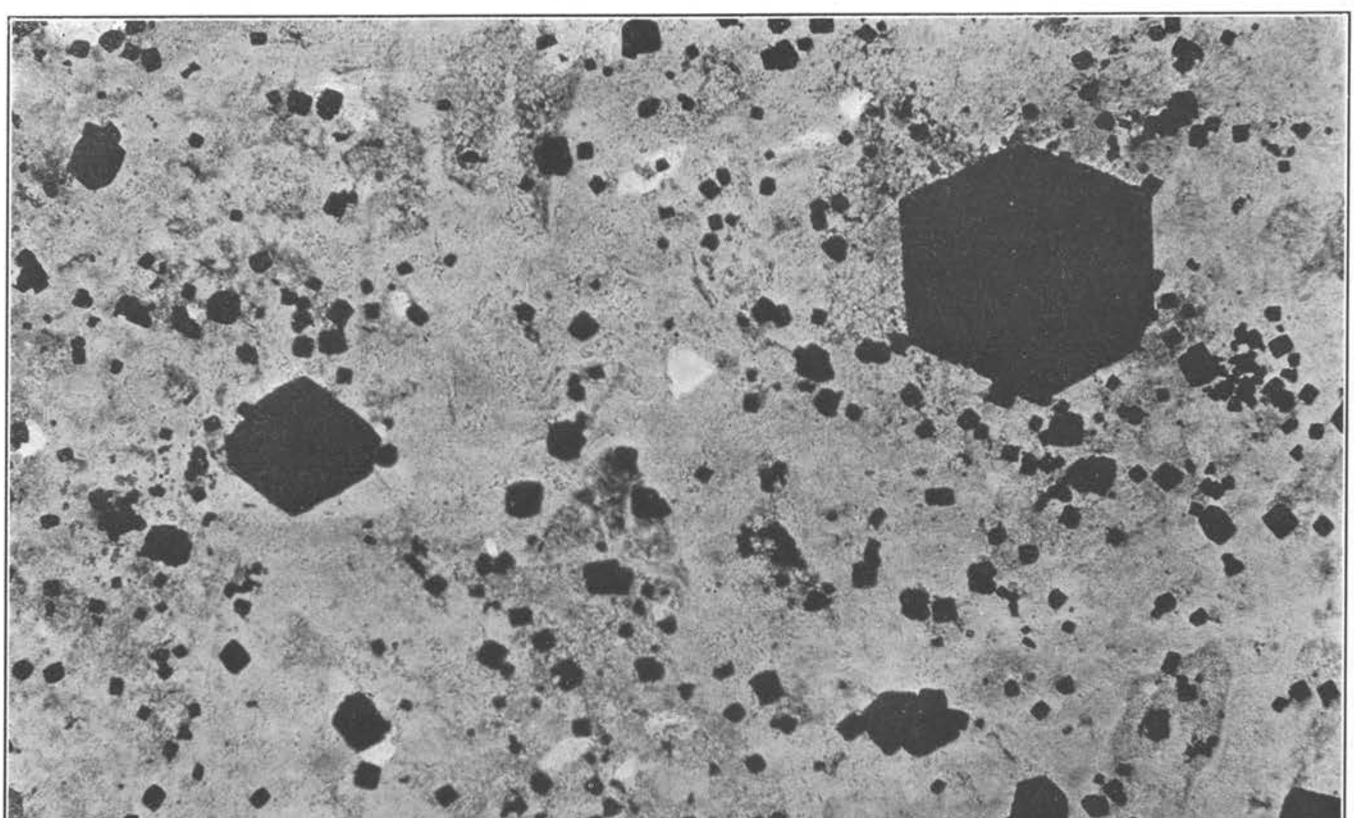
D. EXCHEQUER FAULT AS EXPOSED IN THE EXCHEQUER TUNNEL, KERBER CREEK

The view is taken along the strike of the fault and shows the low angle of easterly dip. White material filling the fault fissure is sericitized gouge.



A. PHOTOMICROGRAPH OF SILICIFIED ANDESITE SHOWING PYRITE AND HEMATITE

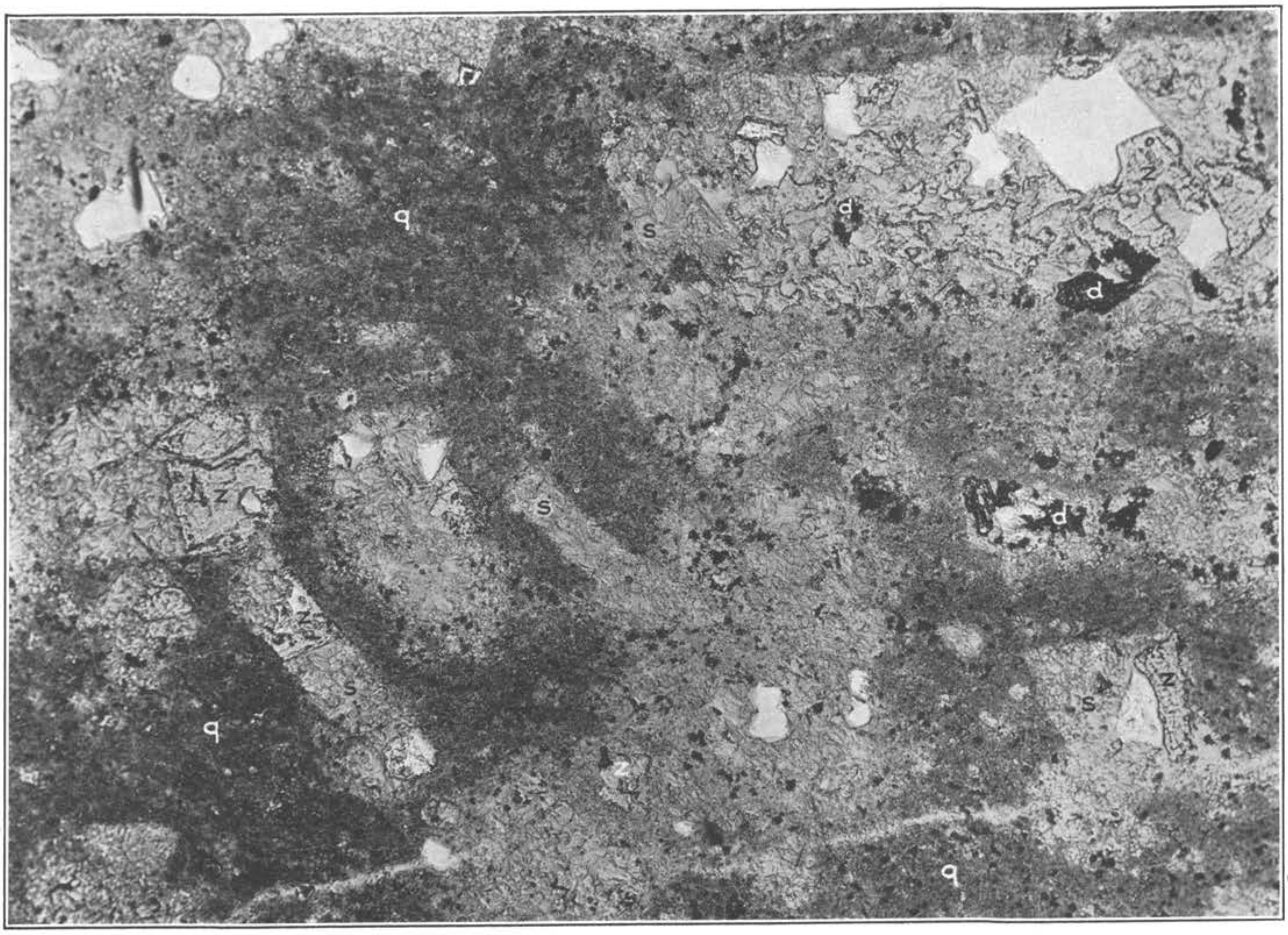
From the Manitou-Sunlight vein, Alder Creek. Reflected light. × 100.



B. PHOTOMICROGRAPH OF DISSEMINATED PYRITE (BLACK) IN RED SILICIFIED ANDESITE FROM THE RAWLEY DRAINAGE TUNNEL

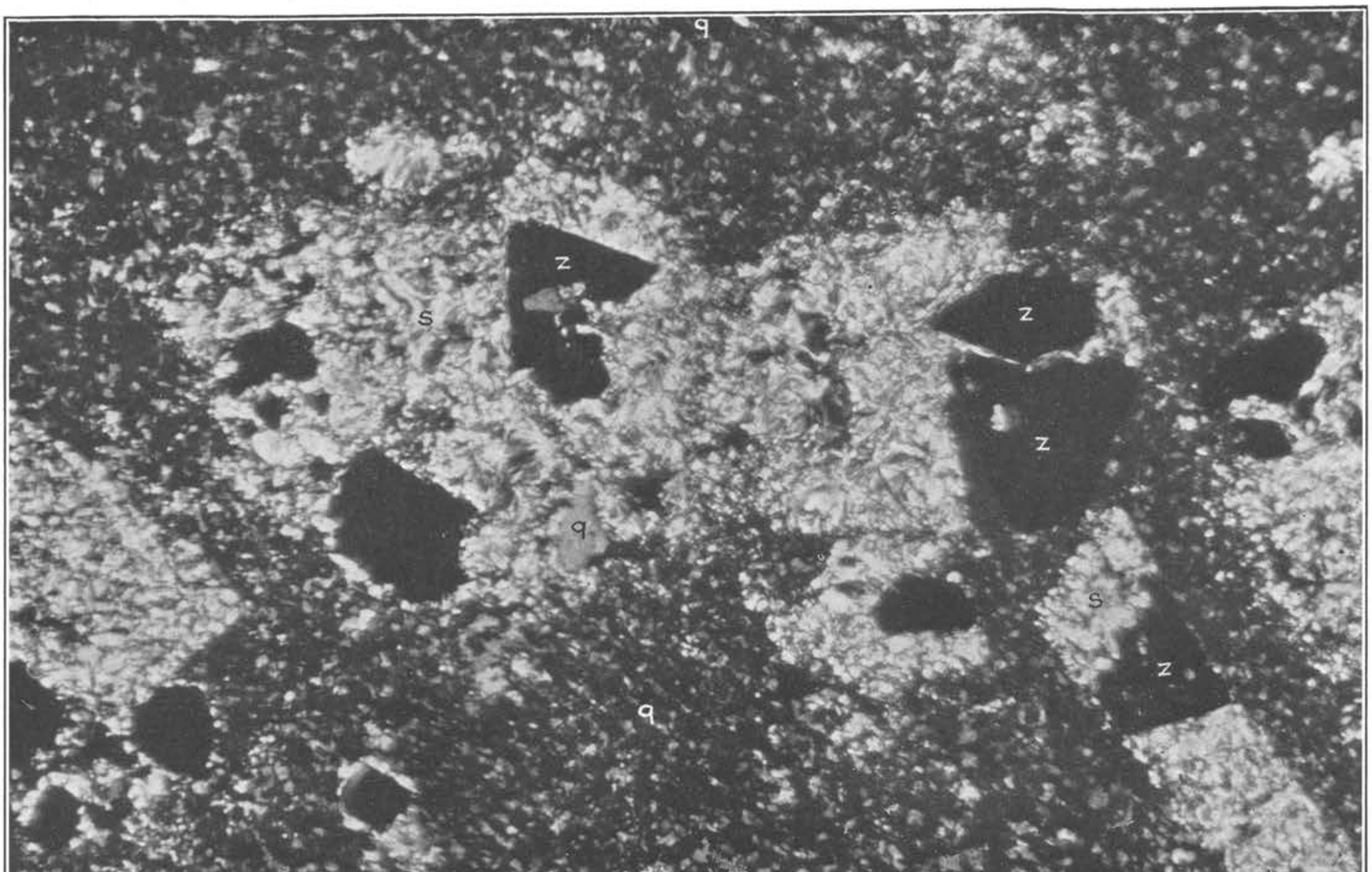
Illustrates even distribution of pyrite crystals in massive jasper. Plain transmitted light. × 40.

PHOTOMICROGRAPHS OF ALTERED ROCKS



A. PHOTOMICROGRAPH OF SILICIFIED PORPHYRITIC ROCK IN WHICH THE FELDSPAR CRYSTALS ARE REPLACED BY DIASPORE, ZUNYITE, AND SERICITE

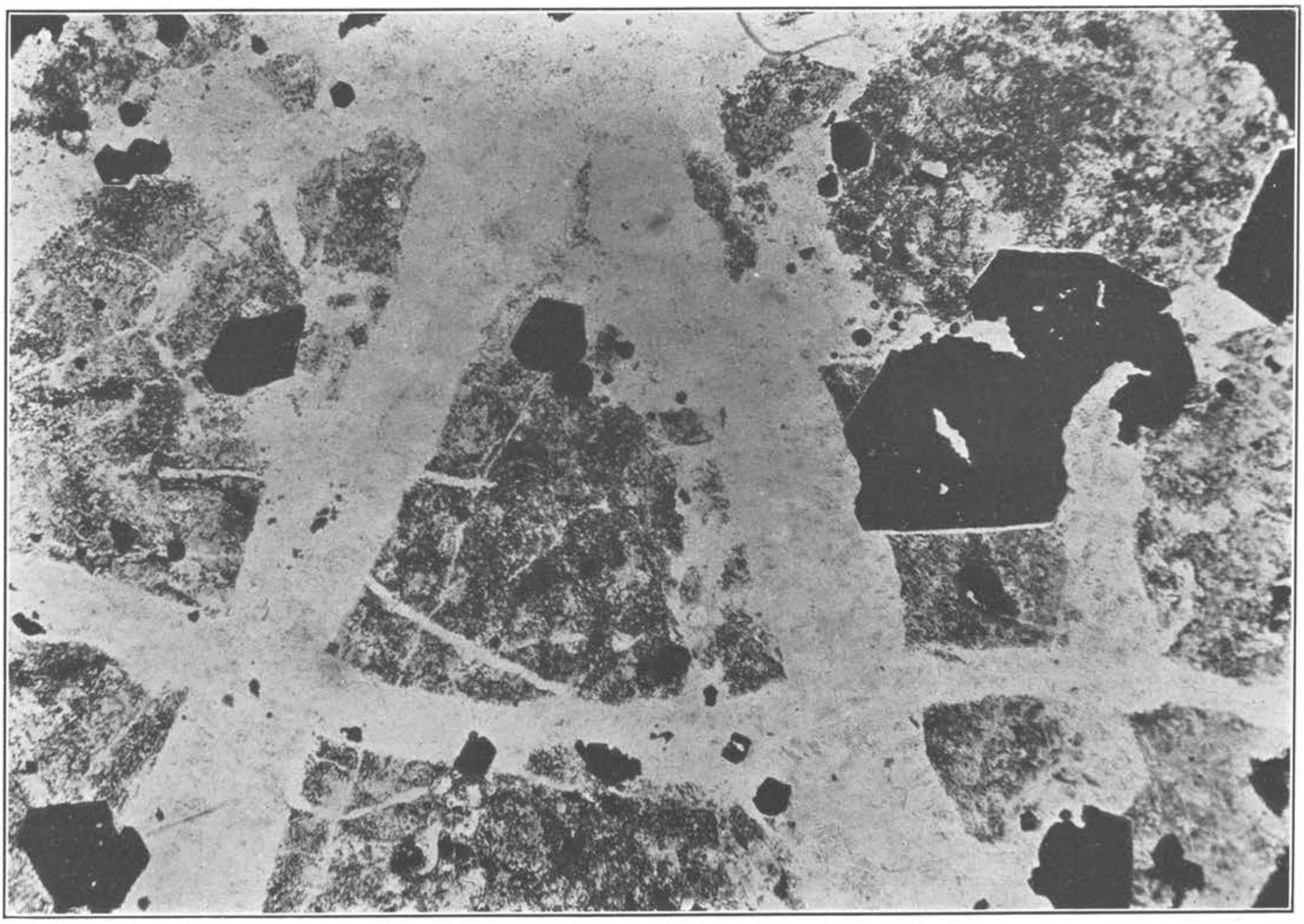
The sericite (s) has partly replaced the earlier formed diaspore (d) and zunyite (z). q, Quartz. The dark specks scattered through the silicified groundmass are in part diaspore and rutile. From the north side of Greenback Gulch, same locality as that shown in Plate 6, *B.* Plain transmitted light. × 45.



B. DETAIL AT HIGHER MAGNIFICATION FROM THE LEFT SIDE OF *A*

Shows the fine granular character of the quartz replacement and also the zunyite, veined and partly replaced by sericite. q, Quartz; s, sericite; z, zunyite. Transmitted light, crossed nicols. × 74.

PHOTOMICROGRAPHS OF ALTERED ROCKS

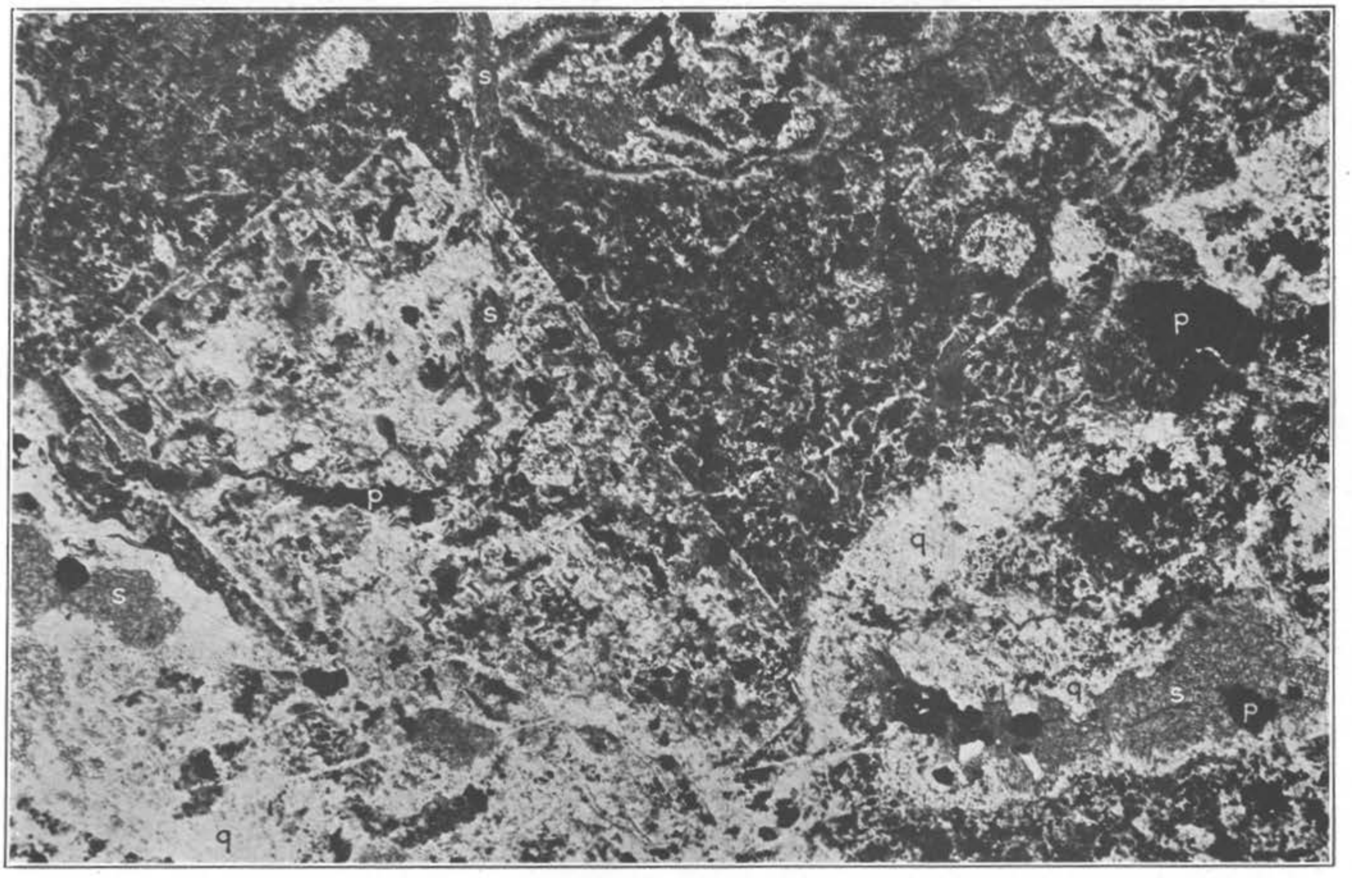


A. PHOTOMICROGRAPH OF RED JASPER FORMED BY SILICIFICATION OF ANDESITE, BRECCIATED AND VEINED BY QUARTZ OF A LATER STAGE

The large opaque crystals are pyrite, and the fine dark material in the jasper is ferric oxide, which gives the jasper its red color. Plain transmitted light. × 40.

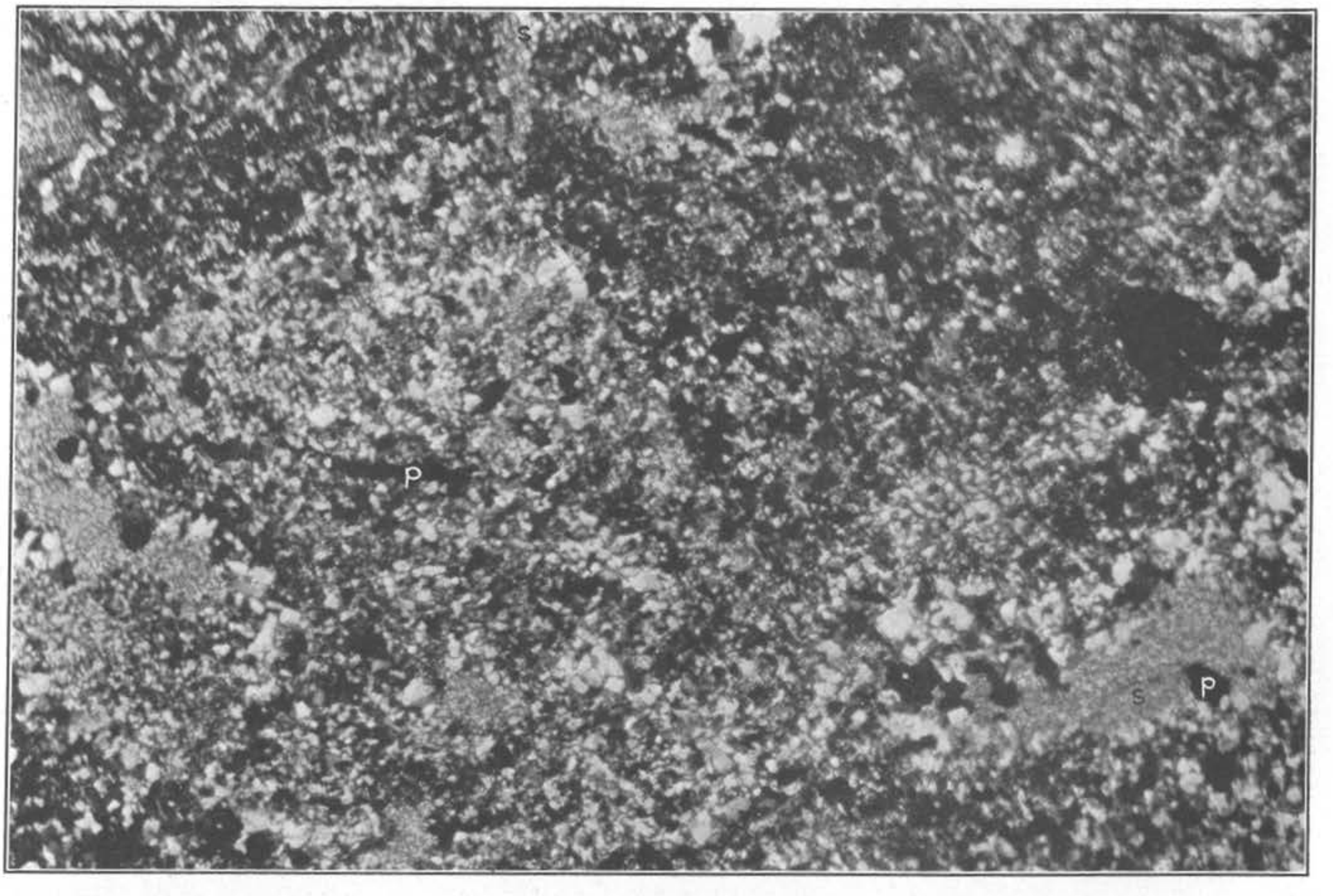
B. SAME AS *A* BUT WITH CROSSED NICOLS, SHOWING DIFFERENCE IN SIZE OF THE EARLIER AND LATER QUARTZ GRAINS

PHOTOMICROGRAPHS OF ALTERED ROCKS



A. PHOTOMICROGRAPH OF SILICIFIED ANDESITE

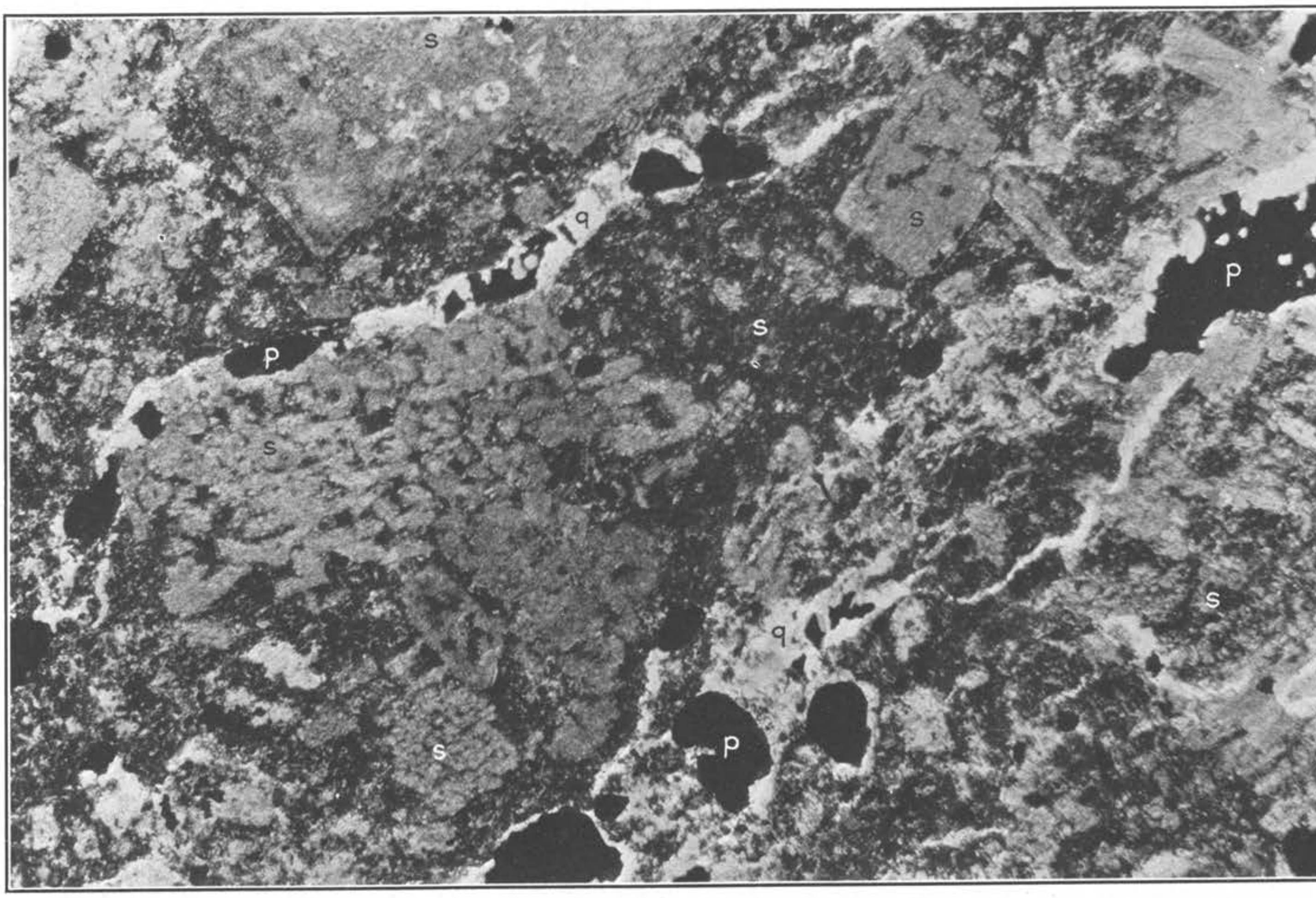
Shows remarkable preservation of certain details of the original texture, particularly the large feldspar phenocryst. The early siliceous material is veined and partly replaced by later quartz (q), pyrite (p), and sericite (s), that were introduced during sulphide mineralization in neighboring fissures. From the Rawley drainage tunnel. Plain transmitted light. × 34.



B. SAME AS *A* BUT WITH CROSSED NICOLS, SHOWING TEXTURE OF THE SILICEOUS REPLACEMENT

p, Pyrite; s, sericite.

PHOTOMICROGRAPHS OF ALTERED ROCKS



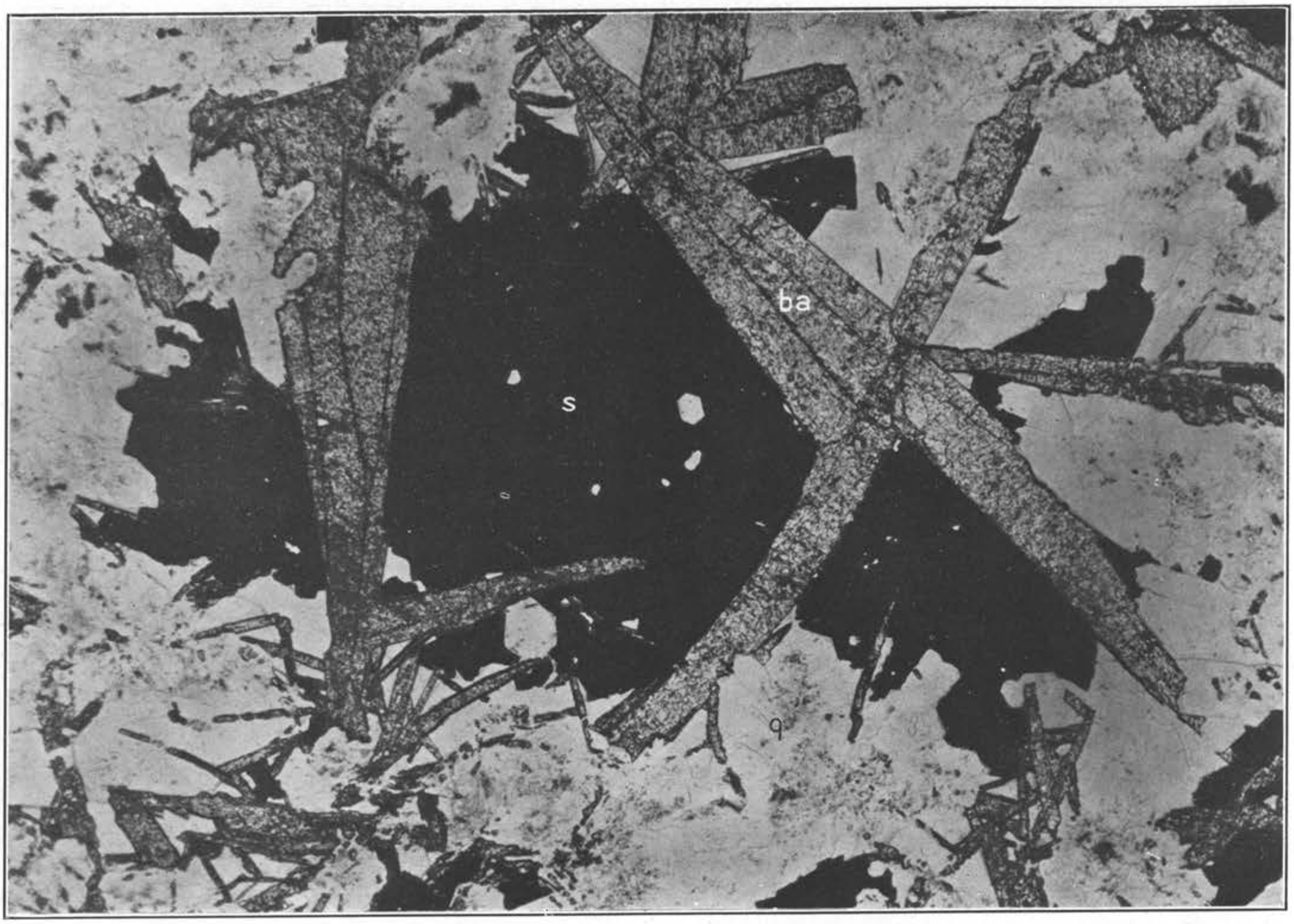
A. PHOTOMICROGRAPH OF ANDESITE ALMOST COMPLETELY REPLACED BY SERICITE AND VEINED BY QUARTZ AND SULPHIDES

Specimen taken near the wall of a mineralized fissure in the Rawley drainage tunnel. Cloudy particles in the sericitized groundmass with some quartz and iron oxide suggest that the formation of sericite has followed early silicification. Compare Plate 12, *A*. p, Pyrite and other sulphides; s, sericite; q, quartz. Plain transmitted light. × 37.

B. PHOTOMICROGRAPH SHOWING GHOSTY OUTLINES OF NEARLY COMPLETELY REPLACED RHODONITE CRYSTALS IN RHODOCHROSITE

Sphalerite (s) partly incloses some of the rhodonite, which was the earliest mineral to form. Gn, Galena. From the Little Jennie vein. Plain transmitted light. × 100.

PHOTOMICROGRAPHS OF ALTERED ROCK AND VEIN MATTER

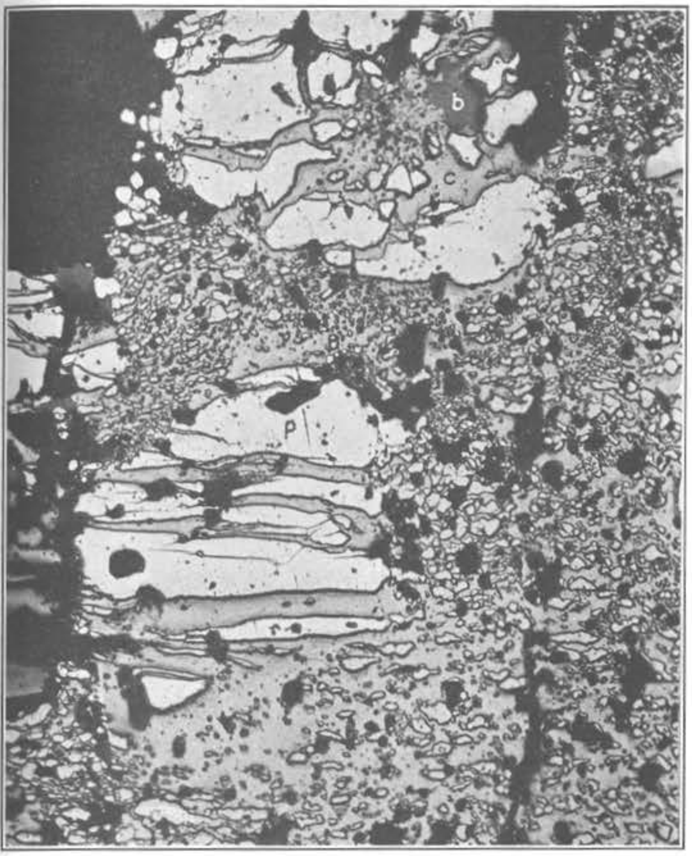


A. PHOTOMICROGRAPH OF EARLY BARITE (ba) SURROUNDED AND SLIGHTLY REPLACED BY QUARTZ (q) AND SULPHIDES (s), LARGELY PYRITE AND CHALCOPYRITE

From the Joe Wheeler vein, Alder Gulch. Plain light. × 28.

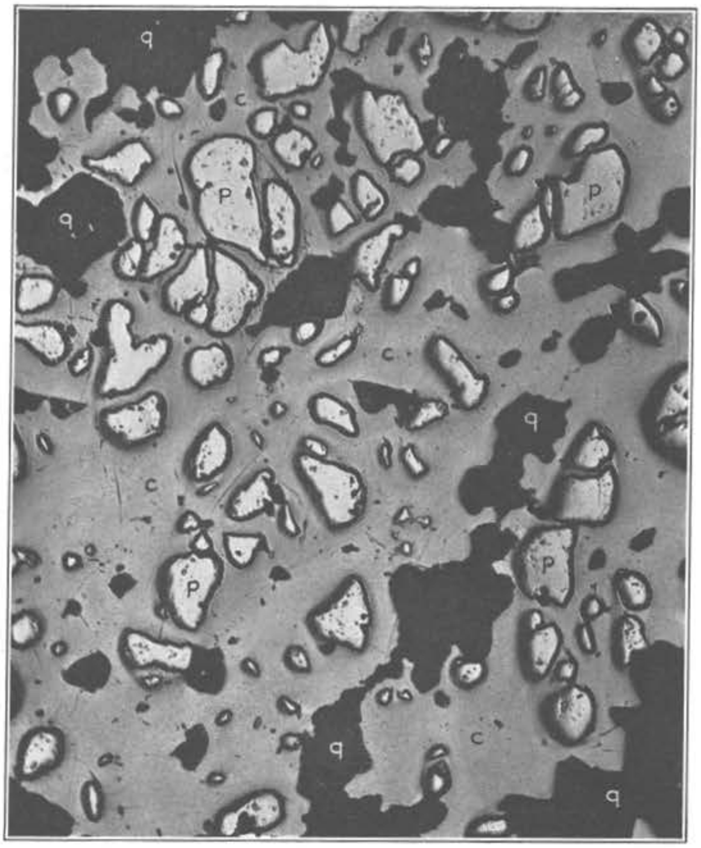
B. SAME AS *A* BUT WITH CROSSED NICOLS. × 28

PHOTOMICROGRAPHS OF VEIN MATERIAL



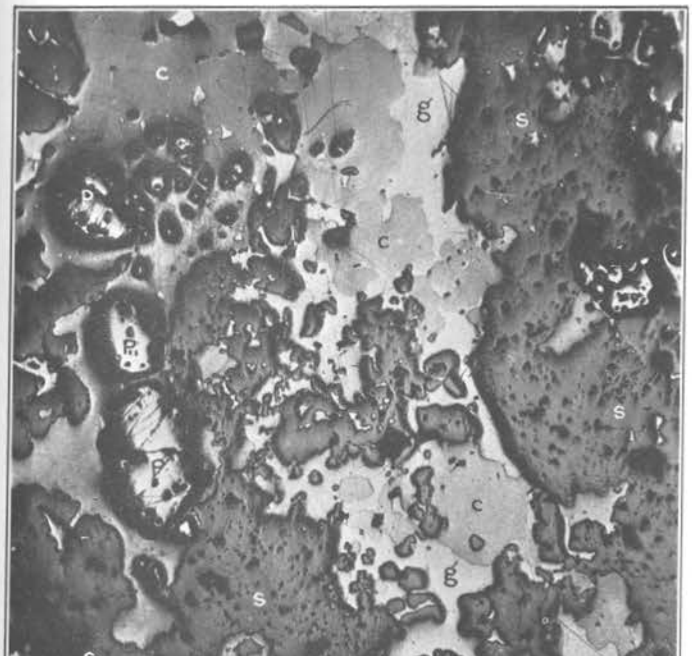
A. BRECCIATED PYRITE (p) PARTLY REPLACED BY CHALCOPYRITE (c) AND BORNITE (b)

Rawley mine, 400 level. Reflected light. × 100.



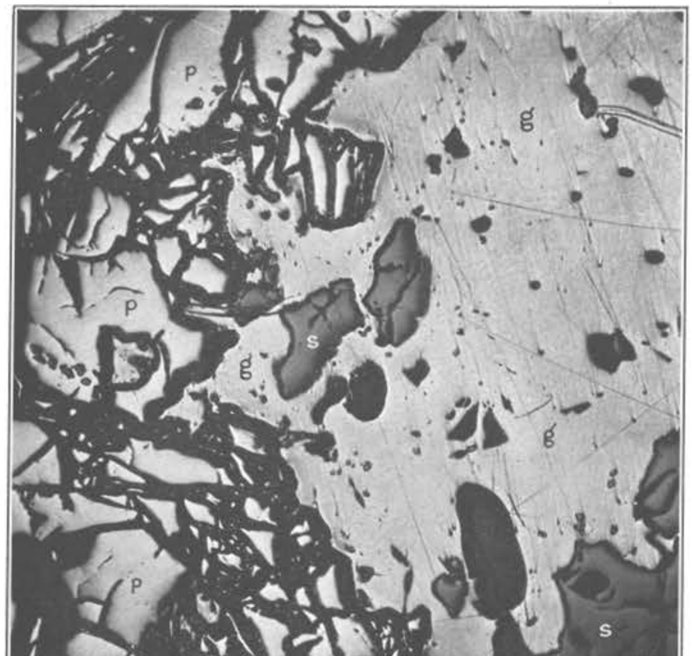
B. PYRITE PARTLY REPLACED BY CHALCOPYRITE

Chalcopyrite (c) and quartz (q) were also probably deposited in part interstitially to pyrite grains (p). Rawley mine, 200 level. Reflected light. × 100.



C. INTERGROWTH OF GALENA (g) AND CHALCOPYRITE (c) WHICH HAS PARTLY REPLACED PYRITE (p) AND SPHALERITE (s)

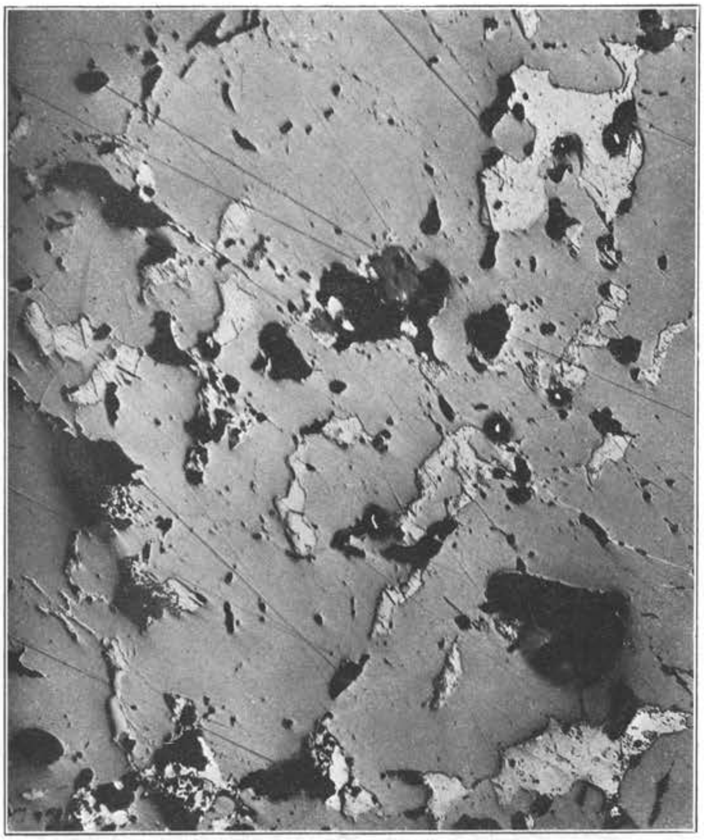
Rawley mine, 600 level. Reflected light. × 45.



D. INTENSE BRECCIATION OF PYRITE (p), FOLLOWED BY DEPOSITION OF SPHALERITE (s) AND GALENA (g)

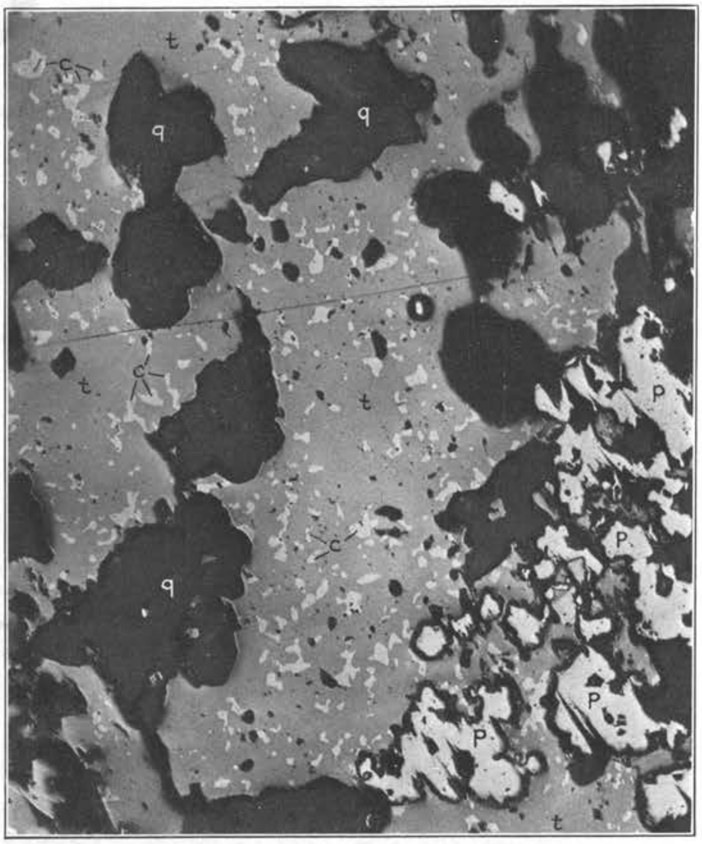
The sphalerite is slightly broken, but the galena is entirely free from brecciation. An example of movement of walls of fissure during period of ore formation. Rawley mine, 1,200 level. Reflected light. × 45.

PHOTOMICROGRAPHS OF ORES



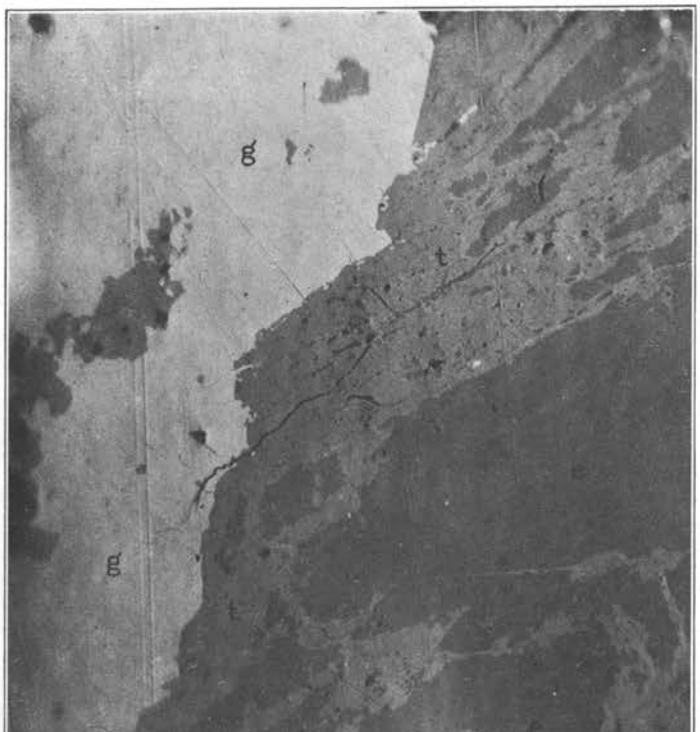
A. TENNANTITE (DARK GRAY) OF HIGH SILVER CONTENT SHOWING INTERGROWTH WITH AN UNKNOWN SILVER-BEARING MINERAL, PROBABLY AN ARGENTIFEROUS LEAD-BISMUTH MINERAL

Cocomongo mine, 300 level. Reflected light. × 100.



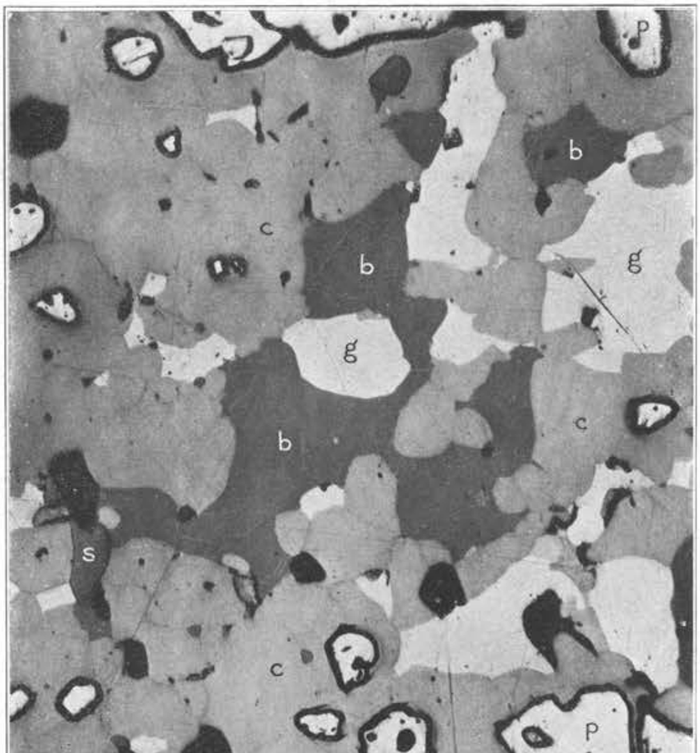
B. SILICEOUS COPPER ORE SHOWING INTERGROWTH OF TENNANTITE (t) AND CHALCOPYRITE (c)

q, Quartz; p, pyrite. Tennantite has partly replaced chalcopyrite. Rawley mine, 600 level. Reflected light. × 100.



C. VERY CHARACTERISTIC ALTERATION OF ENARGITE (e) TO TENNANTITE (t)

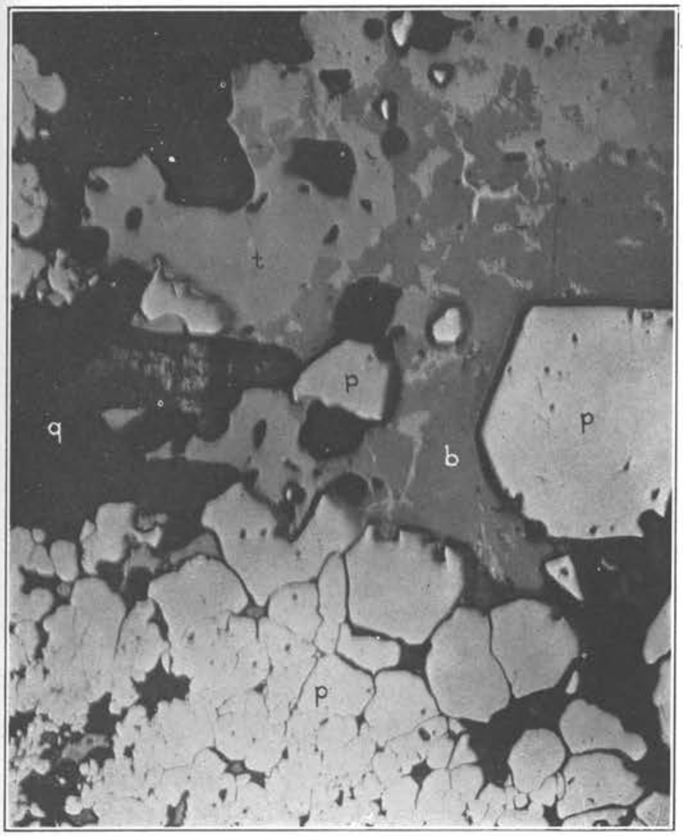
In the deeper level copper ores of the Rawley mine (from 1,200 level). g, Galena. Reflected light. × 450.



D. A TYPE OF MUTUAL INTERGROWTH OF BORNITE (b), CHALCOPYRITE (c), AND GALENA (g)

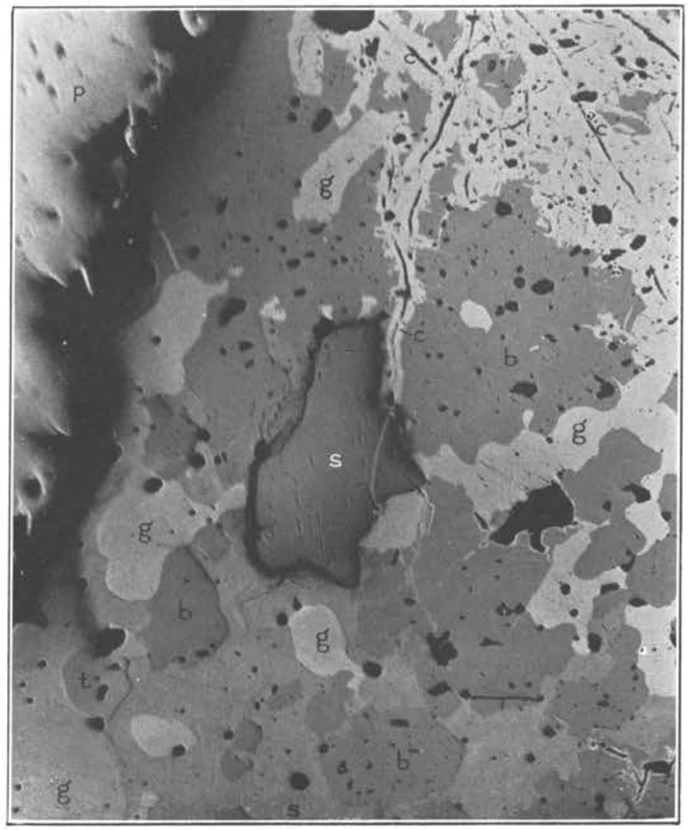
Galena is interpreted to have partly replaced the other minerals along grain boundaries, but the relations are debatable. Boundaries of chalcopyrite grains may be faintly seen. p, Pyrite; s, sphalerite. Joe Wheeler vein, Alder Creek.

PHOTOMICROGRAPHS OF ORES



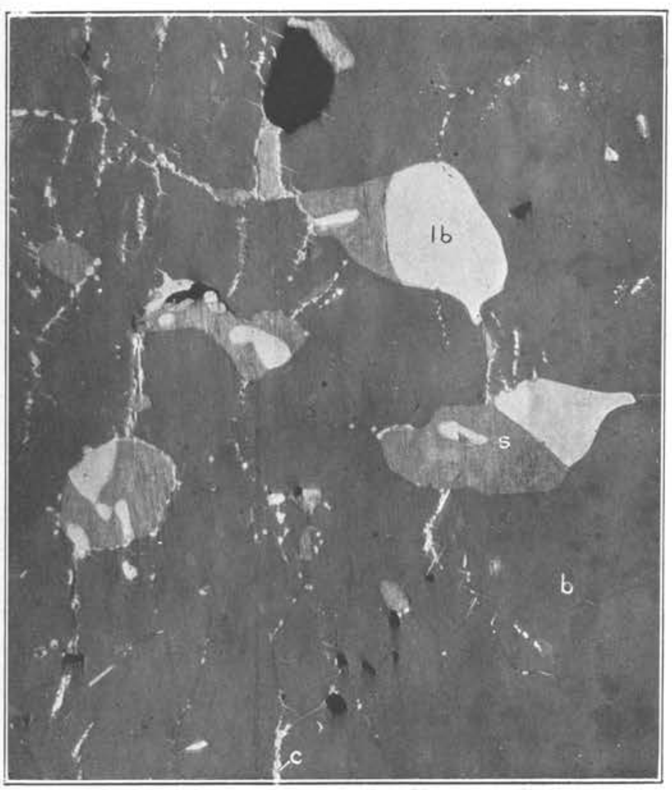
A. TYPICAL SILICEOUS AND PYRITIC COPPER ORE FROM THE 700 LEVEL OF THE RAWLEY MINE

Consists of granular pyrite (p), bornite (b), and tennantite (t). The tennantite is to a large extent a replacement of enargite as shown in Plate 16, *C*, but the intergrowth can not be seen at this magnification. q, Quartz. Reflected light. × 63.



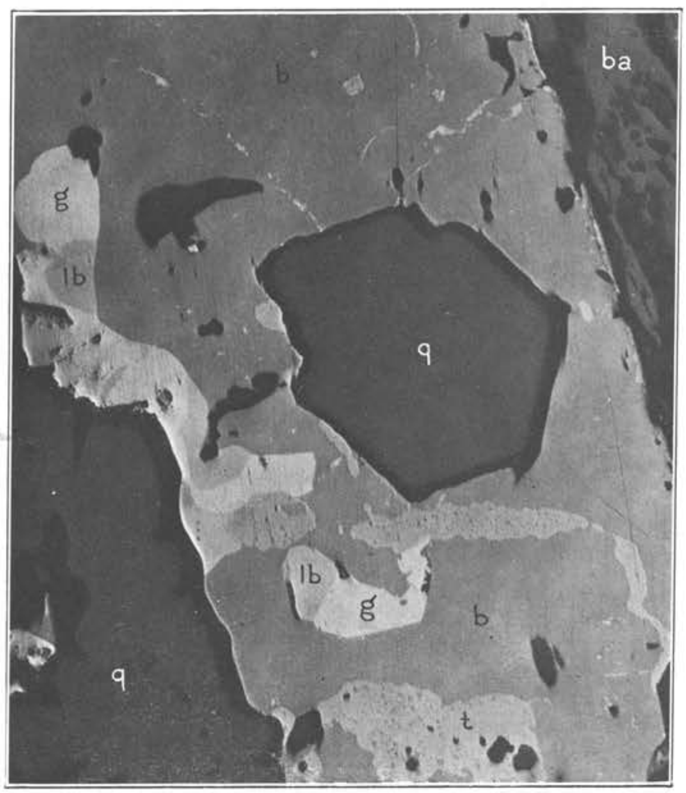
B. MIXED SULPHIDE ORE FROM 400 LEVEL, RAWLEY MINE

Shows supergene chalcopyrite (c) forming along open cracks. p, Pyrite; s, sphalerite (dark gray in center); b, bornite; g, galena; t, tennantite; and s, stromeyerite (light gray). Reflected light. × 100.



C. SMALL ROUNDED MASSES OF STROMEYERITE (s) ASSOCIATED WITH AN UNKNOWN LEAD-BISMUTH MINERAL (lb) IN BORNITE (b)

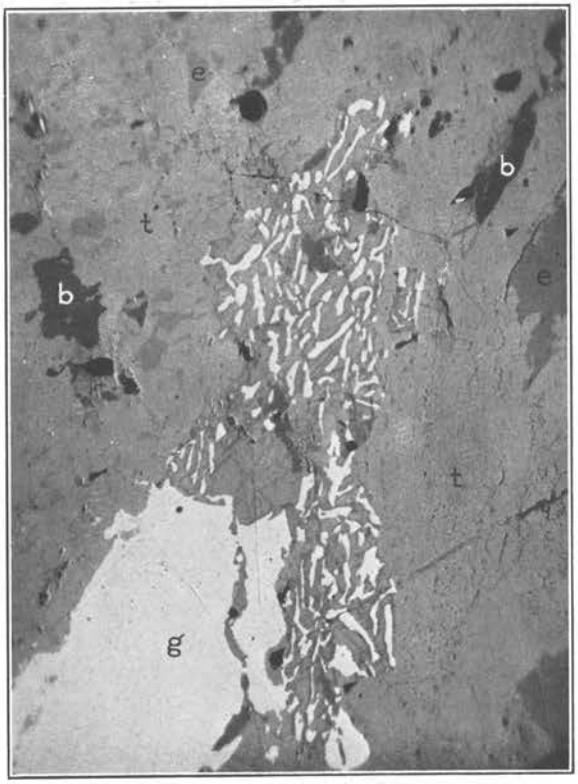
Chalcopyrite (c) occurs along small cracks. From the Joe Wheeler vein, Alder Creek. Reflected light. × 220.



D. ASSOCIATION OF UNKNOWN LEAD-BISMUTH MINERAL (lb) WITH GALENA IN ORE FROM JOE WHEELER MINE, ALDER CREEK

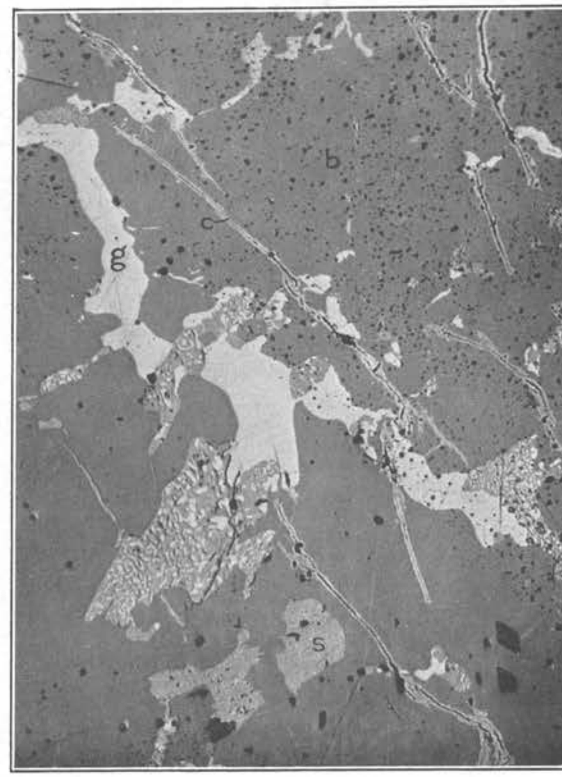
Consists of quartz (q), barite (ba), bornite (b), and tennantite (t). Reflected light. × 100.

PHOTOMICROGRAPHS OF ORES



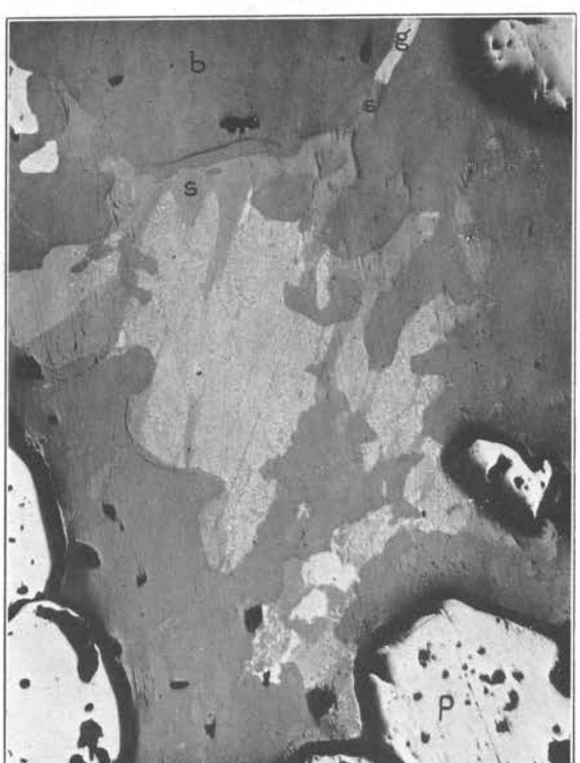
A. ORE OF HIGH SILVER CONTENT PROBABLY ENTIRELY OF HYPOGENE ORIGIN

Interpreted as resulting from successive breaking down of earlier formed minerals and their replacement by later ones. The order of formation is difficult to determine. Consists of bornite (b), enargite (e), galena (g), and tennantite (t), which consists of a fine intergrowth of tennantite and stromeyerite. Rawley mine, 1,200 level. Reflected light. × 450.



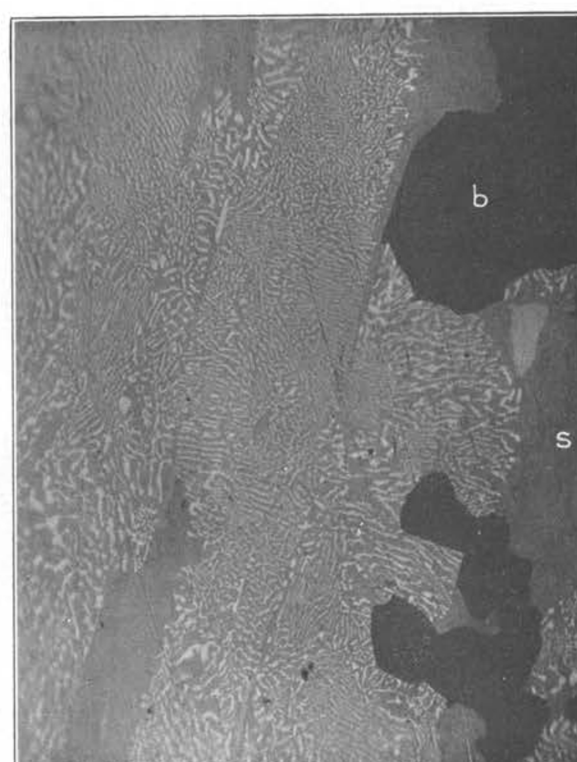
B. GALENA (g) AND STROMEYERITE (s) IN GRAPHIC INTERGROWTH IN BORNITE (b)

Supergene chalcopyrite along open cracks (c). Rawley mine, 900 level. Reflected light. × 100.



C. EXTREMELY FINE GRAPHIC INTERGROWTHS OF GALENA (g) AND STROMEYERITE (s) IN BORNITE (b)

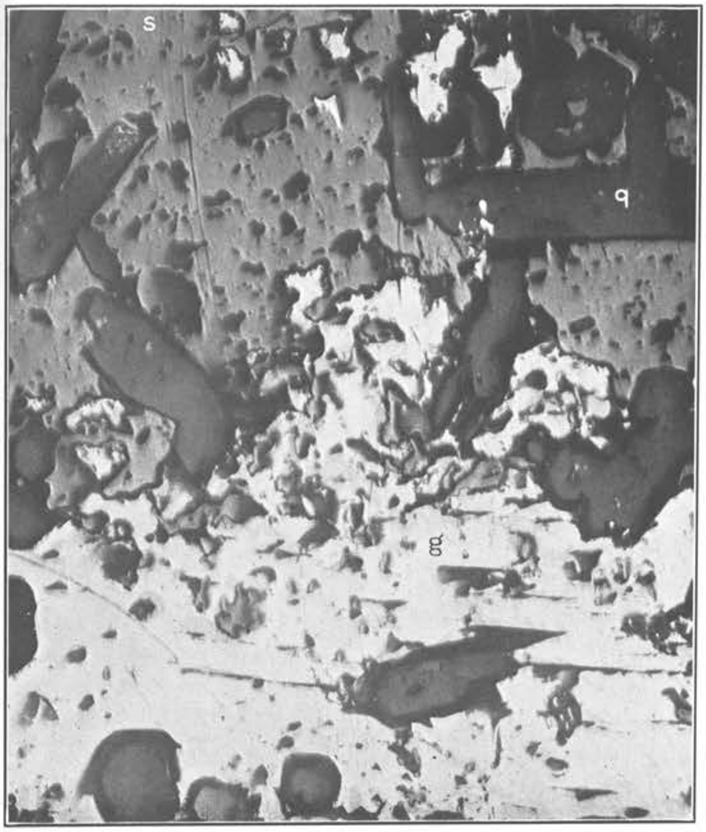
p, Pyrite. Rawley mine, 900 level. Reflected light. × 100.



D. SAME AS *C*, ENLARGED TO SHOW TEXTURE OF INTERGROWTH

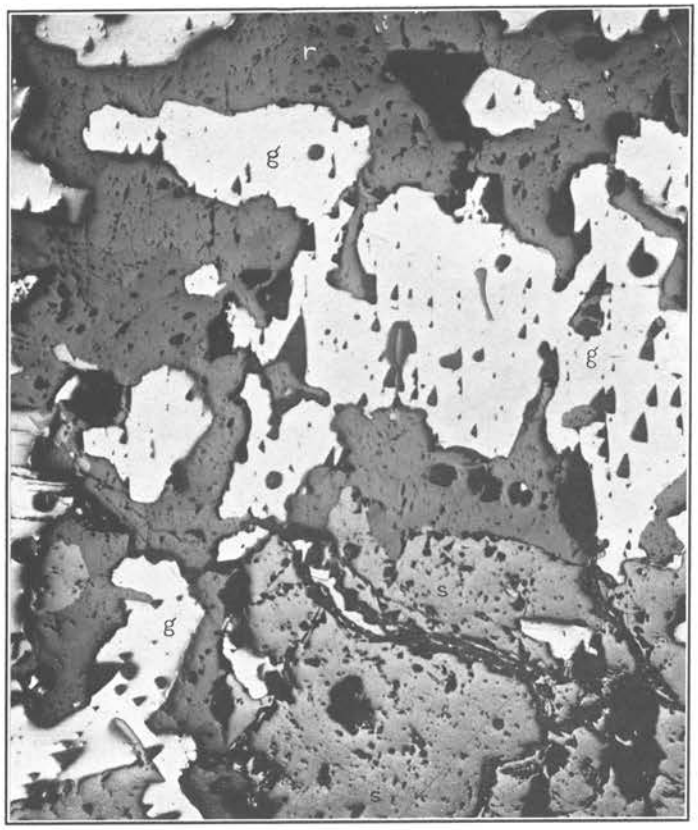
Bornite (b), stromeyerite (s), and galena (white). Reflected light. × 450.

PHOTOMICROGRAPHS OF ORES



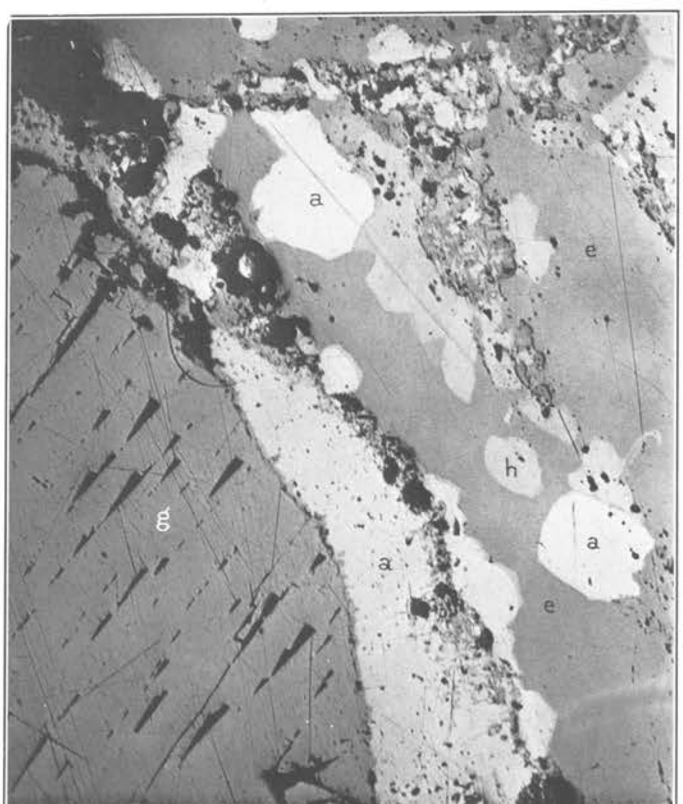
A. COMMON ASSOCIATION OF SPHALERITE (s), GALENA (g), AND QUARTZ (q) IN THE VEINS OF THE NORTHERN PART OF THE DISTRICT

Galena appears to have replaced sphalerite to some extent. Rawley mine, Parallel vein, 300 level. Reflected light. × 65.



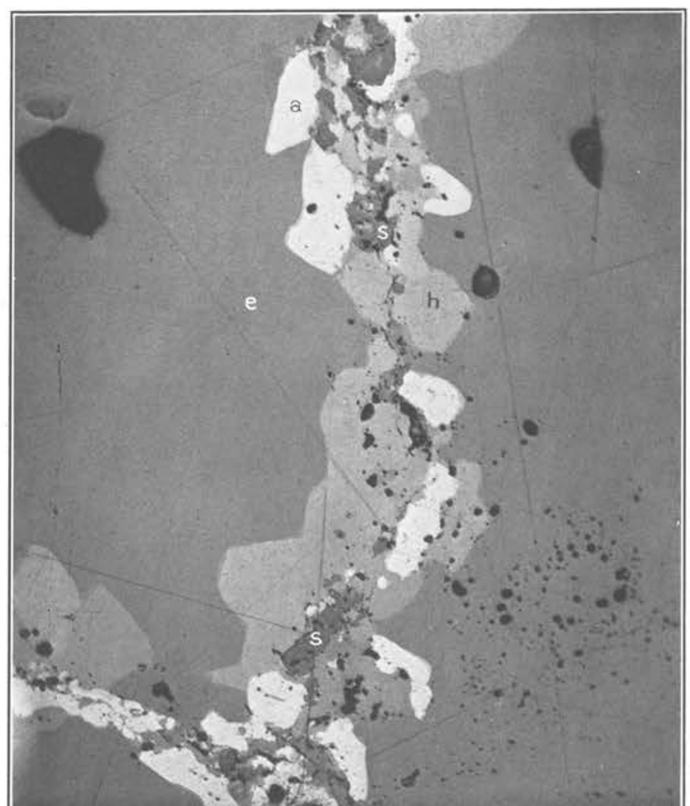
B. TYPICAL ASSOCIATION OF SPHALERITE (s), GALENA (g), AND RHODOCHROSITE (r) IN THE MANGANESE-BEARING VEINS OF THE SOUTHERN PART OF THE BONANZA DISTRICT

Eagle mine, 500 or 600 level. Reflected light. × 45.



C. RIM OF ALTAITE (a) FORMED BETWEEN GALENA (g) AND THE LATER TELLURIDES, EMPRESSITE (e), AND HESSITE (?) (h)

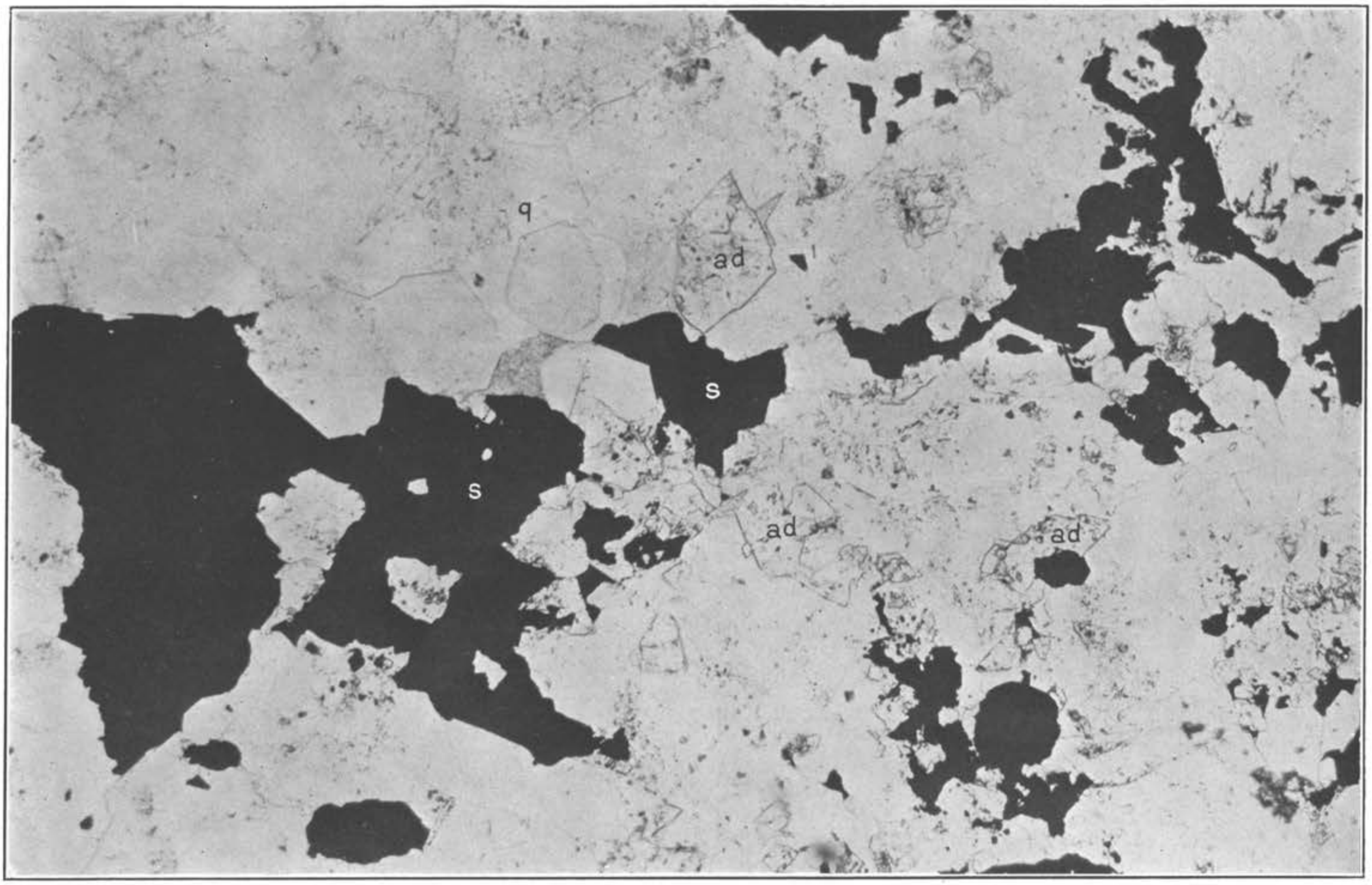
Empress Josephine mine, Copper Gulch. Reflected light. × 63.



D. MODE OF ASSOCIATION OF ALTAITE (a), HESSITE (?) (h), AND SPHALERITE (s), PROBABLY ALONG HEALED CRACKS IN EMPRESSITE (e)

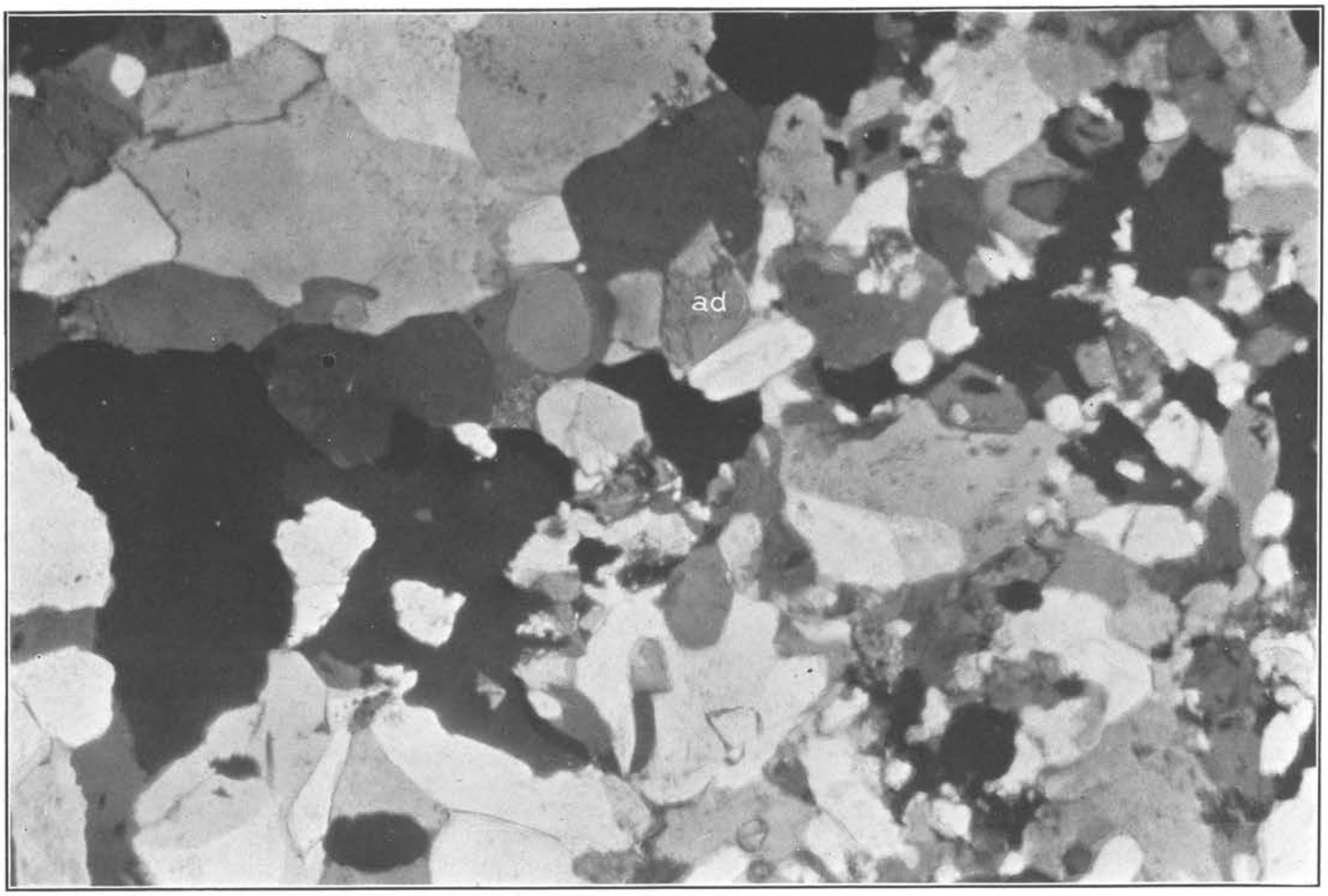
There is commonly a little chalcopyrite in these zones. Reflected light. × 100.

PHOTOMICROGRAPHS OF ORES



A. ASSOCIATION OF MINOR AMOUNTS OF SULPHIDES (s) WITH QUARTZ (q) AND ADULARIA (ad)

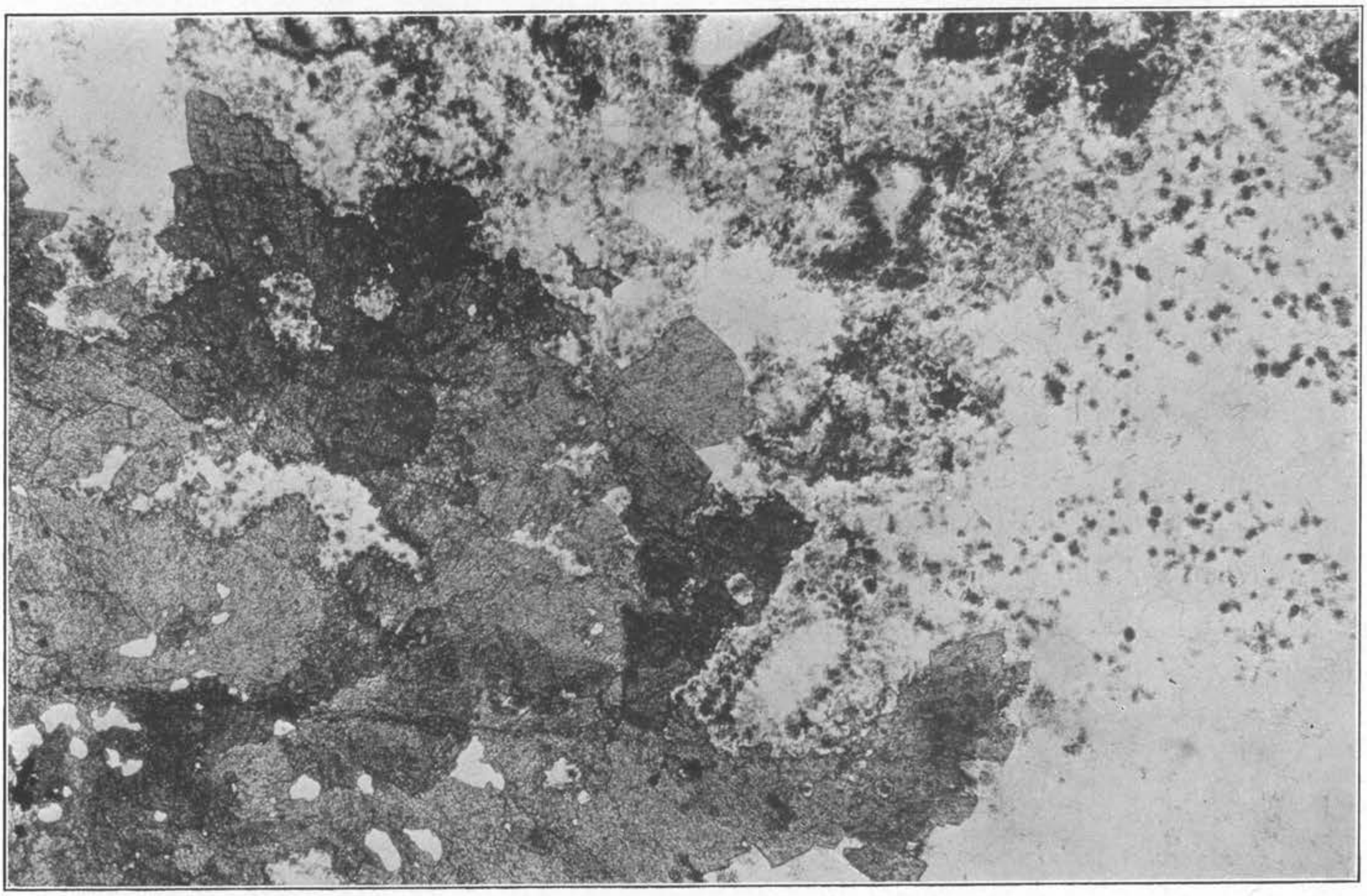
From the Chloride mine, Chloride Gulch. The opaque sulphides consist of pyrite, sphalerite, and galena. Plain transmitted light. × 34.



B. SAME AS *A*, BUT WITH CROSSED NICOLS

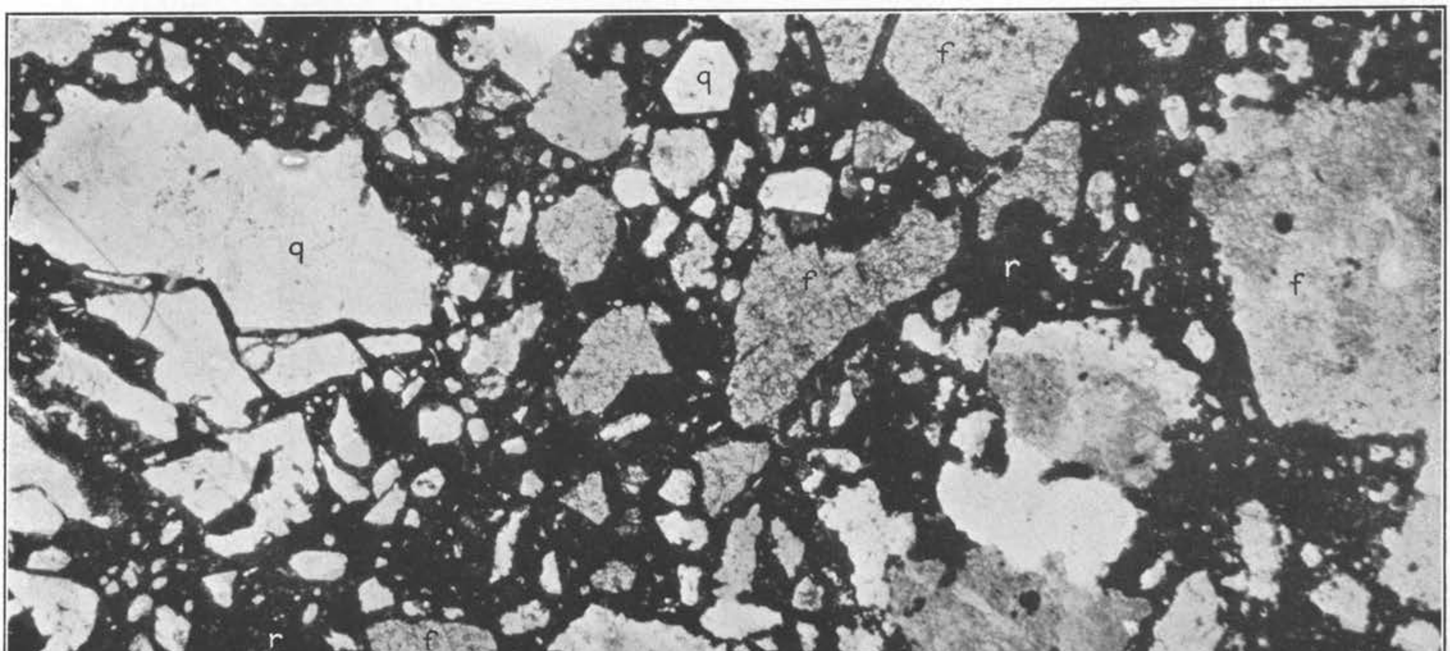
Shows character of vein quartz. ad, Adularia. × 34.

PHOTOMICROGRAPHS OF VEIN MATERIAL



A. EARLY VEIN QUARTZ, PARTLY REPLACED BY RHODOCHROSITE (GRAY) OF A LATER STAGE

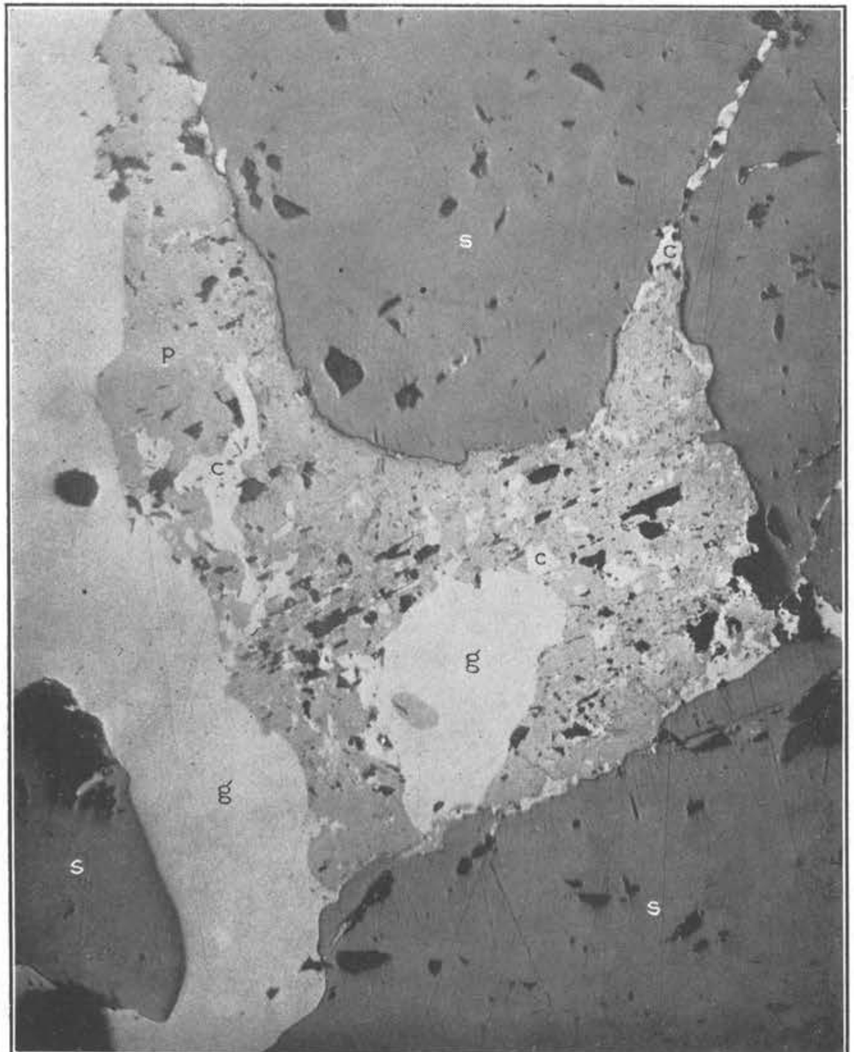
Eagle mine. Plain transmitted light. × 38.



B. EARLY VEIN QUARTZ (q), AND FLUORITE (f), BRECCIATED AND REPLACED BY RHODOCHROSITE (r) OF LATER STAGE OF VEIN FORMATION

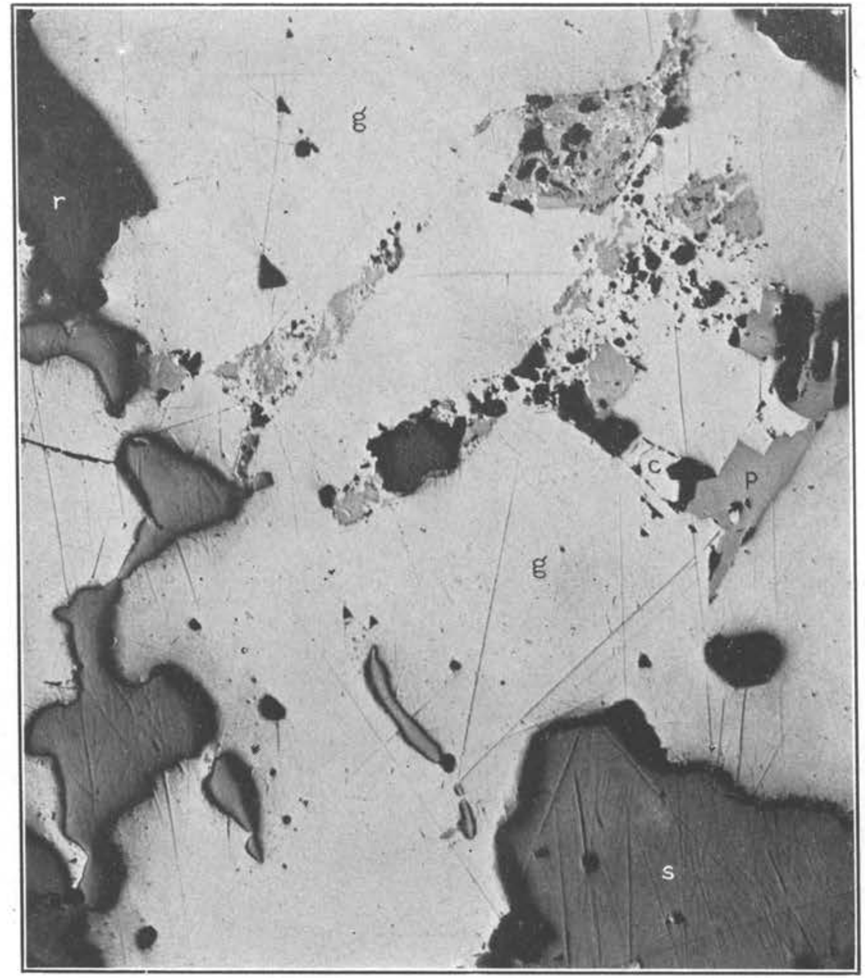
The same succession as shown in *A*, but in this vein brecciation of part of the early filling took place during formation of the vein. Plain transmitted light. × 34.

PHOTOMICROGRAPHS OF VEIN MATERIAL



A. PYRARGYRITE (p) AND CHALCOPYRITE (c) WHICH HAVE PARTLY REPLACED GALENA (g) ALONG BOUNDARY BETWEEN IT AND SPHALERITE (s)

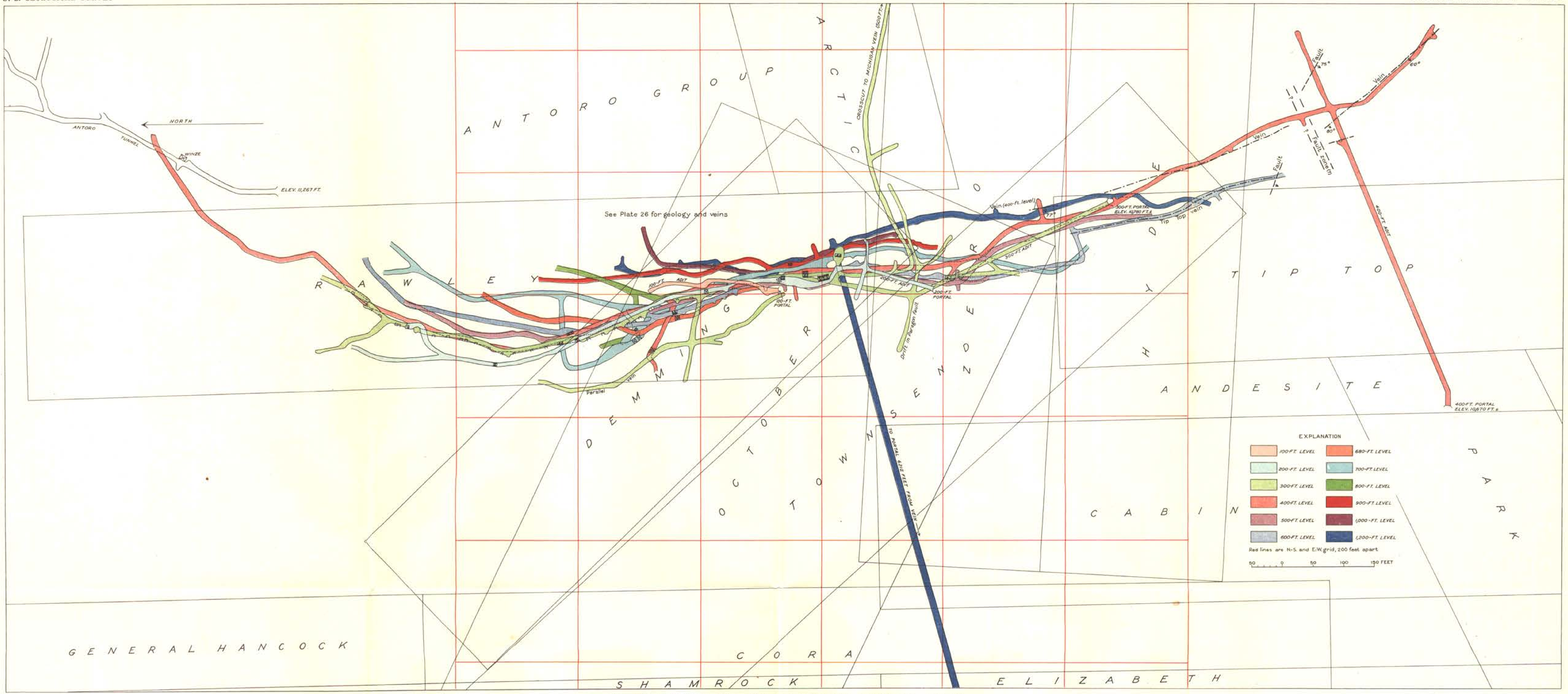
Eagle mine, 500 or 600 level. Eagle Gulch. Reflected light. × 220.



B. PYRARGYRITE (p) AND CHALCOPYRITE (c) WHICH HAVE REPLACED GALENA (g) ALONG CLEAVAGE DIRECTIONS

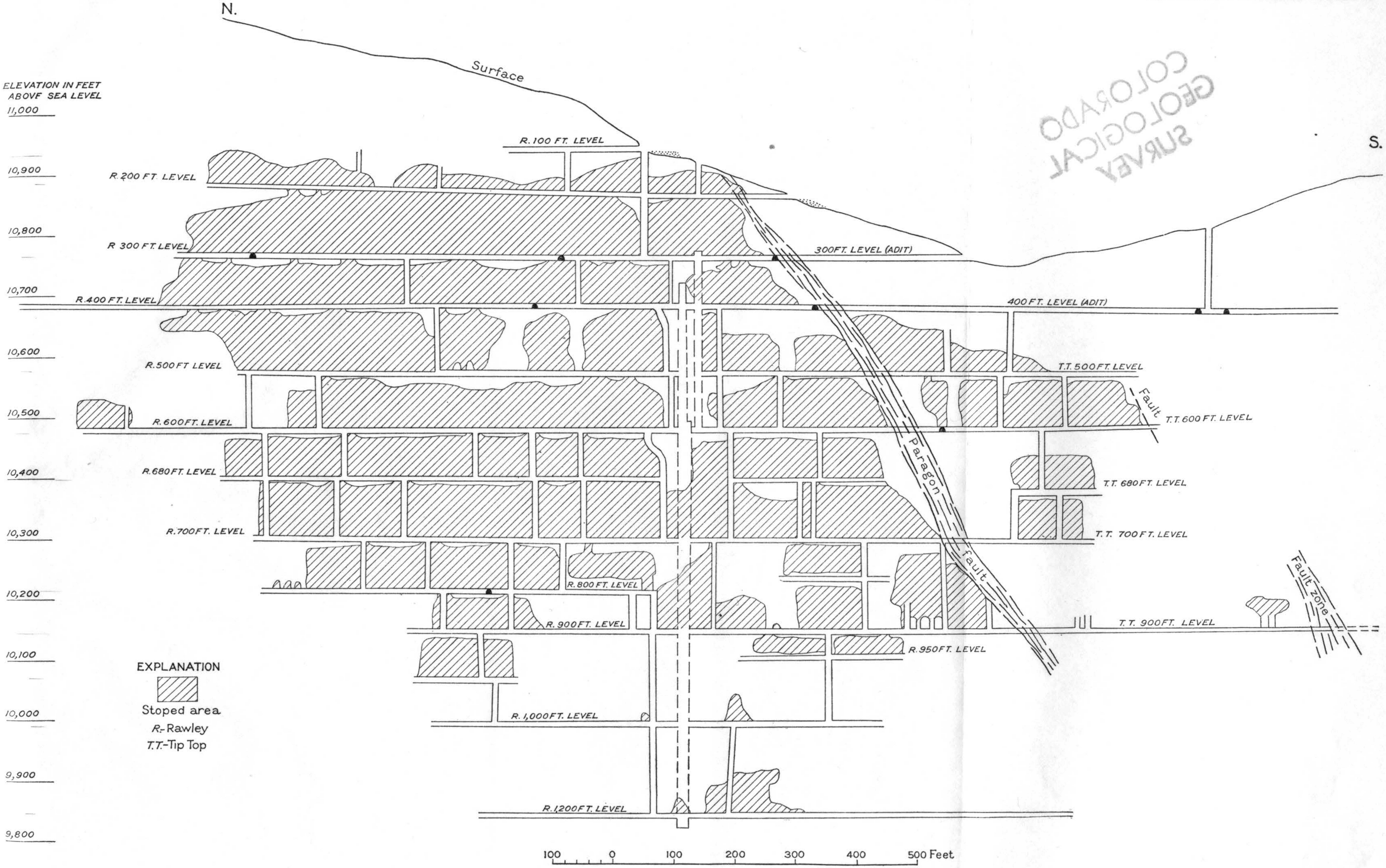
s, Sphalerite; r, rhodochrosite. Eagle mine. Eagle Gulch. Reflected light. × 100.

PHOTOMICROGRAPHS OF ORES



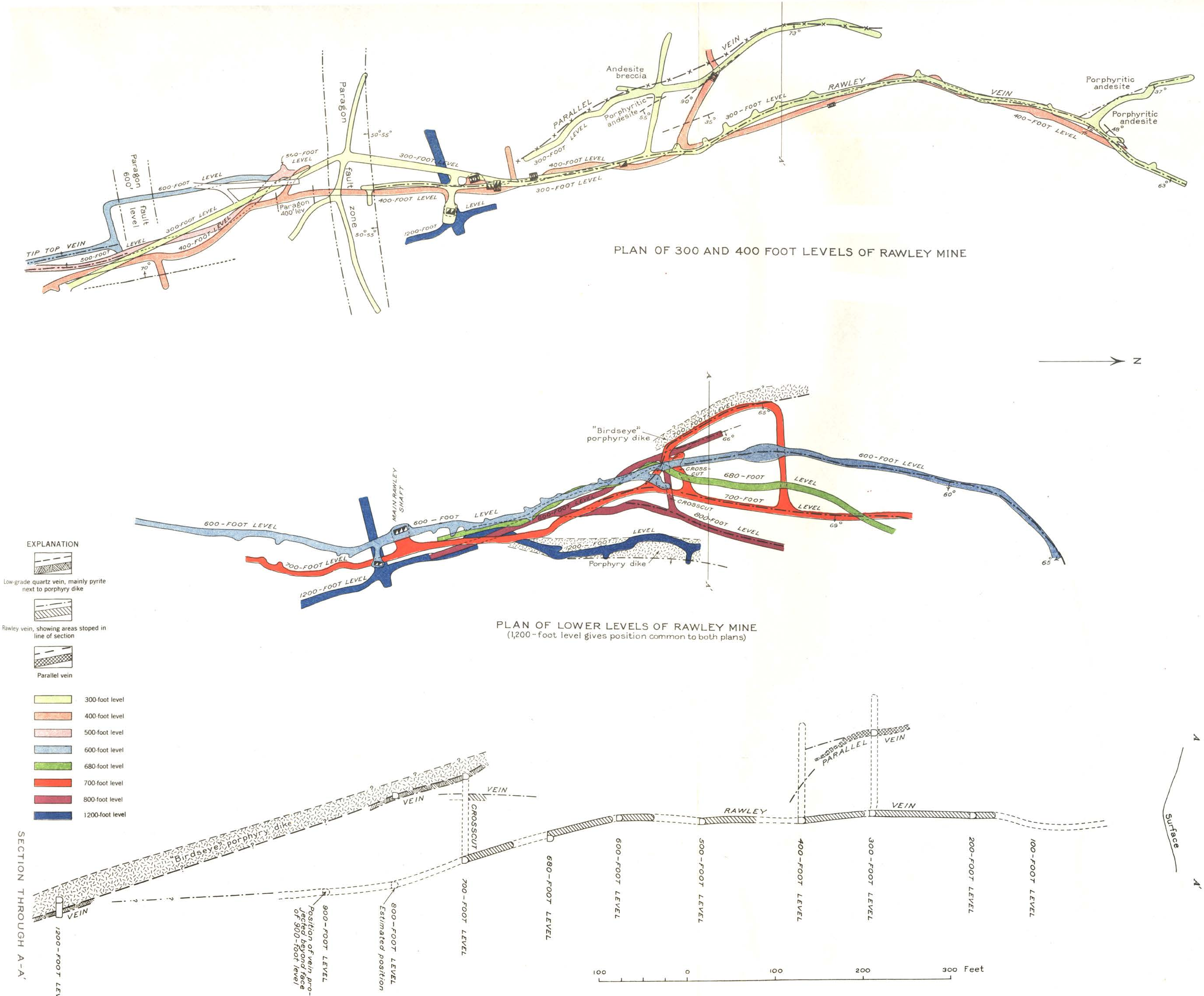
PLAN OF THE WORKINGS OF THE RAWLEY MINE

1931



LONGITUDINAL SECTION OF RAWLEY MINE

GEOLOGIC PLAN AND SECTION OF RAWLEY DRAINAGE TUNNEL

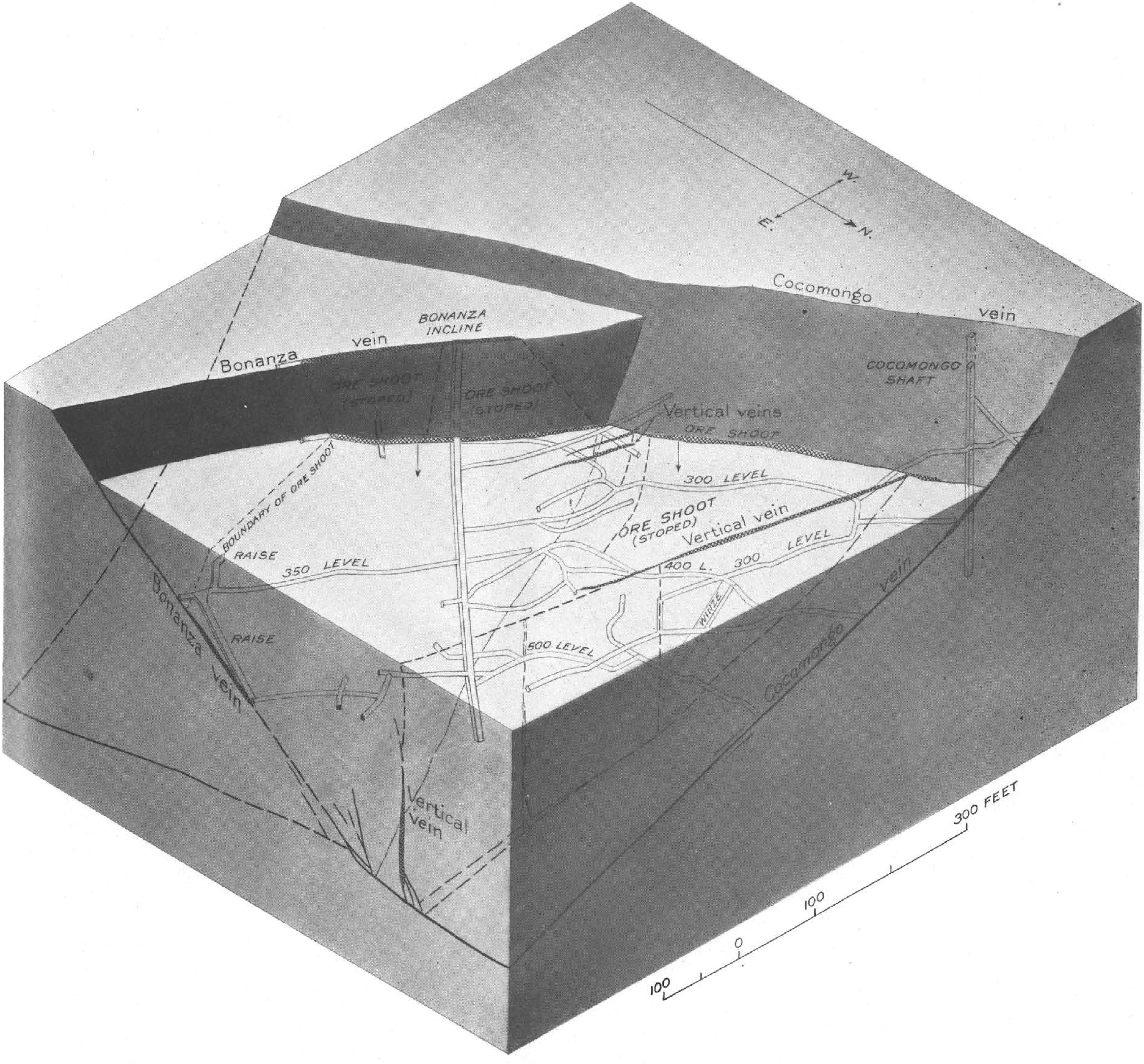


GEOLOGIC PLANS AND SECTION OF PART OF THE RAWLEY VEIN
1931

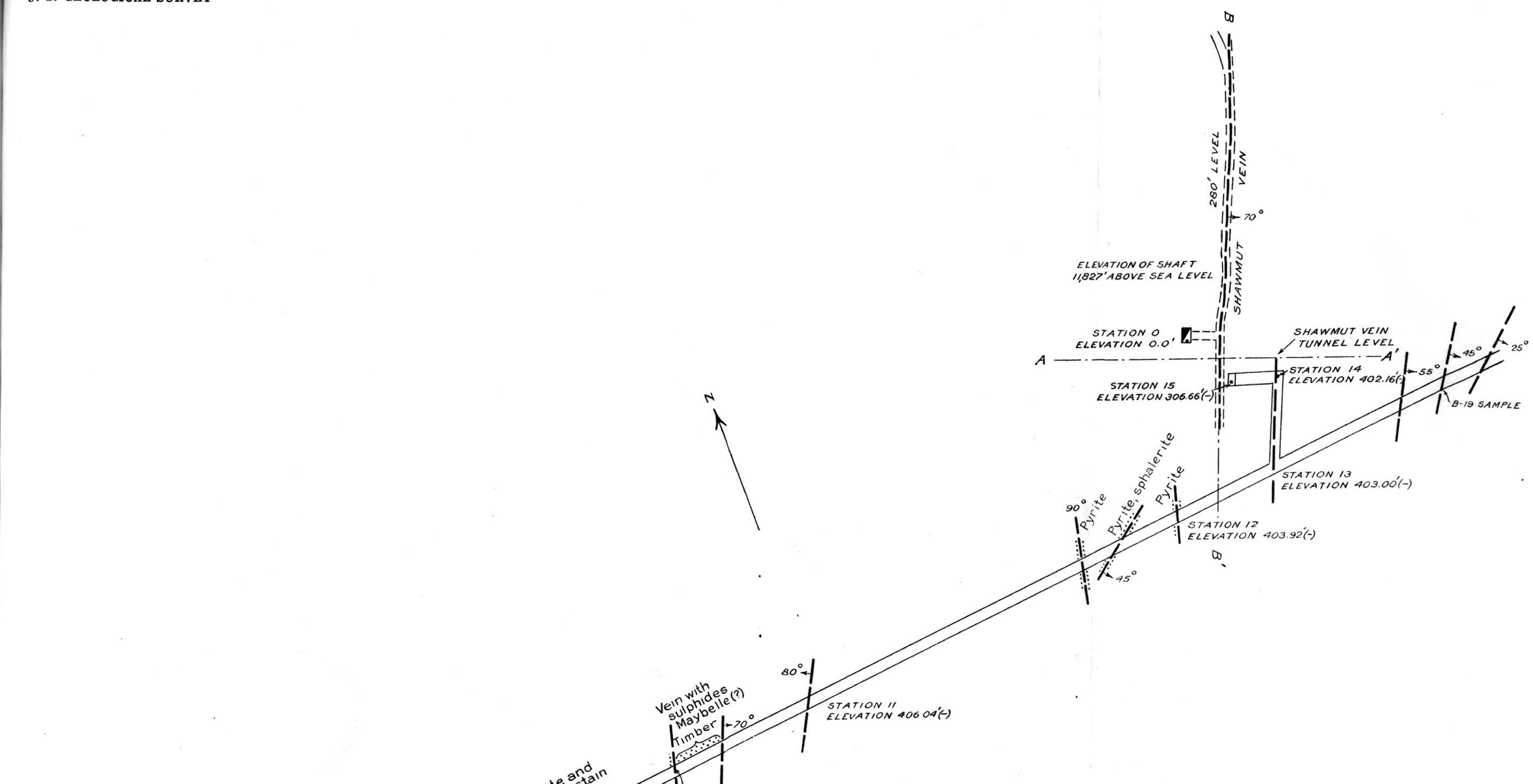
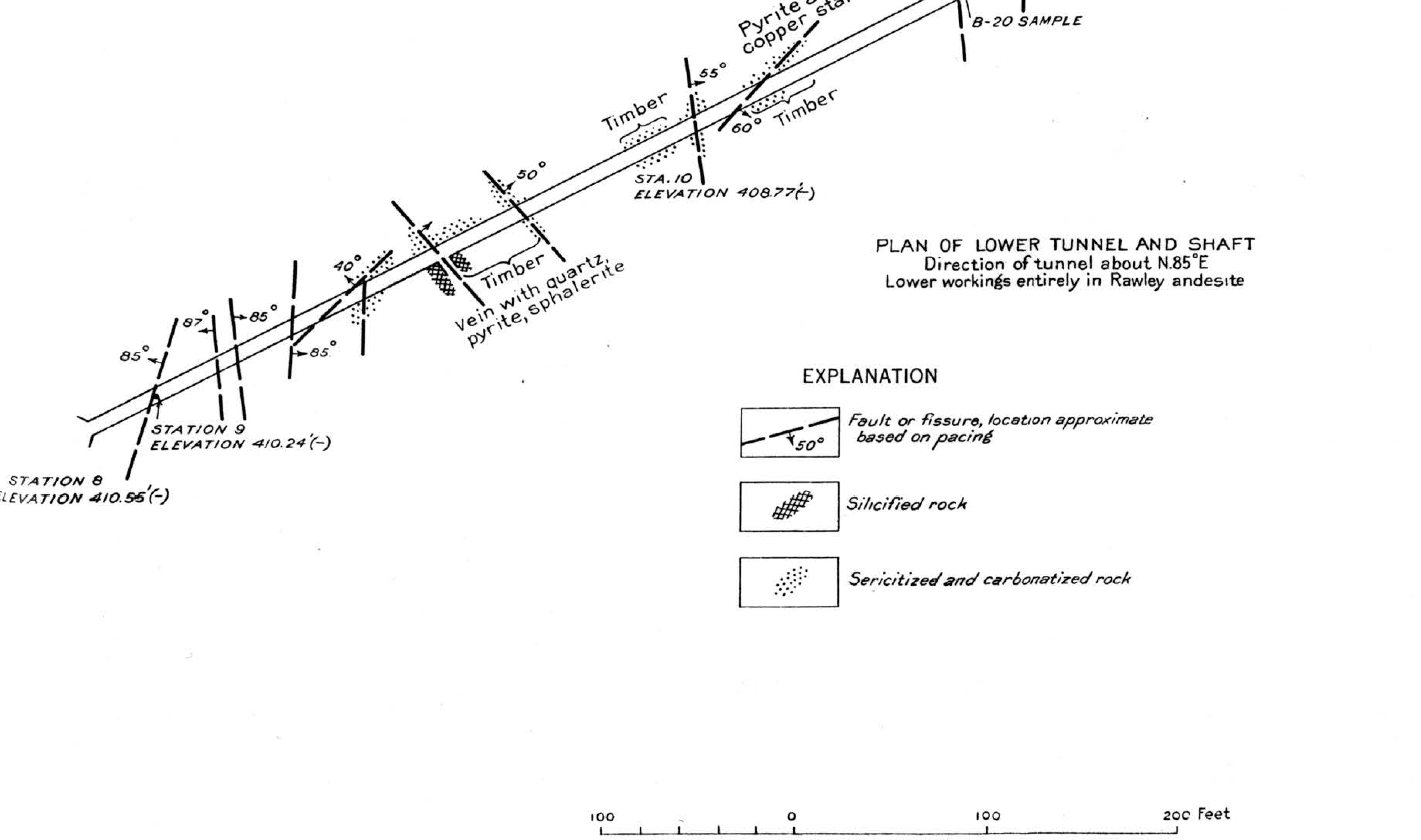
PLAN OF THE WORKINGS OF THE COCOMONGO MINE

1931

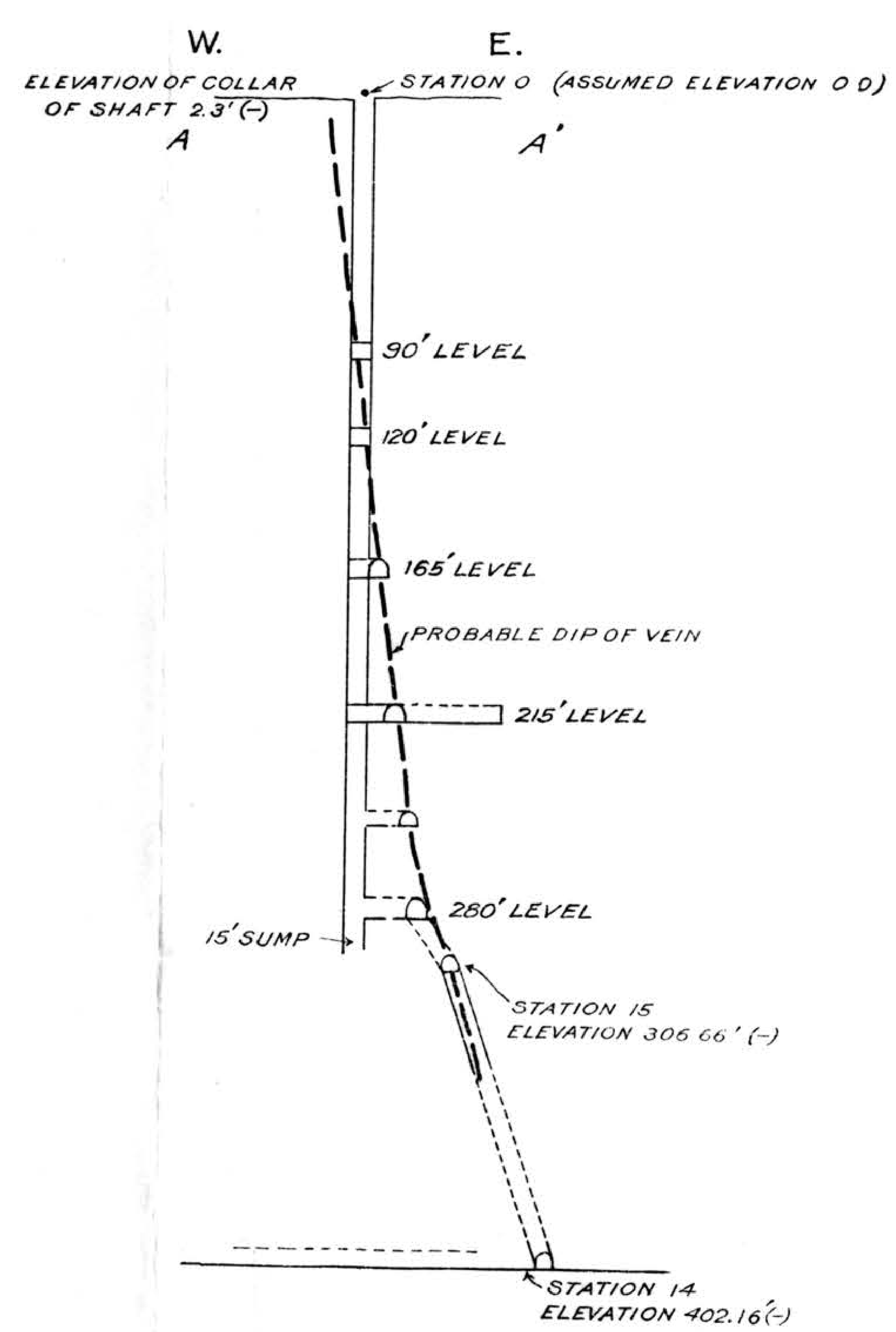
GEOLOGIC PLAN AND SECTIONS OF COCOMONGO AND BONANZA VEINS, COCOMONGO MINE



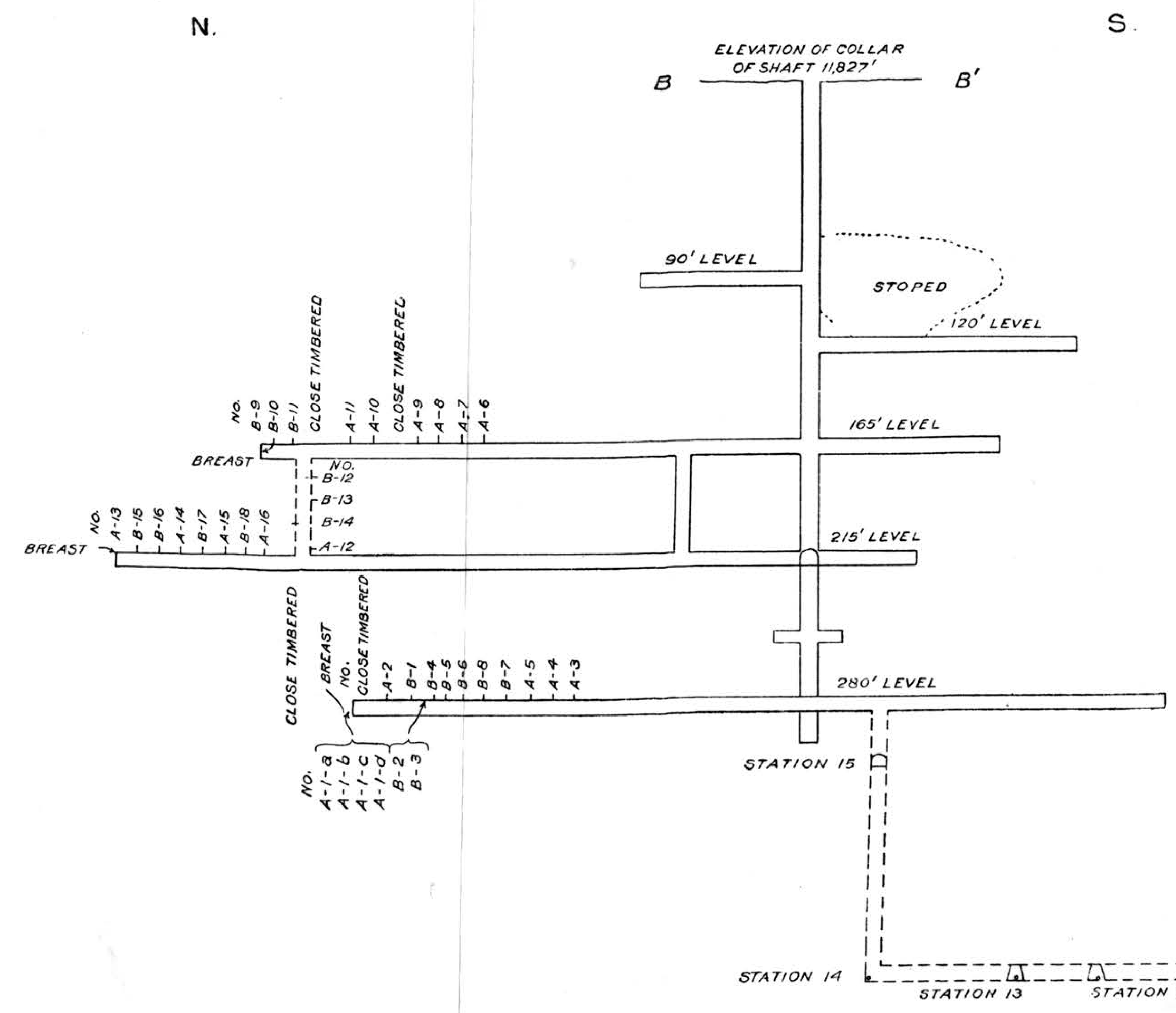
STEREOGRAPHIC PROJECTION OF PART OF COCOMONGO MINE, SHOWING RELATION BETWEEN MINERALIZED COCOMONGO AND BONANZA FAULT FISSURES

PLAN OF LOWER TUNNEL AND SHAFT
Direction of tunnel about N.85°E
Lower workings entirely in Rawley andesite



SECTION ALONG LINE A-A'



SECTION ALONG LINE B-B'

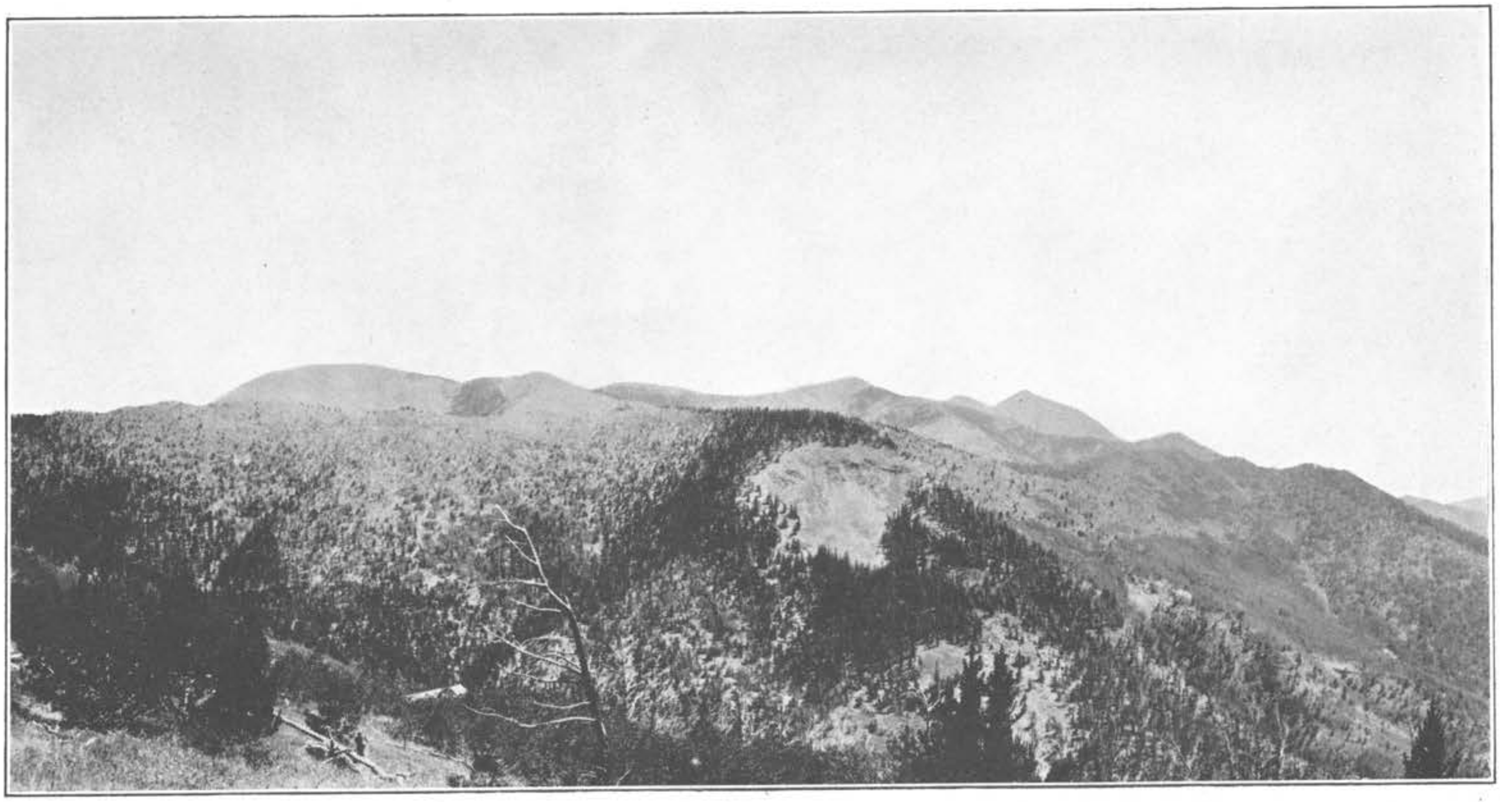
SAMPLES AND ASSAYS

No.	Width (feet)	Gold (ounces to the ton)	Silver (ounces to the ton)	Description
A-1-a	2.8	Tr.	Tr.	Altered andesite porphyry on hanging-wall pyrite.
A-1-b	1.8	0.06	4.74	Quartz with pyrite.
A-1-c	1.1	Tr.	.50	Altered andesite, quartz, and pyrite.
A-1-d	2.5	Tr.	.60	Quartz and pyrite. On footwall.
A-2	3.0	Tr.	1.40	Altered andesite and pyrite.
A-3	0.8	Tr.	3.70	Quartz and sulphides.
A-4	1.0	Tr.	Tr.	Do
A-5	2.7	Tr.	Tr.	Altered andesite, quartz, and pyrite.
A-6	1.0	Tr.	.50	Do
A-7	2.0	Tr.	5.60	Altered andesite with pyrite.
A-8	1.6	Tr.	1.00	Altered andesite, quartz, and pyrite.
A-9	1.5	Tr.	Tr.	Altered rock, quartz, and pyrite.
A-10	3.0	Tr.	Tr.	Altered andesite and pyrite.
A-11	2.8	Tr.	Tr.	Do
A-12	3.8	.03	3.80	Quartz and sulphides.
A-13	6.3	.08	5.62	Do
A-14	4.4	Tr.	1.20	Do
A-15	3.6	.12	17.88	Do
A-16	2.2	.08	5.92	Do
B-1	4.5	.04	1.60	Altered rock, quartz, and pyrite.
B-2	3.7	.01	.30	Do
B-3	1.6	Tr.	Tr.	Quartz, sulphide, and altered andesite.
B-4	4.4	Tr.	Tr.	Do
B-5	4.8	.02	Tr.	Altered andesite, little quartz, and pyrite.
B-6	4.0	.02	Tr.	Altered andesite, with pyrite.
B-7	1.5	Tr.	Tr.	Altered andesite. No sulphide or quartz.
B-8	2.0	Tr.	1.40	Altered andesite with pyrite.
B-9	2.5	.08	14.62	Footwall streak; quartz, chalcopyrite, and pyrite.
B-10	3.0	Tr.	1.00	Quartz and sulphides.
B-11	3.0	Tr.	Tr.	Quartz and 3 inches of sulphides.
B-12	2.6	Tr.	14.00	Quartz and sulphides.
B-13	3.6	Tr.	Tr.	Altered andesite, quartz, and sulphides.
B-14	2.8	.24	50.26	Quartz and sulphides.
B-15	4.2	.24	18.60	Altered rock, 1 foot; quartz, chalcopyrite, and pyrite, 2½ feet.
B-16	2.8	.08	2.92	Quartz and sulphides.
B-17	5.2	Tr.	.40	Altered rock, quartz, and sulphides.
B-18	3.0	.05	13.20	Do
B-19	.3	.06	13.44	Sulphides and chalcopyrite.
B-20	2.2	Tr	2.70	Sulphides and quartz.

PLAN AND SECTIONS OF SHAWMUT DRAINAGE TUNNEL AND MINE

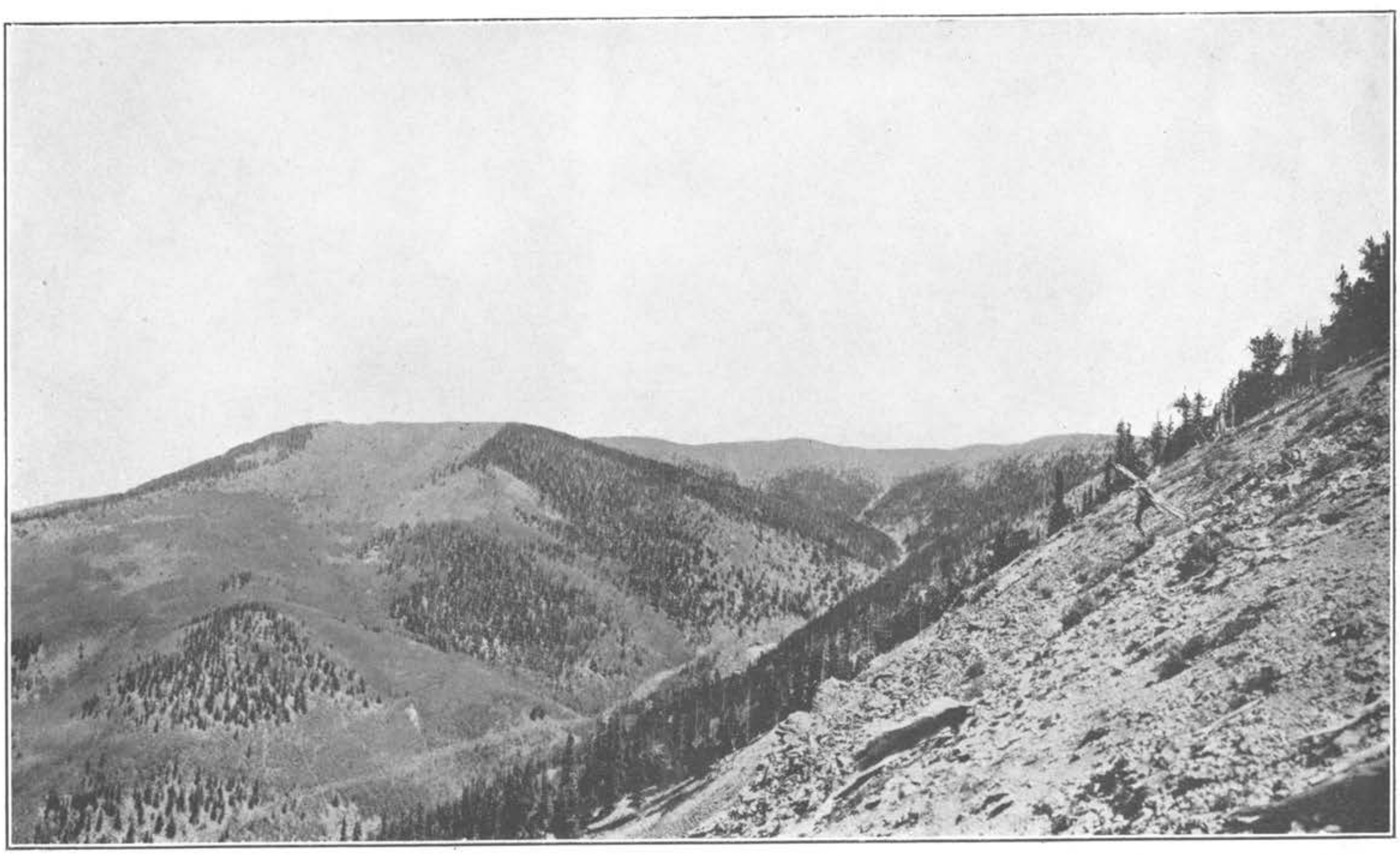
Samples and assays from report by S. J. Burris, jr., on the property of the Kapi Mining & Milling Co.

PLAN OF WORKINGS OF ANTORO MINE



A. VIEW ACROSS COPPER GULCH FROM POINT ABOVE SENATOR MINE

Looking southward. The pyramidal peak at right is Hayden Peak and the round-topped high summit at left is Elkhorn Peak. There is a small landslide scar on the ridge south of the gulch.

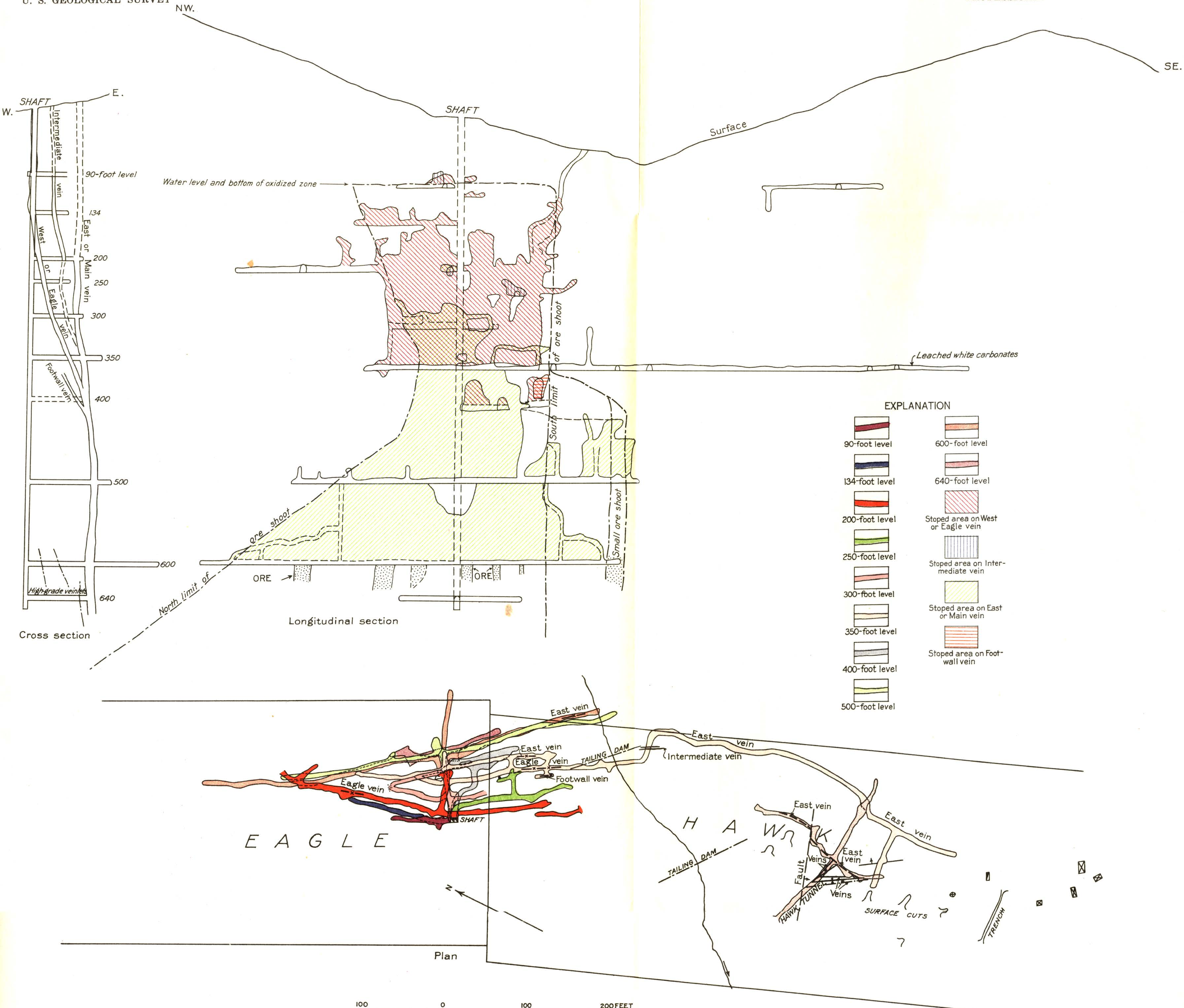


B. VIEW FROM SOUTH SIDE OF COPPER GULCH NORTHEASTWARD TOWARD ITS HEAD

The talus slope in foreground is composed of Bonanza latite.

PLAN AND LONGITUDINAL SECTION OF THE EMPRESS JOSEPHINE AND HORTENSE MINES
1931

MAP OF EXCHEQUER AND MEMPHIS MINES AND VICINITY



PLAN AND LONGITUDINAL SECTION OF THE EAGLE MINE

1931