EPITHERMAL VEIN AND CARBONATE REPLACEMENT MINERALIZATION RELATED TO CALDERA DEVELOPMENT, CUNNINGHAM GULCH, SILVERTON, COLORADO

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by

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THESIS

Presented to the Faculty of the Graduate School of
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in partial fulfillment
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MASTER OF ARTS

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May 1984

To my parents

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James F. Hardwick, Jr.

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ABSTRACT

Epithermal vein and carbonate replacement deposits in Cunningham Gulch are located within the western San Juan Tertiary volcanic field in southwestern Colorado. The Pride of the West epithermal vein system is hosted within the intracaldera facies of the Sapinero Mesa Tuff, a voluminous ash-flow tuff that erupted from and resulted in the formation of the San Juan Caldera at 28 mybp. The Pride of the West vein system is developed along a radial fracture formed during resurgence of the San Juan Caldera prior to eruption of the Crystal Lake Tuff (27.5 mybp). This eruption led to the concomitant collapse of the Silverton Caldera, nested within the larger San Juan Caldera. The Pride of the West, Osceola, and Little Fanny mines are positioned near the intersection of the Pride radial fracture system and the buried structural margin of the San Juan Caldera, suggesting that ore concentration was controlled by this structural setting.

Large limestone blocks of the Mississippian Leadville Formation are incorporated into the intracaldera fill volcanics in the mine area. These blocks appear to have been engulfed within mudflow breccias of the Tertiary San Juan Formation (32.1 mybp). They were then emplaced in their present structural position within a caldera-collapse breccia which caved from the oversteepened margin of the San Juan Caldera.

Regional propylitic alteration of the hosting volcanics to a chlorite-calcite-pyrite assemblage preceded vein-associated alteration and mineralization. The veins are enveloped by a narrow phyllic alteration assemblage of quartz, sericite, illite, kaolinite, and pyrite. The veins are comprised of sphalerite, galena, chalcopyrite, pyrite, hematite, magnetite, quartz, pyroxmangite, calcite, and minor barite. Substantial bodies of replacement ore are present where the vein structures intersect the limestone blocks; the mineral assemblages of the replacement deposits are identical to those of the feeding vein structures. Commonly, replacement textures are spectacular concentrations, especially the "zebra ore" which primarily consists of regularly spaced, alternating bands of sulfides and quartz. These "zebra" laminations are stratigraphically controlled and appear to represent replacement of a depositional or diagenetic fabric. Main ore-stage mineralization began with widespread deposition of quartz with or without pyrite, followed by sphalerite, chalcopyrite, and galena. Post ore-stage brecciation and silicification events are evident and were followed by deposition of calcite and minor barite during the waning stages of the hydrothermal system.

The distributions of Fe, Mn, Pb, and Ca suggest a lateral component of fluid flow from northwest the southeast, away from the structural margin of the Silverton Caldera. Fluid inclusion data from both vein and replacement-type sphalerite and quartz indicate that mineral deposition occurred over a range of 200 to 312°C (mean 243 ° C) from solutions containing 1 to 5% total salts. The high base metal to precious metal content of the ore, the phyllic alteration assemblage, and the temperature and composition of the ore-forming fluid indicate that the mine workings are within the lower portion of a fossil geothermal system.

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ILLUSTRATIONS

Frontispiece. Surface buildings at the Pride of the West mine (lower right) and glory holes of the Osceola mine (arrows, left center) in 1982. Camera orientation: northeast.

> "There are no abandoned mines, only
> idle mines waiting to be reopened."
>
> Anonymous

INTRODUCTION

The Cunningham Gulch area is located within the complex Tertiary volcano-tectonic terrane of the western San Juan Mountains in southwestern Colorado (Fig. 1). The Pride of the West, Osceola, and Little Fanny mines lie outside the structural margin of the Silverton Caldera, and just inside the topographic rim of the larger and earlier formed San Juan Caldera, in which the Silverton Caldera is nested (Fig. 2). Mining activity which has produced more than $10 million worth of base and precious metals has been concentrated along a system of generally parallel vein structures occurring along a fracture radial to these calderas. The ore deposits are located near the intersection of this radial fracture system with the buried structural margin of the San Juan Caldera.

The relationship between vein-type epithermal base and precious metal mineralization and caldera environments has been well-documented for calderas which have undergone complex and extended histories of development (Steven et al., 1974a). The Pride of the West mine area provides an interesting example of this relationship due to the mine's unique structural position within the caldera setting and the presence of both vein and carbonate replacement deposits. Replacement deposits occur exclusively where large blocks of Paleozoic age carbonate rocks, which have been incorporated into the intracaldera fill assemblage, are intersected by metal-bearing veins.

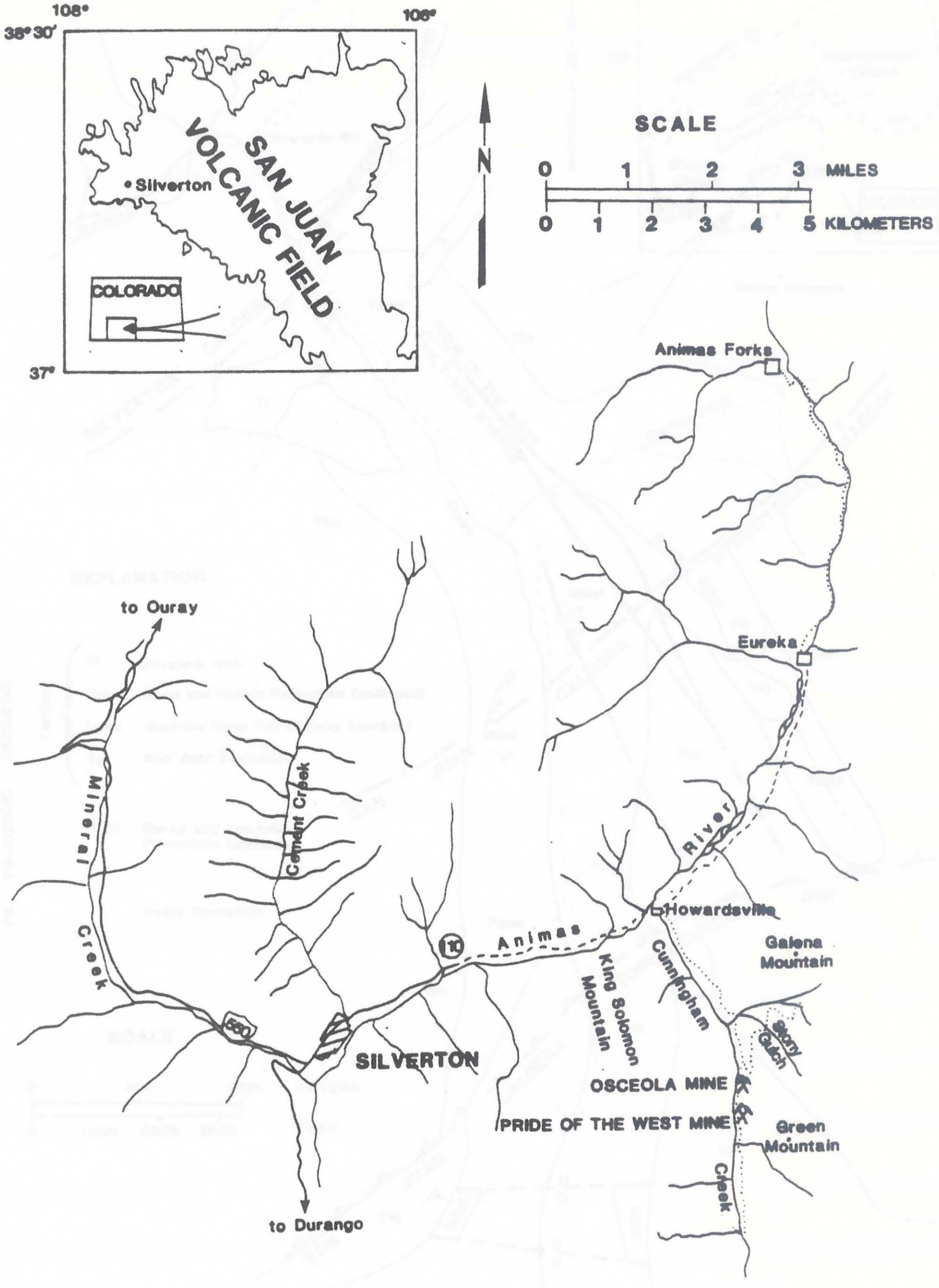


Figure 1. Location map of the Cunningham Gulch area.

The paths of the Animas River and Mineral Creek follow the Silverton Caldera structural margin (modified from Cooper et al., 1980).

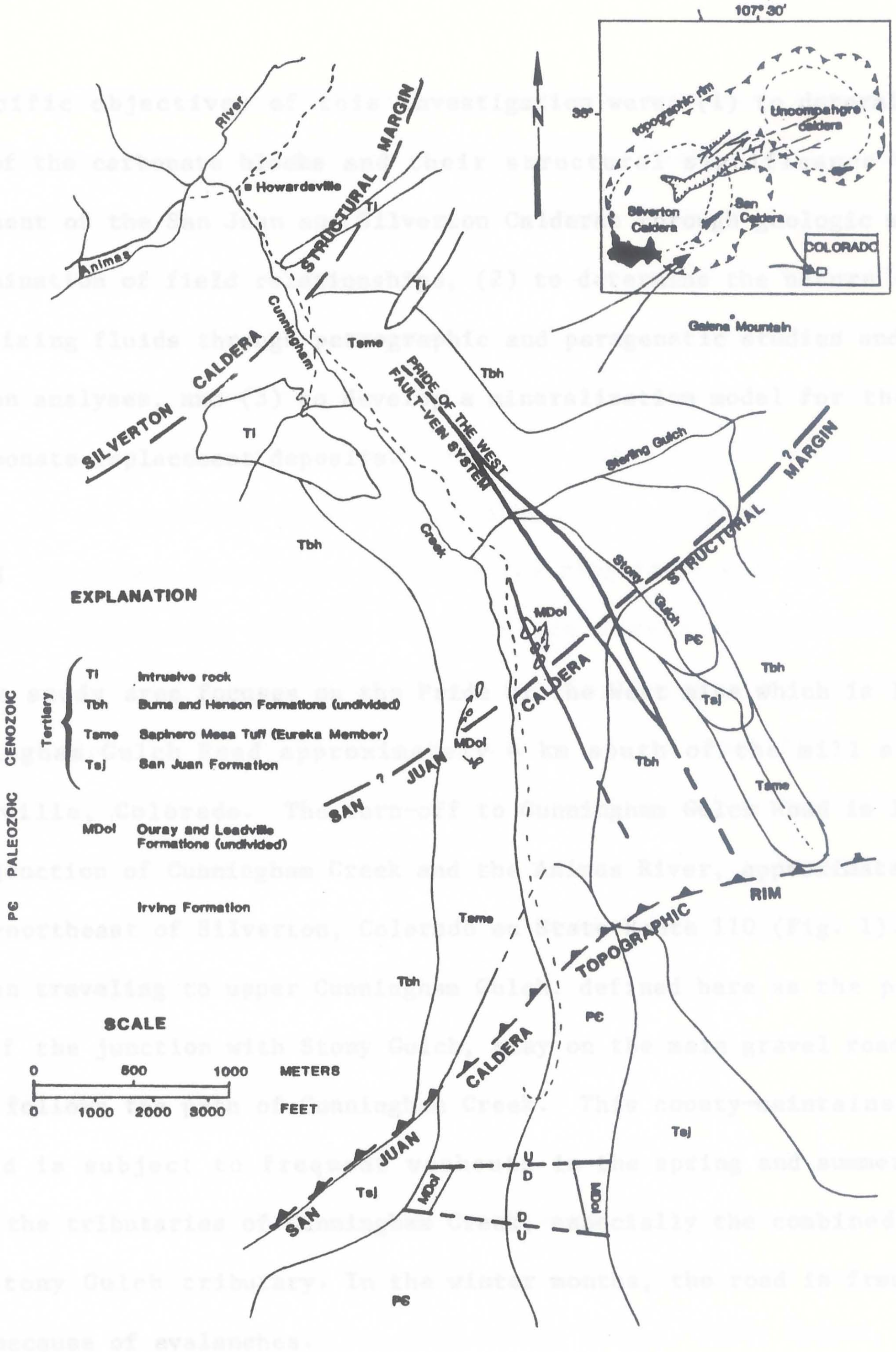


Figure 2. Principal structural features of the Cunningham Gulch area (modified from Cooper et al., 1980)

OBJECTIVES

Specific objectives of this investigation were: (1) to determine the origin of the carbonate blocks and their structural significance to the development of the San Juan and Silverton Calderas through geologic mapping and examination of field relationships, (2) to determine the nature of the mineralizing fluids through petrographic and paragenetic studies and fluid inclusion analyses, and (3) to develop a mineralization model for the vein and carbonate replacement deposits.

LOCATION

The study area focuses on the Pride of the West mine which is located on Cunningham Gulch Road approximately 4 km south of the mill site at Howardsville, Colorado. The turn-off to Cunningham Gulch Road is located at the junction of Cunningham Creek and the Animas River, approximately 6.5 km east-northeast of Silverton, Colorado on State Route 110 (Fig. 1).

When traveling to upper Cunningham Gulch, defined here as the portion south of the junction with Stony Gulch, stay on the main gravel road which closely follows the path of Cunningham Creek. This county-maintained gravel road is subject to frequent washouts in the spring and summer along some of the tributaries of Cunningham Creek, especially the combined Rocky Gulch-Stony Gulch tributary. In the winter months, the road is frequently closed because of avalanches.

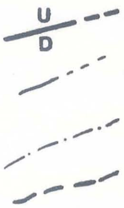
GEOGRAPHY

The western San Juan Mountains contain some extremely rugged terrain with peaks reaching elevations over 4265 m (14,000 feet). Cunningham Gulch is a highly precipitous canyon cut into a thick sequence of Tertiary volcanic rocks in its lower reaches and into basement rocks of Precambrian age in its upper reaches. The uppermost region of the gulch possesses a U-shaped character typical of many of the glacially carved valleys in the region (Cross et al., 1905), although the steep canyon walls have been modified by the northward flow of Cunningham Creek. This creek is a tributary of the Animas River which occupies the ring-fault zone of the Silverton Caldera between the towns of Silverton and Eureka (abandoned). Cunningham Gulch is bounded on the west by King Solomon Mountain, which reaches an elevation of 4089m (13,416 feet) at Little Giant Peak. The east side of the Gulch is bounded in its lower portion by Galena Mountain reaching 4047 m (13,278 feet) and in its upper portion by Green Mountain which reaches 3977 m (13,049 feet). The Continental Divide occurs about 3 km east of Cunningham Gulch.

MINING HISTORY

The Pride of the West and Highland Mary mines were among the first producers of Cunningham Gulch (Fig. 3); the Pride of the West was the first claim (1874) to be staked in San Juan County (Hagan, 1951; Cooper, et al., 1980). The Green Mountain and Osceola claims were also staked in 1874, and

EXPLANATION OF GEOLOGIC MAP OF UPPER CUNNINGHAM GULCH



Fault

Contact

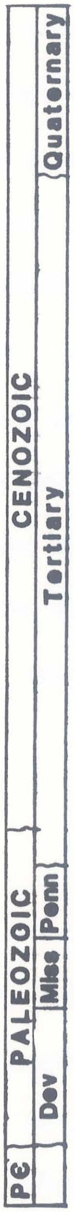
Vein

Road

⅄ **Adit**

Mines

OS	Osceola
LF	Little Fanny
PW	Pride of the West
GM	Green Mountain
HM	Highland Mary



Ql **Landslide**

Intrusive rocks
- Tif Felsic composition
- Tia Andesitic composition

Tbh **Burns and Henson Formations (undivided)** - Post-caldera andesitic to latitic lavas and volcaniclastic rocks.

Sapinero Mesa Tuff - Gray-white to light green rhyolitic ash-flow tuff.

Tsm **Outflow Member** - Gray-white ash-flow sheet with very sparse lithic fragments locally preserved outside San Juan caldera margin

Tsm **Eureka Member** - Thick intracaldera accumulation (up to 800 meters) of partly welded ash-flow tuff typically containing angular fragments of andesite

Tsm **Megabreccia Member** - Caldera-collapse breccia composed of material from the San Juan caldera wall. Dominantly consists of San Juan Formation with up to 50 meter Paleozoic carbonate blocks and minor local fragments of Outflow Member.

Tsj **San Juan Formation** - Precaldera intermediate composition lavas and mudflow breccias. Highly variable nature and size of clasts including gneiss, schist, and granite in basal portion. Preserved in over 200 meter accumulation outside San Juan caldera margin.

Pm **Molas Formation** - Red calcareous siltstone.

MDo **Ouray and Leadville Formations (undivided)** - Typically dense light gray limestone and dolostone.

De **Elbert Formation** - Light gray to tan, calcareous siltstone to silty limestone

P€ **Irving Formation** - Foliated biotite gneiss and schist.

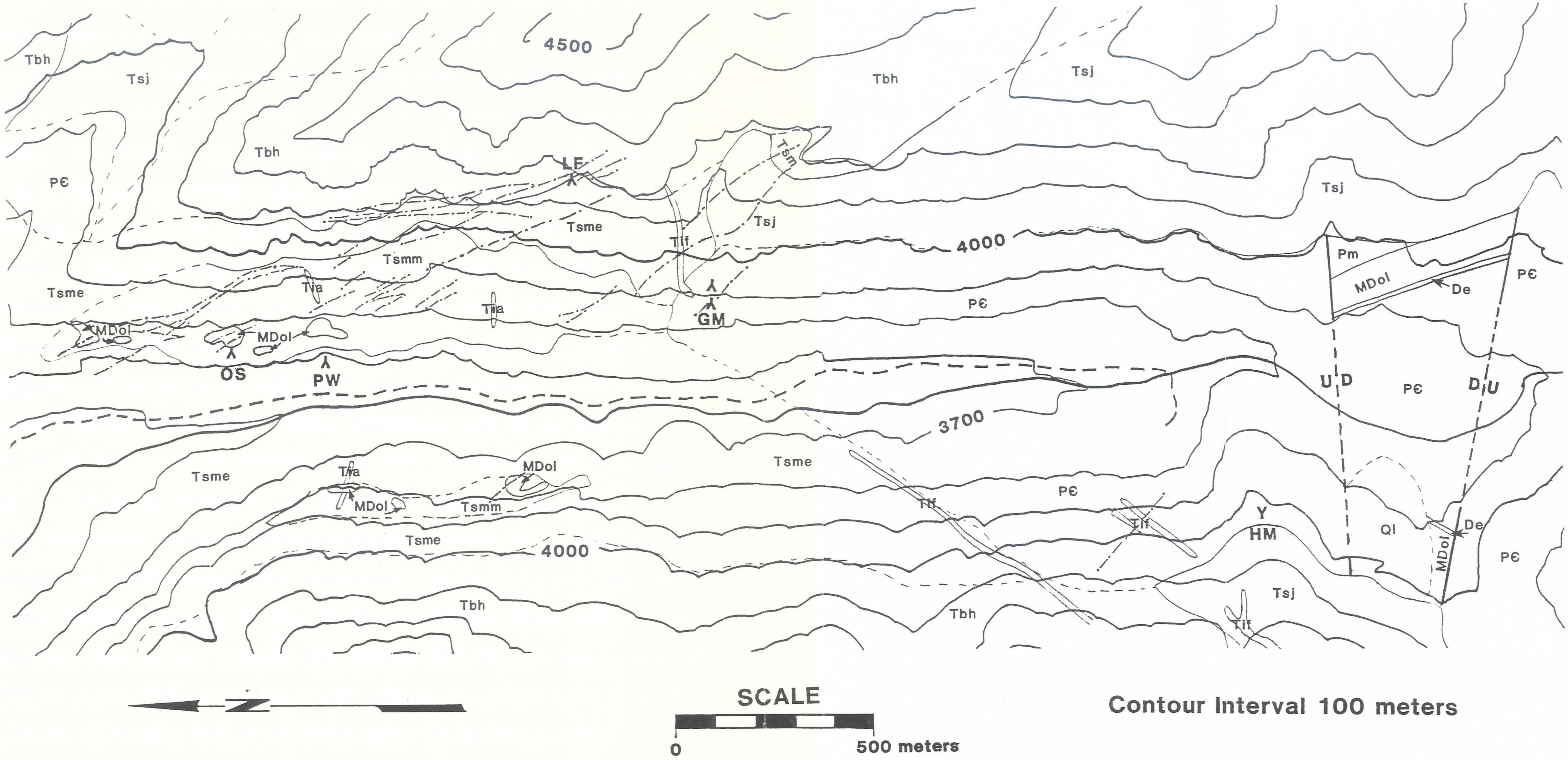


Figure 3. Generalized geologic map of upper Cunningham Gulch. See explanation on facing page. (modified after Cook, 1952 and Varnes, 1963)

the Highland Mary mine produced silver ore in 1875 (Hagan, 1951). The first ore at the Pride of the West mine was taken out by pack animals in 1874 from the upper workings (third level?) and was reported to have contained handsome masses of wire silver (Ransome, 1901).

The Pride of the West and Osceola mines have had a rather complex history of development and production since the beginning of mining operations. An extensive history of owners and lessees was compiled by Cooper et al. (1980) for the Osceola mine. Early production figures for many of the mines of upper Cunningham Gulch are unavailable. However, available production data for the mines pertinent to this study have been summarized in Table 1. Total production from the Pride of the West mine has been estimated at 300,000 metric tons; approximately 120,000 metric tons of this averaged 0.07 oz/ton Au (2 ppm), 4.17 oz/ton Ag (140 ppm), 0.22% Cu, 6.59% Pb, and 1.5% Zn (Fearn, 1980). Total production from the Osceola mine has been estimated at about 200,000 metric tons averaging 0.095 oz/ton Au (3 ppm), 2.0 oz/ton Ag (70 ppm), 0.4% Cu, 5% Pb, and 7% Zn (Barge, 1973). Total production from the adjacent Green Mountain mine (to 1948) has been estimated at 35,000 metric tons, averaging 0.03 oz./ton (1 ppm) Au, 3 oz./ton (100 ppm) Ag, 0.15% Cu, 4% Pb, and 3% Zn (Hagen, 1951). Total production from the Little Fanny mine between 1924 and 1949 has been estimated at about 1800 metric tons, averaging 0.13 oz/ton Au (4 ppm), 50.0 oz/ton Ag (1700 ppm), 0.8% Cu, 5.5% Pb, and 1.3% Zn (Fearn, 1980).

At the initiation of this project in January of 1981, the Pride of the West, Osceola, and Little Fanny properties were being leased and operated on a limited basis by the Maverick Mining Company of Silverton, Colorado of

TABLE 1

Mine	Date	Ore type	Levels	Tons	Au oz/ton	Ag oz/ton	Cu %	Pb %	Zn %
Osceola	to 1973	replacement	--	150,000	0.095	2.00	0.40	5.00	7.00
	to 1973	vein	--	50,000	--	--	--	--	--
Pride of the West	1935-37	vein	4&5	18,500	0.13	11.40	0.30	9.50	2.60
	1941-46	vein	all 7	130,000	0.07	4.17	0.22	6.59	1.50
	to 1973	vein	all 7	350,000	--	--	--	--	--
Little Fanny	1924-49	vein	--	2,026	0.13	50.00	0.8	5.50	1.30

Available production figures for mines along the Pride of the West radial fracture system in upper Cunningham Gulch. As listed, mines are in order from NW to SE and increasing elevation along the vein system. Compiled from Barge (1973) and Fearn (1980).

which Mr. Stephen C. Fearn was president. The properties are owned by Mr. Ed Barge of Durango, Colorado. The lease is presently held by P & G Mining Company of Silverton, Colorado of which Mr. Richard Peck is president. The Pride and Osceola properties are not being operated at the present time, but reserves are being evaluated for reopening within a more favorable economic climate.

PREVIOUS WORK

Steven and Lipman (1976) summarized the geologic history of the San Juan Volcanic Field and included a discussion of the development of the known calderas and the current stratigraphic nomenclature of the ash-flow sheets. Ransome (1901) completed the first major study on the economic geology of the Silverton 15' Quadrangle including a description of its geologic setting and mining history, as well as a detailed section on individual mines and lodes. The first geologic mapping in Cunningham Gulch was completed on a reconnaissance scale by Cross, Howe, and Ransome (1905) for their work on the geology of the Silverton Quadrangle.

Varnes (1963) summarized the geology and ore deposits of the South Silverton Mining Area, including rock unit descriptions and underground geologic maps of the Pride of the West and Osceola mines. The accompanying geologic map (1:12000 scale) of the South Silverton Mining Area was compiled from mapping by Burbank in 1932 and Varnes in 1945-46, and includes the west side of Cunningham Gulch. The most detailed study on the geology of the Pride of the West vein system is the PhD. dissertation by Cook

(1952), which includes detailed petrography of many of the rock units as well as of the ore and gangue minerals. Detailed geologic maps on a scale of 1:600 of the Pride of the West mine property were a major contribution of this study. During this period, Hagan (1951) completed a geologic study and map of the adjacent Green Mountain mine. Cooper et al. (1980) completed an unpublished composite report (for B.A. degrees at Ft. Lewis College, Durango, Colorado) on the geology of the carbonate replacement deposits at the Osceola mine and reported some fluid inclusion homogenization temperatures and some geochemical analyses of wallrock samples.

METHOD OF INVESTIGATION

The objectives of this study were accomplished through a combination of field and laboratory studies. Geologic mapping of upper Cunningham Gulch and a portion of Stony Gulch on a scale of 1:12000 was undertaken to determine the structural and spatial position of the Pride of the West and Osceola mines within the volcano-tectonic setting of the nested San Juan and Silverton Calderas. Previously published maps on various portions of the area were utilized during this investigation and helped with the present interpretation of the geology. Thus, the accompanying geologic map (Fig. 3) is essentially a combination of original work and modifications of previous investigations. Rock unit terminology was standardized to conform with presently accepted stratigraphic nomenclature. The topographic base used for the geologic map is modified from the U.S. Geological Survey Howardsville 7-1/2' Quadrangle (1955).

Underground samples were collected on all reasonably accessible levels of the Pride of the West mine to determine the general characteristics of the deposit, and to obtain ample vertical and horizontal sample distributions for the mineralogic and fluid inclusion studies. Despite limited access to most of the upper levels, the main portal of the Pride mine, which also serves the Osceola mine, remains open and in good condition, as are the number 1 level of the Pride and corresponding Osceola 29.5 level. Dump samples were collected from inaccessible adits (i.e., 7th level Pride) and from the Little Fanny mine, at which underground sampling was not attempted.

Approximately 30 standard thin sections were prepared for petrographic analysis of the rock units and preliminary wallrock alteration study. About 20 doubly polished thin sections of ore and gangue mineral assemblages from both vein and replacement type deposits were prepared for reflected light petrographic analysis to determine the opaque mineral phases present and their paragenetic relationships. After reflected light studies, the thick sections were either thinned to 30 microns for use in transmitted light studies, or were cut for fluid inclusion analysis. Over 100 fluid inclusions from vein and replacement-type quartz and sphalerite were analyzed for homogenization temperature and salinity (freezing point depression), in order to determine the nature and composition of the ore-forming fluid.

Clay minerals were identified using X-ray diffraction analysis, crystal morphology, and energy dispersive spectra on the scanning electron microscope. This latter method was also used to determine the presence of manganese in some samples of calcite.

REGIONAL GEOLOGIC SETTING

PRE-TERTIARY GEOLOGIC HISTORY

Precambrian

Precambrian rocks of the western San Juan Mountains are strikingly exposed in the Needle Mountains, south of Silverton, Colorado. This complex of metamorphic rocks was formed in two cycles of deposition, folding, metamorphism, and intrusion of plutonic rocks; the first cycle at 1,800 to 1,700 mybp and the second about 1,650 to 1,450 mybp (Barker, 1969). The metasediments which make up the Irving Formation, exposed in upper Cunningham Gulch, were deposited during the first cycle with the observed lineation modified during the Uncompahgre disturbance of the second cycle. The final events were batholithic intrusion of the Eolus and Tribble Granites (1,460 mybp) accompanied with doming, uplift, high angle faulting and intrusion of dikes and stocks into the Irving Formation (Barker, 1969). This plutonic phase was followed by widespread peneplanation from late Precambrian through Ordovician time and possibly in Devonian time (Kelley, 1957).

Paleozoic

During most of early Paleozoic time, the western San Juan Mountain region was a positive lowland area and the first sediments to be deposited on the eroded surface of Precambrian rocks were siliciclastic units of the late Cambrian Ignacio Formation (Kelley, 1957). The area may have been broadly domed during Silurian and Devonian time, largely removing the Cambro-Ordovician strata. During Devonian and Mississippian times, the region was a rather stable shelf upon which the first siliciclastic (Elbert Formation) and carbonate sediments (Ouray and Leadville Formations) were deposited. The area apparently was exposed at the end of the Mississippian Period resulting in widespread karstification of the Leadville Formation (Kelley, 1957).

During Pennsylvanian and Permian times the region gradually subsided to accumulate continental sediments of the Molas, Hermosa, and Cutler Formations; with continued subsidence and rapid rise of the source areas the the northeast and northwest, shelf carbonates and siliciclastics became the dominant sediment types. During late Permian time, the region again underwent erosion. Triassic and lower Jurassic rocks are generally absent from the western San Juan Mountains, but during the Cretaceous time, the San Juan region subsided and was buried by a few kilometers of marine and terrestrial sediments (Kelley, 1957). The Paleozoic history of the region ended with the emplacement of igneous stocks and formation of the San Juan dome which shed sediments to the San Juan basin (Kelley, 1957).

TERTIARY GEOLOGIC HISTORY

San Juan Volcanic Field

The San Juan Volcanic Field of southwestern Colorado is the largest erosional remnant of a once vast volcanic plateau of dominantly intermediate composition volcanic rocks which covered most of the southern Rocky Mountains in mid-Tertiary time (Steven and Lipman, 1976). This composite volcanic field began accumulating during the Oligocene (35-30 mybp) from scattered stratovolcanoes of andesitic to rhyodacitic composition on a broad, low relief surface of Precambrian metamorphic and Paleozoic sedimentary rocks (Lipman et al., 1973; Steven and Lipman, 1976). Aprons of lava flows, mudflow breccias, and volcanoclastics accumulated on the flanks of these volcanic vents and merged into a thick plateau (Steven and Lipman, 1976; Lipman, 1980).

This style of volcanism gave way to large volume pyroclastic eruptions of quartz latitic and rhyolitic composition in late Oligocene time from 30-26 mybp to produce 18 known widespread major ash-flow sheets and at least 15 known and possibly 18 associated calderas (Fig. 4; Table 2; Steven and Lipman, 1976; Lipman, 1980).

Beginning in early Miocene time and extending from about 25 to 5 mybp, the style of volcanism changed again to a bimodal suite of alkali rhyolite and mafic volcanic rocks, coincident with the beginning of extensional tectonics and widespread Basin and Range faulting in the western United States (Steven and Lipman, 1976; Steven et al., 1974).

The distribution of volcanic rocks in the San Juan volcanic field is nearly coincident with a large regional gravity low which has been interpreted to represent a shallow batholith beneath the volcanic field (top at 2 to 7 km) which is genetically related to the near surface caldera complex

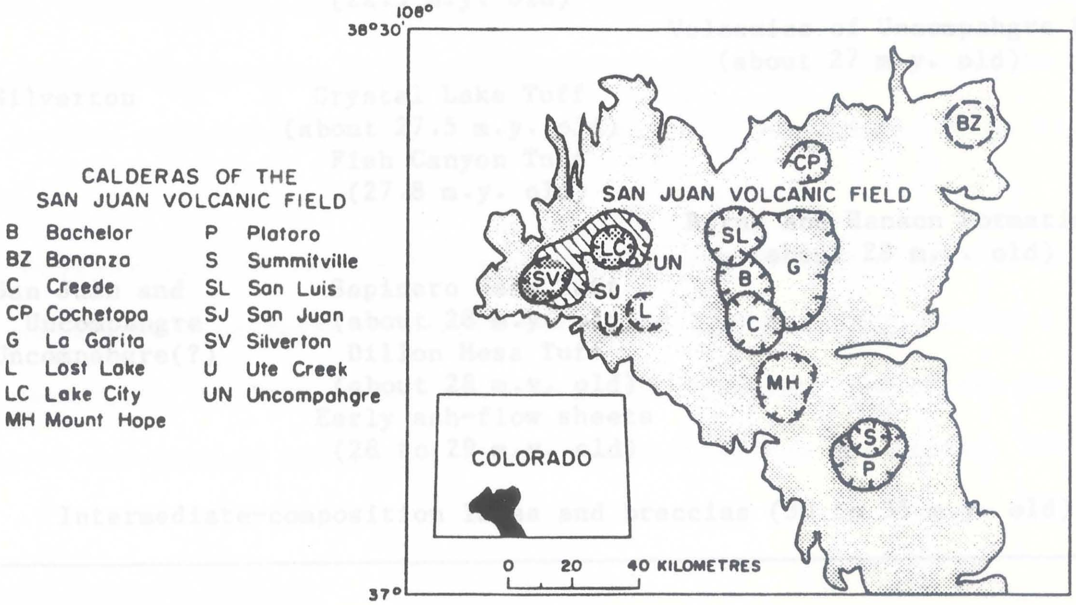


Figure 4. Calderas of the San Juan volcanic field. (modified from Lipman, 1976a)

TABLE 2

<table>
<tr><td colspan="3">Basalt and rhyolite of the Hinsdale Formation (5 to 25 m.y. old)</td></tr>
<tr><th>Calderas</th><th>Ash-flow sheets</th><th>Intracaldera lavas</th></tr>
<tr><td></td><td></td><td>Quartz latites of Grassy and Red Mountains (22.4 m.y. old)</td></tr>
<tr><td>Lake City</td><td>Sunshine Peak Tuff (22.5 m.y. old)</td><td></td></tr>
<tr><td></td><td></td><td>Volcanics of Uncompahgre Peak (about 27 m.y. old)</td></tr>
<tr><td>Silverton</td><td>Crystal Lake Tuff (about 27.5 m.y. old)</td><td></td></tr>
<tr><td></td><td>Fish Canyon Tuff (27.8 m.y. old)</td><td></td></tr>
<tr><td></td><td></td><td>Burns and Henson Formations (about 28 m.y. old)</td></tr>
<tr><td>San Juan and Uncompahgre</td><td>Sapinero Mesa Tuff (about 28 m.y. old)</td><td></td></tr>
<tr><td>Uncompahgre(?)</td><td>Dillon Mesa Tuff (about 28 m.y. old)</td><td></td></tr>
<tr><td></td><td>Early ash-flow sheets (28 to 29 m.y. old)</td><td></td></tr>
<tr><td colspan="3">Intermediate-composition lavas and breccias (30 to 35 m.y. old)</td></tr>
</table>

Generalized stratigraphic relations between ash-flow sheets, caldera collapses, and intracaldera lavas in the western San Juan Mountains (Lipman, 1976a).

(Plouff and Pakiser, 1972). In addition, local gravity anomalies superimposed over the regional anomaly have been correlated with individual calderas and intrusive centers (Plouff and Pakiser, 1972). Tertiary volcanism of the San Juan volcanic field has been interpreted as recording the rise and differentiation of successive segments of this shallow magma chamber. The early intermediate composition volcanics represent deep ventings of the chamber, whereas the associated caldera collapses are triggered by high level accumulations of intermediate silicic composition magma developing in the roots of the volcano clusters (Steven and Lipman, 1976; Lipman, 1980).

Development of the calderas of the San Juan volcanic field generally conform to the succession of stages described by Smith and Bailey (1968) for resurgent caldera complexes (Fig. 5). However, few of the San Juan calderas demonstrate all stages of development (Steven and Lipman, 1976).

Western Caldera Complex

The western caldera complex consists of six calderas: Ute Creek, Lost Lake (buried), Uncompahgre, San Juan, Silverton, and Lake City (Steven and Lipman, 1976). The first five calderas formed within a span of 2 my, with the Lake City Caldera forming about 5 my later in response to the eruption of a petrologically distinct high-silica ash-flow tuff (Steven and Lipman, 1976). Eruptions of the Ute Ridge Tuff and Blue Mesa Tuff around 28 mybp led to the collapse of the Ute Creek and Lost Creek Calderas, respectively,

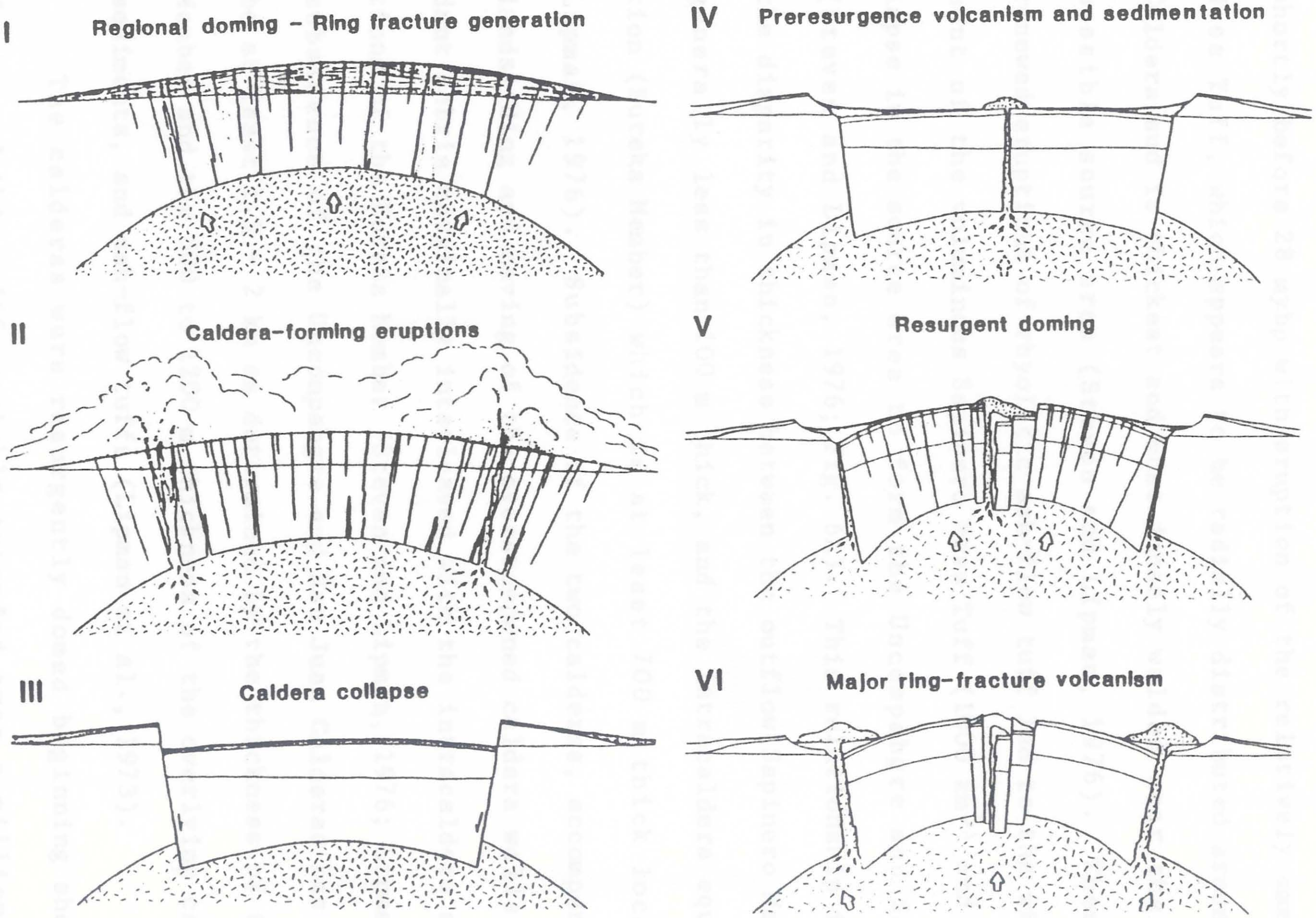


Figure 5. Typical stages of the resurgent-cauldron cycle.

Most avalanches and slides from the caldera walls occur during stages III and IV. Mineralization typically occurs long after the wanning stages of caldera development (modified from Smith and Bailey, 1968).

in the southeast portion of the western caldera complex (Steven and Lipman,1976).

Development of the Uncompahgre and San Juan Calderas probably began shortly before 28 mybp with eruption of the relatively small volume Dillon Mesa Tuff, which appears to be radially distributed around the Uncompahgre Caldera and is thickest and most densely welded near the margins of this possible source area (Steven and Lipman, 1976). Then, about 28 mybp, renewed eruptions of rhyolitic ash-flow tuff led to the widespread emplacement of the voluminous Sapinero Mesa Tuff (1000 km^3) and simultaneous collapse in the source area to form the Uncompahgre and San Juan Calderas (Steven and Lipman, 1976; Fig. 6A). This relationship is demonstrated by the disparity in thickness between the outflow Sapinero Mesa Tuff, which is generally less than 100 m thick, and the intracaldera equivalent accumulation (Eureka Member) which is at least 700 m thick locally (Steven and Lipman, 1976). Subsidence of the two calderas, accompanied by widespread landsliding and caving of the oversteepened caldera walls, produced abundant debris marginally interleaved with the intracaldera ash flow accumulations of the Eureka Member (Steven and Lipman, 1976; Lipman, 1976a). Total subsidence of the Uncompahgre and San Juan Calderas has been estimated to be at least 1.5 - 2 km as determined by the thickness of the exposed Eureka Member and the 800 to 1200 m thickness of the overlying caldera-fill lavas, sediments, and ash-flow tuffs (Lipman et al., 1973).

The calderas were resurgently domed beginning shortly after subsidence, and this uplift probably extended over a million years while the depressions were being filled with locally derived lavas and sediments and

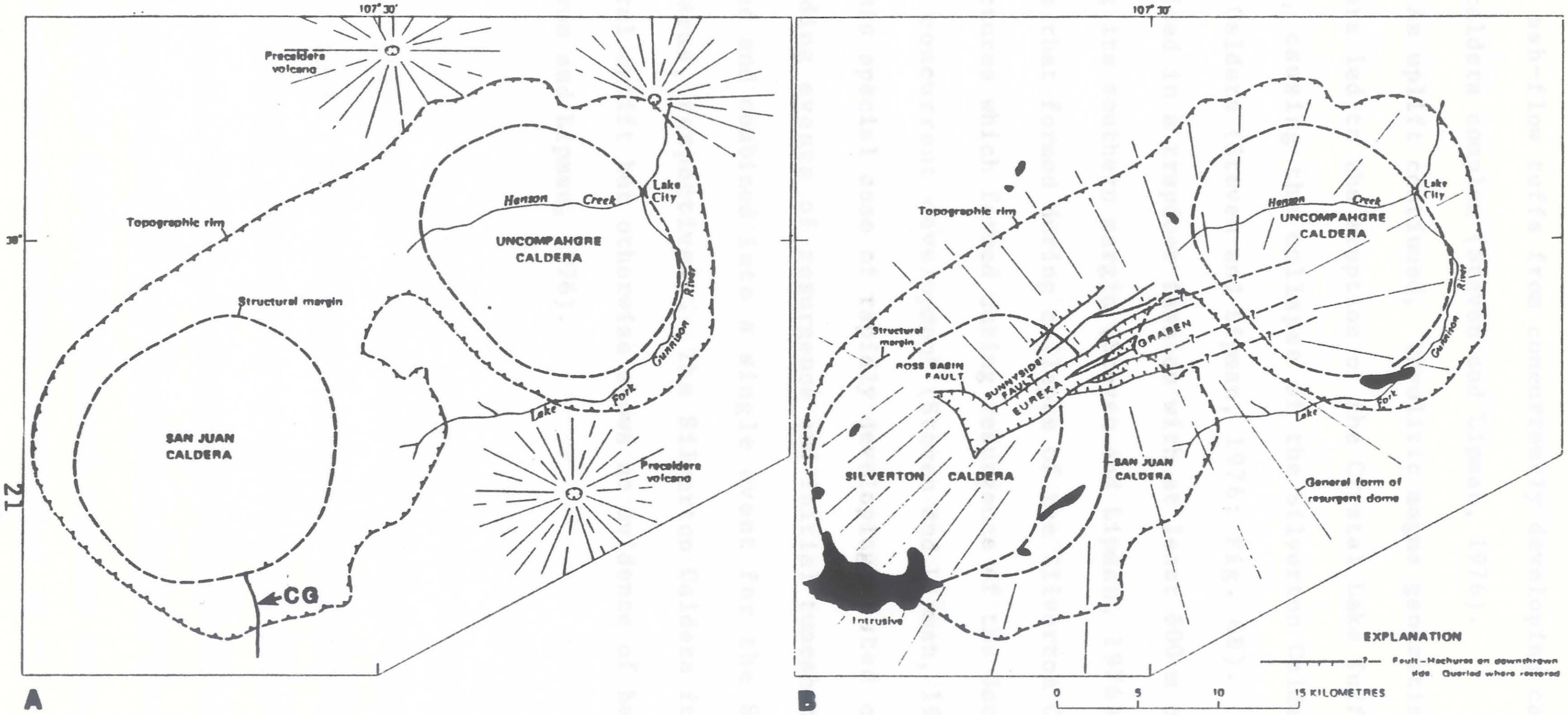


Figure 6. Sketch maps of the Western San Juan Caldera complex.

(A) After subsidence of the San Juan Caldera, related to eruption of the Sapinero Mesa Tuff (28 mybp), and
(B) After subsidence of the Silverton Caldera, related to eruption of the Crystal Lake Tuff (27.5 mybp).
Note location of Cunningham Gulch (CG) and precaldera volcano east of the San Juan Caldera in (A), which may have been a source for precaldera intermediate composition volcanics of the San Juan Formation (32 mybp) in upper Cunningham Gulch (modified from Steven and Lipman, 1976).

with ash-flow tuffs from concurrently developing calderas within the eastern caldera complex (Steven and Lipman, 1976).

As uplift continued, rhyolitic magma generating beneath the San Juan Caldera led to the eruption of the Crystal Lake Tuff between 27.8 and 26.7 mybp, causing the collapse of the Silverton Caldera within the older San Juan Caldera (Steven and Lipman, 1976; Fig. 6B). The Silverton Caldera subsided in a trapdoor fashion with at least 600 m of downward displacement along its southern margin (Steven and Lipman, 1976). Apparently, structures that formed during collapse of the Silverton Caldera merged with some structures which formed during resurgence of the San Juan Caldera, indicating concurrent development (Steven and Lipman, 1976). This implies that in this special case of rapidly developing nested calderas, the caldera-building events of resurgence and initial tumescent doming may have overlapped and combined into a single event for the San Juan and Silverton Calderas, respectively. The Silverton Caldera formed during a period of general uplift but otherwise shows no evidence of being resurgently domed (Steven and Lipman, 1976).

STRATIGRAPHY

PRE-TERTIARY

Precambrian

The Irving Formation of the Precambrian metamorphic rock complex of the Needle Mountains is exposed in upper Cunningham Gulch from the approximate location of the Green Mountain mine southward throughout the study area. In hand specimen, the Irving Formation is dominantly light green to brown, fine-grained, well-foliated biotite gneiss. This plagioclase-quartz-biotite gneiss probably represents a metamorphosed plutonic rock of dioritic to granodioritic composition although a marine volcanic component is indicated by interlayered amphibolite and the presence of pillow structures near the Highland Mary lakes (Barker, 1969). In addition, Lipman (1976b) suggested that this unit may be in part metasedimentary. The thickness of the Irving Formation is undeterminable since the lower contact is not exposed in the study area, but it is at least a kilometer thick (Barker, 1969).

The green coloration of these rocks is apparently due to retrograde metamorphism (Barker, 1969) which has produced sericite, chlorite, epidote, and calcite. This assemblage is closely analogous to the propylitic alteration which has affected much of the volcanic section throughout the area. Clear evidence of intense hydrothermal alteration exists in the vicinity of vein structures near the Highland Mary mine where the gneiss has been altered to a tan or rust-colored jarositic stain, indicative of reaction with acidic hydrothermal solutions.

Paleozoic

Sedimentary rocks of Paleozoic age are preserved in an east-west trending graben dropped into the Precambrian Irving Formation at the head of Cunningham Gulch just south of the Highland Mary mine (Fig. 7). The depositional units exposed within this graben are: Devonian Elbert Formation, Devonian-Mississippian Ouray Formation, Early Mississippian Leadville Formation, and remnants of the Pennsylvanian Molas Formation. These units were deposited on the flanks of the ancient Grenadier Highlands (Baars and See, 1968). Local exposures of these units at Kendall Mountain just south of Silverton, Colorado, together with those in the Cunningham Gulch graben (Fig. 7), suggest that Paleozoic age rocks were widespread in this area prior to pre-Tertiary erosion.

The Paleozoic units most important to this study are the Ouray and Leadville Formations which occur in the Pride of the West and Osceola mine area as isolated blocks engulfed in Tertiary volcanic rocks and locally host replacement-type ore bodies. Fossil assemblages and stromatolitic laminae in both formations indicate that they were deposited in shallow marine and tidal flat environments (Baars and See, 1968). These carbonate units are virtually indistinguishable from one another due to their similar depositional environments and because both units have been dolomitized locally (Baars and See, 1968).

Although algal laminae are present in these formations within the

Figure 7. Graben in upper Cunningham Gulch.

Prominent white cliff (center) is Leadville Formation. Camera orientation: southeast. See Fig. 3 for explanation of symbols.

graben, probably the best examples of stromatolitic laminae within the dolomitized Leadville Formation occur at Molas Lake Park, about 6 km south of Silverton, Colorado (Fig. 8; Price, 1980). Also at Molas Lake Park are several karst towers of Leadville Formation surrounded by red calcareous shale of the Molas Formation, indicating a period of intense post-Mississippian weathering.

TERTIARY

San Juan Formation

The oldest Tertiary unit present in Cunningham Gulch is the Oligocene San Juan Formation (32.1 mybp; Lipman et al., 1973) which unconformably overlies both the Precambrian Irving Formation and the Paleozoic units of the graben. The San Juan Formation consists dominantly of intermediate composition lavas and breccias and represents a clastic facies of material which accumulated to great thicknesses on the flanks of the pre-caldera clustered andesitic stratovolcanoes (Lipman et al., 1973). This unit probably accumulated as a series of intercalated lava flows, debris flows, and volcaniclastic sediments, yielding a composite plateau of great variability and complexity. According to Lipman et al. (1973), the San Juan Formation of the western San Juan Mountains is correlative with the Picayune and Lake Fork Formations which represent vent facies of the vast accumulation.

In upper Cunningham Gulch, the San Juan Formation is highly variable

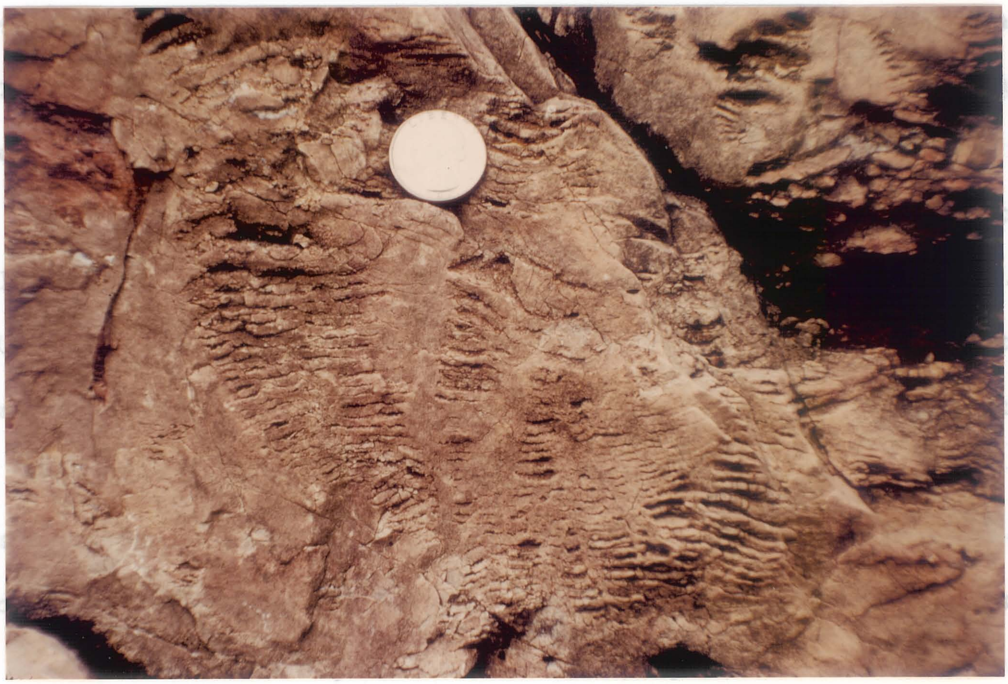


Figure 8. Zebra dolomite.

Zebra dolomite texture as preserved in an outcrop of Leadville Formation at Molas Lake Park south of Silverton, Colorado. Note the undulose banded fabric and abundant open spaces left by the diagenetic dolomitization process. Much of this secondary porosity is now filled with quartz and minor pyrite. Diameter of coin is 2.4 centimeters.

in nature and composition, although everywhere its clastic and brecciated nature is apparent. This unit typically has a purplish-green color due to pervasive propylitic alteration. The lithology consists of very poorly sorted, subrounded to subangular clasts of intermediate composition lavas, breccias, and volcaniclastic sediments; angular fragments of the underlying Precambrian gneiss (Irving Formation), and subrounded to rounded cobble-to-boulder size clasts of granite, all supported within a matrix which also lacks sorting and consists of subrounded to subangular fragments of apparent intermediate composition volcanic and volcaniclastic rocks (Fig. 9). The angular fragments of gneiss are present only within the basal portion of the unit, and their angularity reflects the competent nature of the well-foliated gneiss. Clasts of green chloritized fine- to coarse-grained volcaniclastic sediments commonly reach 10-15 cm in diameter and probably represent reworked clastic material which accumulated at the distal portion of the eroding flanks of the stratovolcanoes. The granitic clasts, which are apparently diagnostic indicators of the basal San Juan Formation in this area, typically range from 5 cm to 1 m in diameter, although a single boulder 3 m in diameter is present in the study area. The roundness of these cobbles and boulders probably reflects not only abrasive action during transport within the mudflows, but also the exfoliation properties of the granite. These clasts are probably Precambrian Eolus Granite (1,460 mybp; Steven et al., 1974); the only known outcrops are about 12 km south of the graben area. Assuming these clasts are Eolus Granite and that the present exposures reflect its original extent, this implies northward transportation by the mudflow deposits. This direction of transport is

Figure 9. Lithologic and textural character of the San Juan Formation in Upper Cunningham Gulch.

indicative of a source vent somewhere to the south, possibly the Carson City Volcano southeast of the Cunningham Gulch area (Fig. 6A). This proposed northward transportation direction suggests that the Precambrian surface to the south of the study area sloped northward as a result of Pre-Tertiary erosion. In some places, the granitic fragments are transected by intermediate composition material of the San Juan Formation matrix which may suggest incorporation into a hot lahar.

Erosional remnants of the San Juan Formation in the study area are exposed only outside the San Juan Caldera wall, where they are up to several hundred meters thick. The San Juan Formation thins to the north and ends abruptly at the San Juan Caldera wall, where all pre-caldera rocks are down-dropped into the caldera and covered by younger intracaldera fill. Thus, the topographic wall of the caldera is defined by stratigraphic relationships where the pre-caldera rocks are in unconformable contact with the younger caldera fill sequence of the Sapinero Mesa Tuff and post-collapse lavas and breccias (Fig. 10).

Sapinero Mesa Tuff

Eruption of the Sapinero Mesa Tuff concurrently with collapse of the San Juan Caldera resulted in a thick intracaldera accumulation. Lipman (1976b) recognized two major divisions of the Sapinero Mesa Tuff in the Lake City area. These are: (1) the Outflow Member, a welded ash flow tuff that is radially distributed about the Uncompahgre and San Juan Calderas,

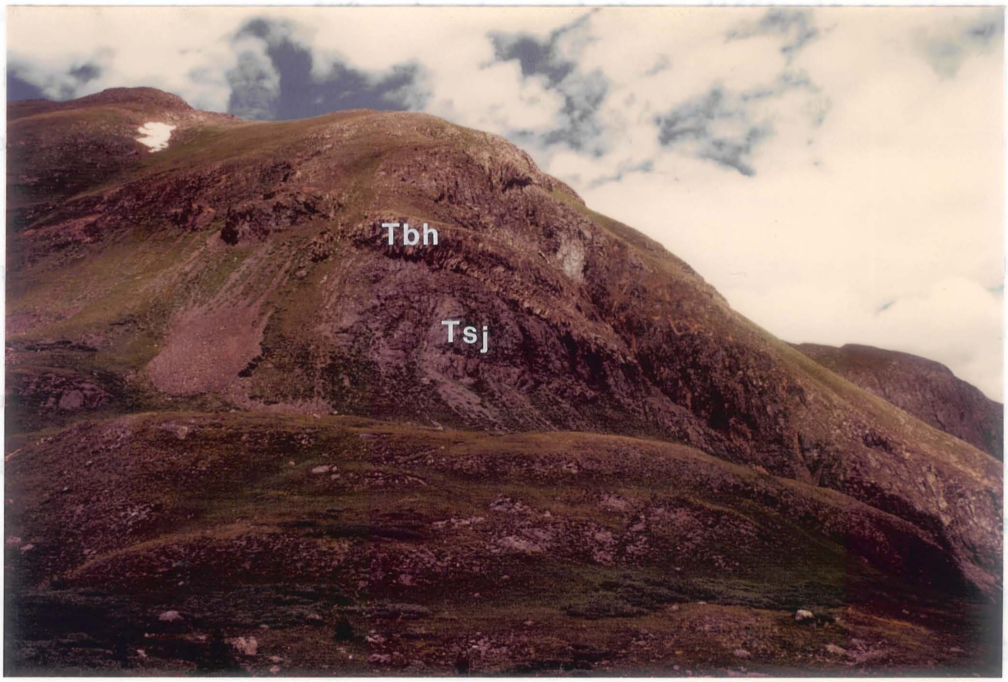


Figure 10. Topographic margin of the San Juan Caldera of the West side of Cunningham Gulch.

The topographic rim of the caldera is recognized by the unconformity between the San Juan Formation (Tsj) of the caldera wall and the overlying caldera-filling andesitic lavas of the Burns and Henson Formations (Tbh). Camera orientation: northwest.

and (2) the Eureka Member, which occurs exclusively within these two calderas. The Eureka Member is a complex, interfingering assemblage of ash flow tuffs and material which caved from the Uncompahgre and San Juan Caldera walls that were oversteepened during caldera collapse. In addition, Lipman (1976b) recognized three members of caldera-collapse material: (1) the Landslide Breccia Member, composed of caldera wall fragments typically up to 50 m in size, (2) the Picayune Megabreccia Member, composed of caldera wall fragments up to 500 m in size and thus difficult to distinguish from the pre-caldera floor, and (3) the Welded Tuff Megabreccia Member, composed of fragments of outflow Sapinero Mesa Tuff which were deposited on pre-caldera rocks in the vicinity of the caldera margin and later caved from the wall in response to caldera collapse. For the purposes of this study, all material which is interpreted to have caved from the San Juan Caldera wall is termed "Megabreccia Member."

Essentially all of the Sapinero Mesa Tuff exposed in the study area occurs exclusively within the topographic margin of the San Juan Caldera and belongs to the Eureka and Megabreccia Members. However, a minor amount of the Outflow Member in the map area occurs as an isolated erosional remnant resting on the San Juan Formation just outside the caldera wall on the east side of Cunningham Gulch (Fig.3). A single 1 m diameter boulder of this outflow material was recognized within the collapse breccia material stratigraphically above the carbonate blocks on the west side of Cunningham Gulch.

Eureka Member

This unit was originally named the Eureka Rhyolite of the Silverton Volcanic Group by Cross et al. (1905) and later redefined as the Eureka Tuff by Burbank and Leudke (1963). Normative analyses by Varnes (1963) indicate that this unit is less silicic and more aluminous than a typical rhyolite and led him to propose the name Eureka Formation for this unit. Lipman, et al. (1973) proposed the name Eureka Member of the Sapinero Mesa Tuff for this complex intracaldera accumulation in order to reflect its exclusive occurrence within the San Juan and Uncompahgre Calderas. Burbank (1933) recognized three units of the Eureka Rhyolite in the Arrastre Basin just west of Cunningham Gulch: (1) a lower rhyolite, (2) a medial tuff breccia, and (3) an upper flow breccia. Cook (1952), on the basis of detailed mapping (1:600) in the Pride of the West mine area, determined six mappable units of the Eureka Rhyolite by recognizing sub-units of the medial and upper flow units. However, this terminology was not adhered to during the present investigation due not only to problems of scale, but also because the terminology of Lipman (1976b) is preferred for genetic interpretations.

The Eureka Member in the study area is a complex intercalated assemblage of tuffs, flow breccias, and caldera-collapse breccias. The recognition of the caldera-collapse breccia aids in explaining the complex stratigraphic relationships observed at the Pride and Osceola mines (Fig. 11), whose workings appear to be largely within the caldera-collapse breccia. The Eureka Member is generally a gray-white to light green welded ash-flow

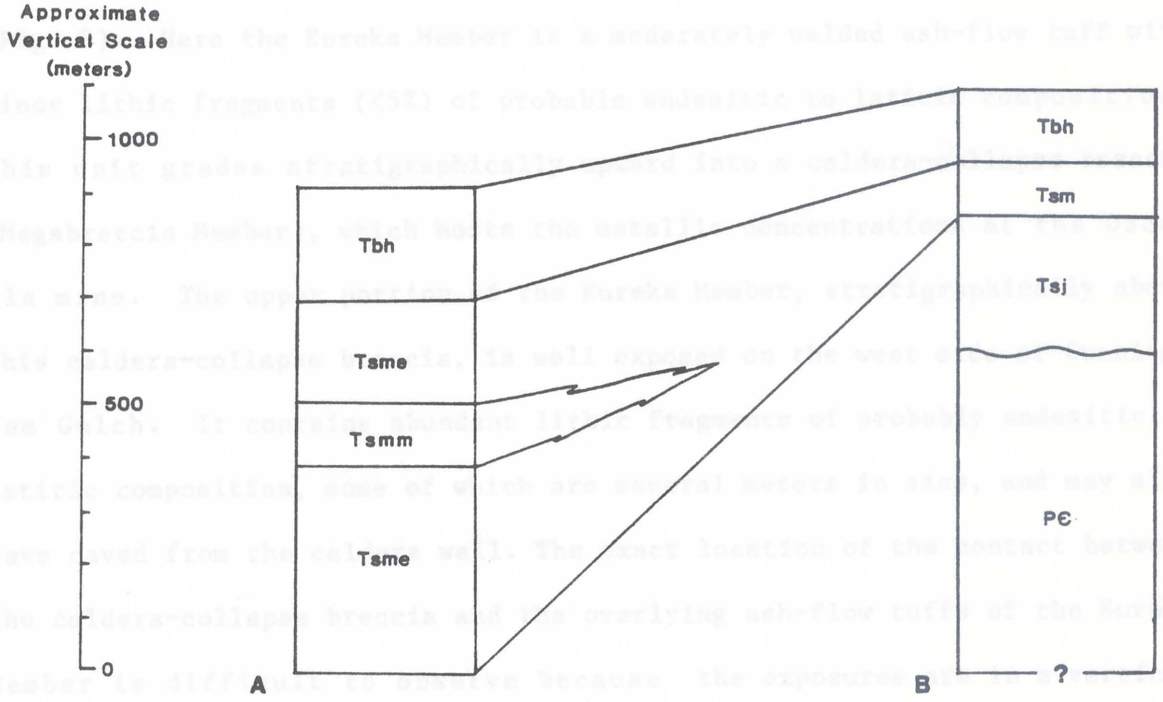


Figure 11. Generalized stratigraphic sections in upper Cunningham Gulch.

(A) Inside the topographic rim of the San Juan Caldera and
(B) Outside the caldera topographic rim
Refer to geologic map (Fig. 3) for explanation of symbols.

tuff which shows well-developed flow banding and compaction of pumice fragments. According to Lipman (1976b), this member generally contains 5-10% phenocrysts of plagioclase, sanidine, and biotite. The greenish tinge of the unit is due to alteration of the groundmass to a propylitic assemblage of albite, calcite, and epidote. The lower portion of the Eureka Member is excellently exposed at the Lawerence level adit of the Osceola mine (Fig. 3). Here the Eureka Member is a moderately welded ash-flow tuff with minor lithic fragments (<5%) of probable andesitic to latitic composition. This unit grades stratigraphically upward into a caldera-collapse breccia (Megabreccia Member), which hosts the metallic concentrations at the Osceola mine. The upper portion of the Eureka Member, stratigraphically above this caldera-collapse breccia, is well exposed on the west side of Cunningham Gulch. It contains abundant lithic fragments of probably andesitic to latitic composition, some of which are several meters in size, and may also have caved from the caldera wall. The exact location of the contact between the caldera-collapse breccia and the overlying ash-flow tuffs of the Eureka Member is difficult to observe because the exposures are in a vertical cliff face. However, the outcrop pattern (Fig. 3) indicates the caldera-collapse breccia is a lenticular-shaped body encased within the Eureka Member.

The lower portion of the Eureka Member generally exhibits near horizontal flow banding and compaction direction. However, steeply eastward dipping to vertical flow banding was observed in several discontinuous, partially covered outcrops in Cunningham Gulch. Examples of these exposures are located (1) just below the northernmost exposed carbonate block on the west side of the gulch, and (2) just north of the Pride surface buildings on the east side of Cunningham Gulch road. Lipman et al. (1973) noted about a 20° northeasterly dip to the foliation direction of the Eureka Member within the Uncompahgre Caldera in the Lake City area, and attributed it to later regional northeast tilting. Also, original flow banding directions in the Cunningham Gulch area may have been reoriented during resurgence of the San Juan Caldera. However, this does not account for the abrupt changes observed in discontinuous outcrops. The location of these outcrops, stratigraphically below and near the proposed base of the caldera-collapse breccia, suggests that they are blocks of outflow Sapinero Mesa Tuff which also caved from the San Juan Caldera wall. Since a 1 m diameter boulder of this material is clearly present within the Megabreccia Member, it is reasonable to interpret that these larger (50 m size) blocks also originated from the caldera wall and represent welded tuff megabreccia. In addition, near vertical flow banding is also observed locally at the contact between Eureka Member ash-flow tuffs and the Precambrian portion of the San Juan Caldera wall on the west side of Cunningham Gulch. This flow banding may represent local ponding of material against the caldera wall.

Megabreccia Member

Lipman (1976a) recognized that the intracaldera assemblage of the Eureka Member contain intercalated caldera-collapse breccias in the Lake City area and suggested promoting these breccias in rank to a separate member of the Sapinero Mesa Tuff. This member is perhaps the most intriguing of all units exposed in the field area, for it has much to reveal about the development of the San Juan Caldera in this area and is the major host to vein and replacement-type deposits.

The Megabreccia Member in Cunningham Gulch is for the most part lithologically identical to the San Juan Formation. However, the Megabreccia Member occurs exclusively within the topographic boundary of the San Juan Caldera and clearly contains large blocks of Paleozoic carbonate rocks not found in the San Juan Formation in Cunningham Gulch. This material was first recognized as a caldera-collapse breccia due to its striking similarity to the San Juan Formation and its stratigraphic position, since this material is underlain and overlain by ash-flow tuffs of the Eureka Member on the west side of Cunningham Gulch. Caldera-collapse breccias are commonly composed of material that makes up the caldera wall (Lipman, 1976a), which, in this area, consists of Precambrian gneiss and overlying thick accumulations of the San Juan Formation. The general paucity of large blocks of gneiss within the landslide breccia is probably due to the competence of this material and its greater resistance to slumping. Lipman (1976a) noted a decrease in the number of caldera-collapse breccias within the southern boundary of the Lake City Caldera, where the caldera wall is competent Precambrian granite. In contrast, the less competent debris flow accumulations of the San Juan Formation in Cunningham Gulch would have been much more susceptible to slumping and caving from the oversteepened caldera wall. However, underground exposures of Precambrian rock in the Pride of the West mine may not be in place (Varnes, 1982, personal communication) and may represent fragments which also caved from the caldera wall. The relative locations of in-place Outflow Member at the caldera wall and welded tuff megabreccia fragments, the greater abundance of apparently jumbled blocks of caldera-collapse breccia material on the east side of Cunningham Gulch, and the general thinning of the Megabreccia Member from east to west (Fig. 3) suggest that the caldera-collapse breccia originated at the easternmost area of the exposed San Juan Caldera wall in Cunningham Gulch and slumped in a westward direction.

Cook (1952) first recognized the similarity in lithology as he mapped both the caldera-collapse breccia on the west side of Cunningham Gulch and San Juan Formation of the caldera wall on the east side of the gulch as the Volcanic Conglomerate subdivision of the Eureka Rhyolite. In addition, Cook (1952) mapped the unit overlying the volcanic conglomerate as a flow breccia with an absence of granitic cobbles, and noted that this material was the major ore host at the Pride of the West mine. However, this unit is also very similar to the San Juan Formation but contains fewer lithic fragments and granitic cobbles. This unit is also interpreted to be a portion of the caldera-collapse breccia which originated by caving from the San Juan Caldera wall. It contains the large carbonate blocks which are mineralized at the Osceola mine, where it has been called the "cap rock" as it appears always to "cap" the replacement bodies. In exposures near the glory holes of the Osceola mine, granitic boulders are again present within this "cap rock" unit (Fig. 12), indicating it is part of the Megabreccia Member.

Figure 12. Rounded cobble of granite within "caprock" unit at glory hole of the Osceola mine.

Granitic cobbles are common in the basal portion of the San Juan Formation in the Cunningham Gulch area. The presence of these clasts indicates that this unit is a portion of the San Juan Formation now comprising the Megabreccia Member of the Sapinero Mesa Tuff.

Large blocks of Paleozoic carbonate are engulfed within the intracaldera fill volcanics and have been assigned to the Megabreccia Member. Although these blocks were first recognized by Ransome (1901) and were mapped by Cook (1952) and Varnes (1963), the origin of their present structural position has remained a mystery. Cook (1952) proposed that the blocks were rafted into the Eureka Rhyolite, probably originating from the south and somehow sliding down the northward-sloping Precambrian erosional surface. Varnes (1963) noted that he was uncertain whether the carbonate blocks were in place. This determination is clearly hampered by most of the exposures being covered by grassy slopes (Fig. 13). However, several zones of chert nodules, which commonly form along bedding planes, were recognized to trend in a wide variety of directions within the blocks, indicating they are clearly out of place.

In the vicinity of these large carbonate blocks, the hosting unit also contains granitic boulders suggesting the unit belongs to the basal portion of the San Juan Formation. However, since the blocks and hosting units occur within the caldera, stratigraphically above ash-flow tuffs of the Eureka Member, this hosting unit is interpreted to be a detached portion of the San Juan Formation. Apparently, the carbonate blocks were incorporated as megaclasts into the debris flows of the San Juan Formation and came to rest in the vicinity of the later-developed caldera wall. One of the carbonate blocks appears to be plastically deformed (Fig. 14A), perhaps from being incorporated into a hot lahar, although reaction phenomena are not apparent at the carbonate-volcanic contact (Fig. 14B). The carbonate

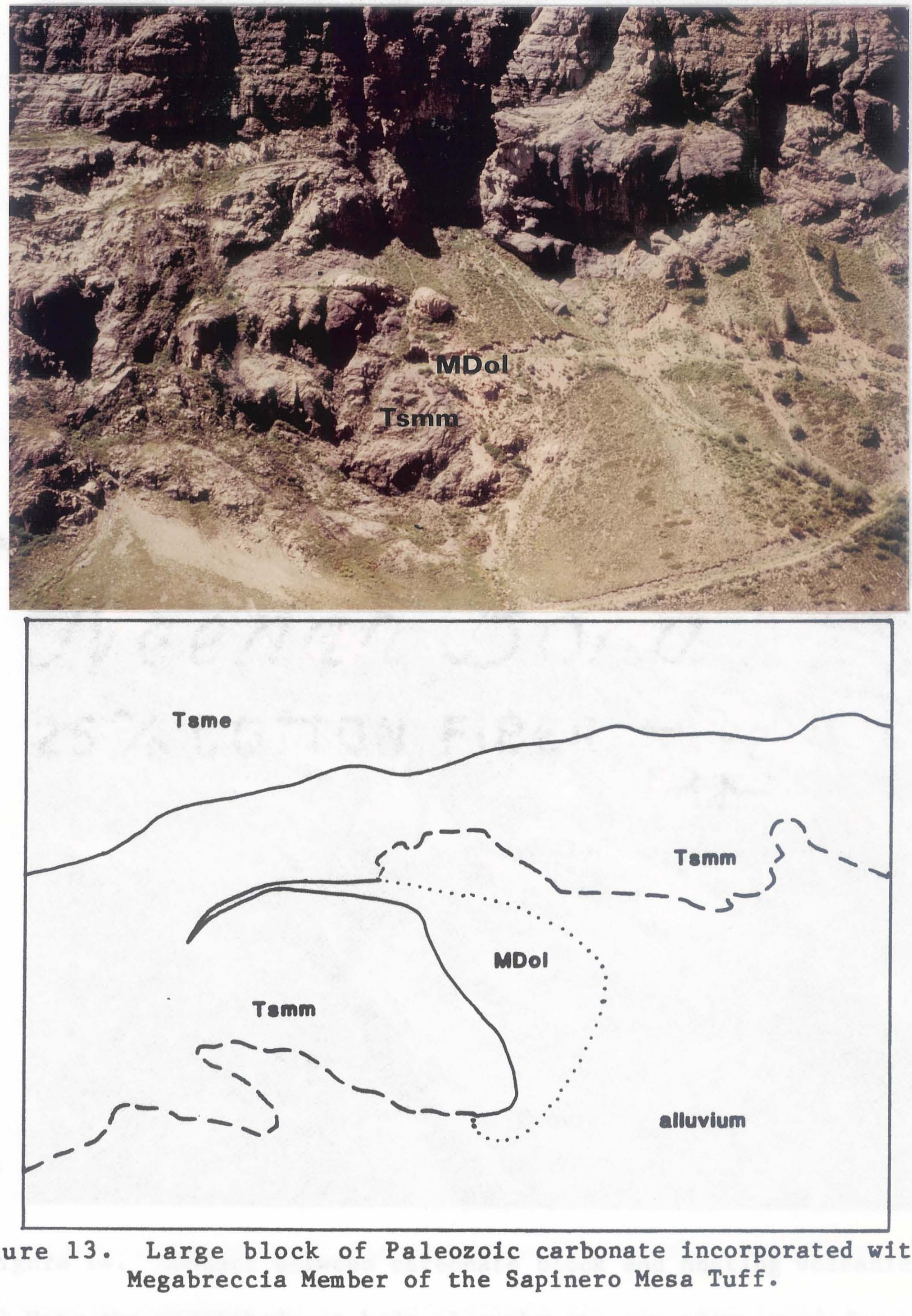


Figure 13. Large block of Paleozoic carbonate incorporated within Megabreccia Member of the Sapinero Mesa Tuff.

Line drawing shows outline of carbonate block (MDol) and contact between Megabreccia Member (Tsmm) and overlying ash-flow tuffs of the Eureka Member (Tsme). Contact dotted where concealed. Exposure located on west side of Cunningham Gulch. Camera orientation: west.

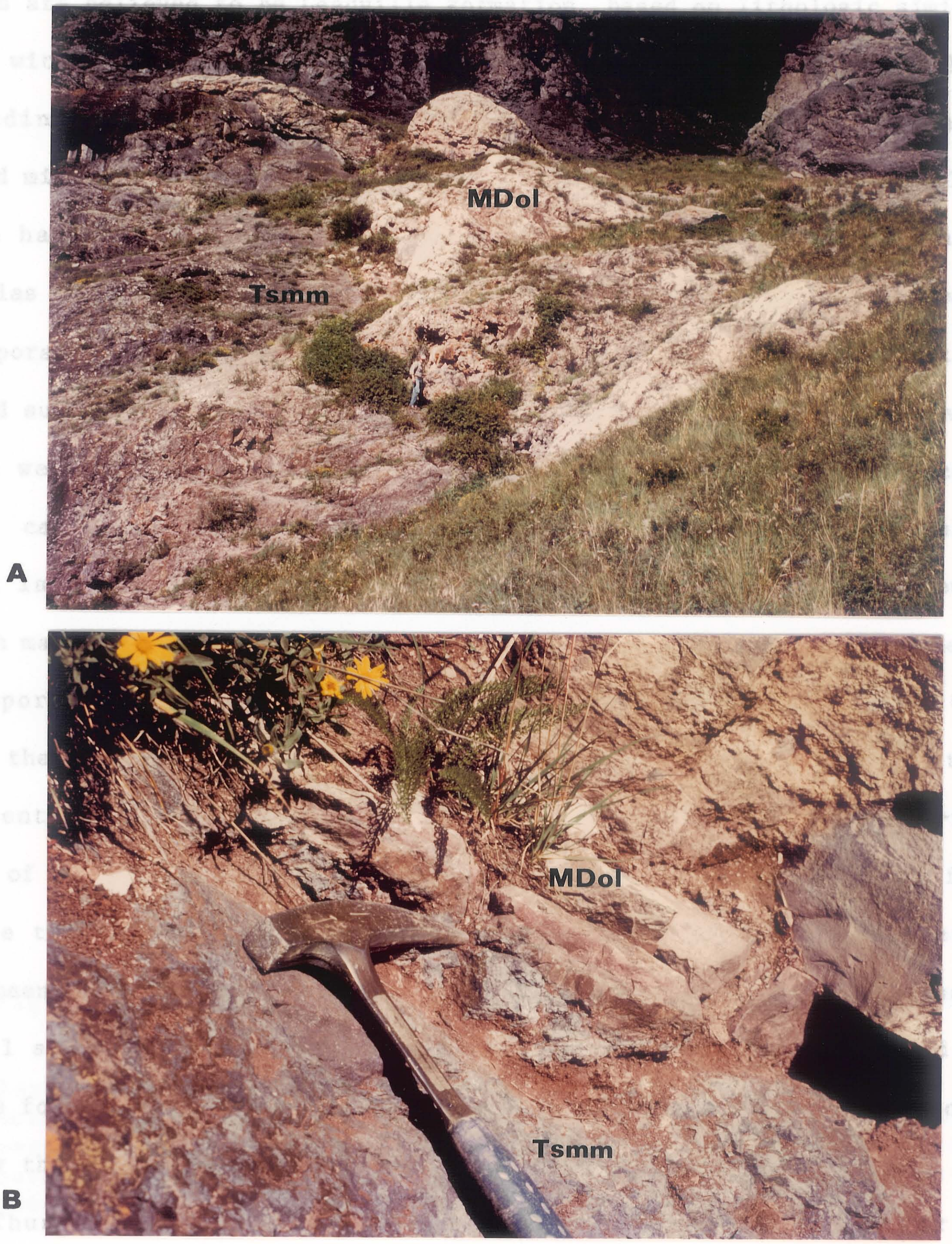


Figure 14. Contact between carbonate block and hosting volcanics.

(A) Note the stretched-out body of carbonate extending away from the main mass of the carbonate block (upper left), suggesting incorporation into a hot lahar. (B) Although evidence of extensive reaction is not present at the contact with the hosting volcanics (Tsmm), the carbonate (MDol) does appear to be slightly discolored and baked. Camera orientation: (A) west, (B) northwest.

blocks are believed to be Leadville Formation, based on lithologic similarities with the Leadville sequence exposed in the Cunningham Gulch graben, including red calcareous Molas Formation within some blocks. An underground mine face in the Osceola mine exposes an unreplaced carbonate block which has been interpreted to represent a Leadville karst tower surrounded by Molas regolith (Fig. 15). This may indicate that carbonate blocks were incorporated into the San Juan Formation as the debris flow covered a karstified surface of the Leadville Formation and plucked off karst towers which were standing in relief and easily detached. A likely source of these carbonate blocks is the graben area at the head of Cunningham Gulch, which is the closest exposure of Paleozoic rocks, although a mudflow of enough magnitude to transport these blocks is probably also capable of transporting them greater distances. During collapse of the San Juan Caldera, the carbonate blocks and their encasing matrix of San Juan Formation apparently slumped together as a megabreccia fragment onto lower ash-flow tuffs of the Eureka Member. These ash-flow tuffs were probably lithified before the breccia mass slumped, as no injection dikes of Eureka material have been observed in the breccia body. This unit provided a roughly horizontal surface for the caldera-collapse megabreccia to rest on, and accounts for the distribution of the observed carbonate blocks at approximately the same elevation (Fig. 3).

Thus, a two-stage model of emplacement is favored to account for the present structural position of the carbonate blocks (Fig. 16). These blocks were apparently pre-existing as clasts within the San Juan Formation making up the caldera wall at the time of the caldera collapse and associated

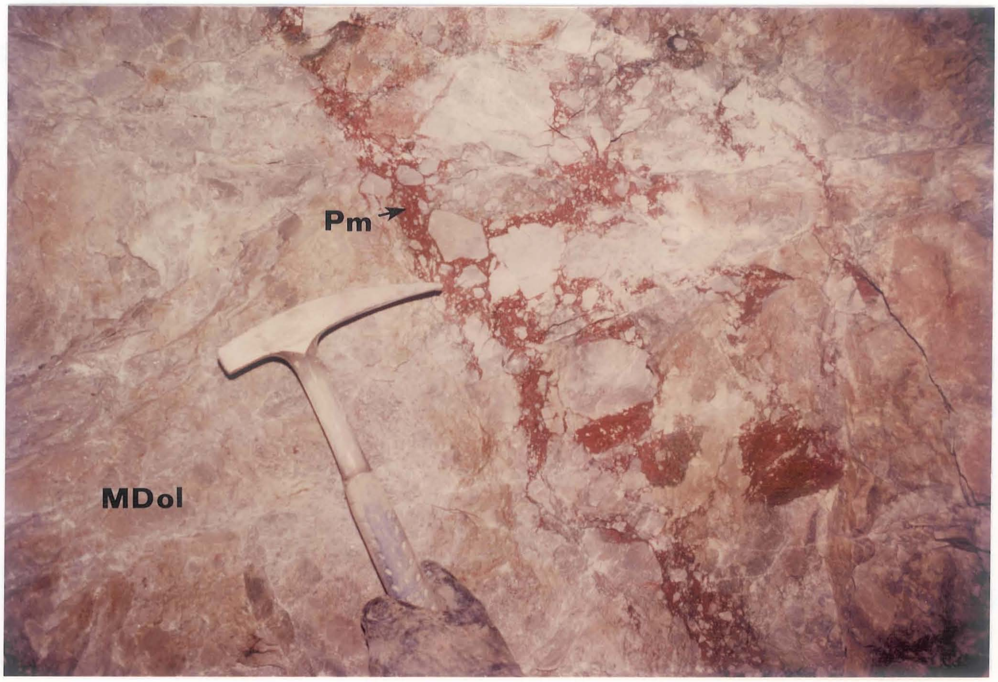


Figure 15. Unreplaced Leadville Formation karst tower on the 29.5 level of the Osceola mine.

Karst fragments are hosted within red calcareous siltstone of the Molas Formation (Pm) which is highly pyritic, suggesting this zone is permeable and highly favorable to sulfide concentrations. This exposure indicates that the carbonate (MDol) was subaerially exposed before being incorporated into the volcanic rocks.

1. Early Oligocene composite plateau of andesitic stratavolcanoes and related volcaniclastic sediments and mudflow breccias comprising the San Juan Formation (Tsj). Note igneous intrusion of Eolus granite (+), pinchout of Paleozoic sediments beneath the volcanic pile, and future location of the southeastern structural margin of the San Juan Caldera (SMSJ).

2. Expanded view in the vicinity of the yet developed structural margin of the San Juan Caldera. Note northward (right to left) sloping Precambrian erosional surface and incorporation of granite boulders and carbonate blocks into the basal portion of the San Juan Formation. The mudflows probably plucked off easily detached karst towers of Leadville Formation as they covered the Cunningham Gulch graben, and transported them downslope to rest near the position of the later developed structural margin of the San Juan Caldera.

3. Eruption of the Sapinero Mesa Tuff (Tsm) led to the concomitant collapse of the San Juan Caldera, resulting in the caldera wall being oversteepened. The unstable upper portion of this wall was comprised dominantly of San Juan Formation with the carbonate blocks.

4. The caldera wall caved onto lithified ash-flow tuffs of the Eureka Member (Tsme). Volcanism continued to fill the depression and eventually buried the caldera-collapse breccia, now referred to as the Megabreccia Member (Tsmm), and the surface expression of the San Juan Caldera structural margin.

5. Post-collapse volcanism and sedimentation of the Burns and Henson Formations (Tbh) apparently filled the depression before the San Juan Caldera was resurgently domed. This doming preceded eruption of the Crystal Lake Tuff which resulted in the trapdoor-style collapse of the Silverton Caldera nested within the San Juan Caldera.

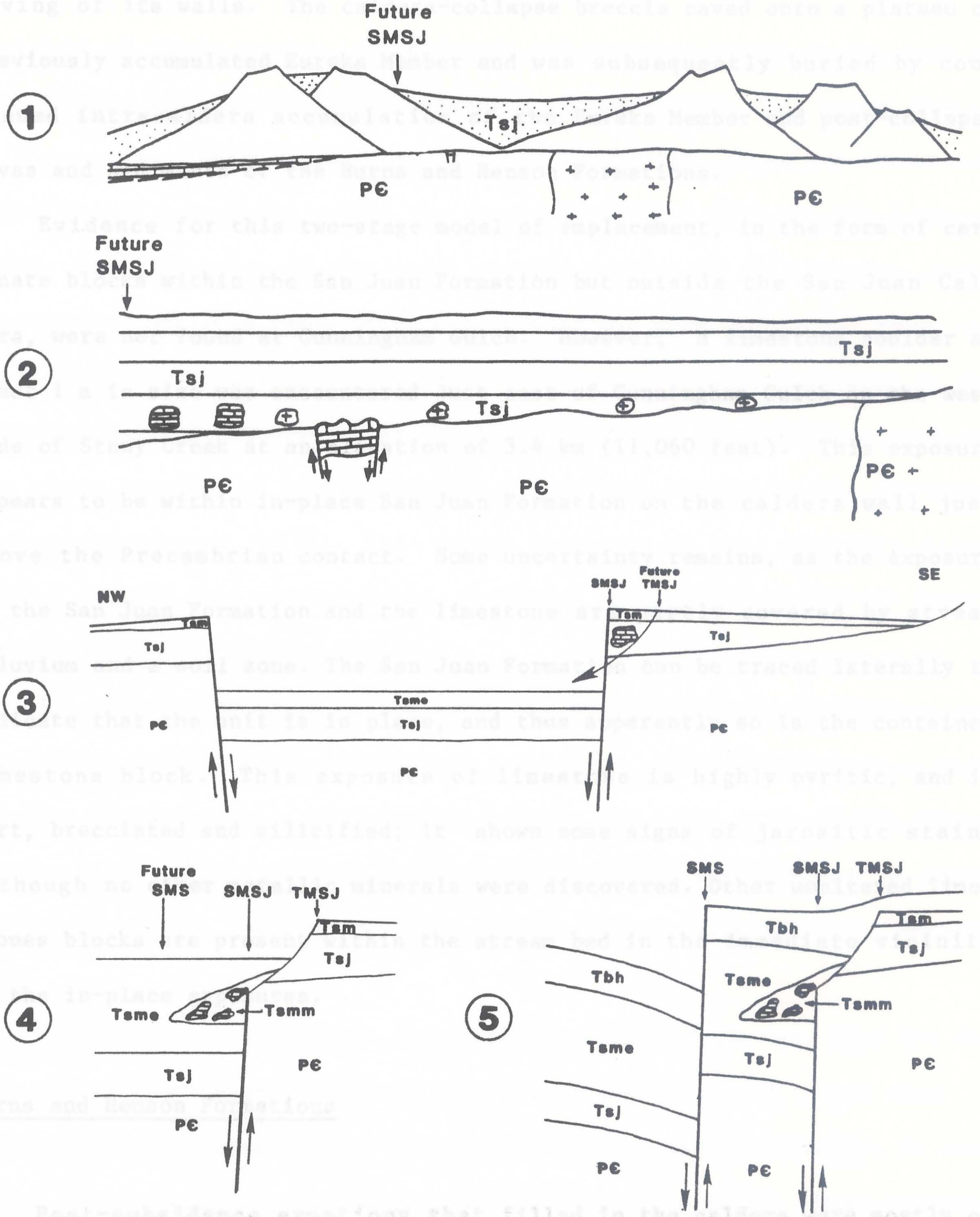


Figure 16. Schematic representation of development of the southeastern margin of the San Juan Caldera and emplacement of the carbonate blocks in the Cunningham Gulch area.

See explanation on facing page.

caving of its walls. The caldera-collapse breccia caved onto a plateau of previously accumulated Eureka Member and was subsequently buried by continued intracaldera accumulation of the Eureka Member and post-collapse lavas and sediments of the Burns and Henson Formations.

Evidence for this two-stage model of emplacement, in the form of carbonate blocks within the San Juan Formation but outside the San Juan Caldera, were not found at Cunningham Gulch. However, a limestone boulder at least 1 m in size was encountered just east of Cunningham Gulch on the west side of Stony Creek at an elevation of 3.4 km (11,060 feet). This exposure appears to be within in-place San Juan Formation on the caldera wall just above the Precambrian contact. Some uncertainty remains, as the exposure of the San Juan Formation and the limestone are partly covered by stream alluvium and a soil zone. The San Juan Formation can be traced laterally to indicate that the unit is in place, and thus apparently so is the contained limestone block. This exposure of limestone is highly pyritic, and in part, brecciated and silicified; it shows some signs of jarositic stain, although no other metallic minerals were discovered. Other unaltered limestones blocks are present within the stream bed in the immediate vicinity of the in-place exposures.

Burns and Henson Formations

Post-subsidence eruptions that filled in the caldera were mostly of viscous, coarsely porphyritic lavas of predominantly rhyodacitic and quartz-latitic composition which formed local domes and thick flows in the vicinity of their vents. Pyroclastic and reworked debris in the form of bedded tuffs and volcaniclastic sediments accumulated in low areas distal to the vents. This assemblage of thick porphyritic flows and associated bedded deposits has been called the Burns Formation (Steven and Lipman, 1976). The character of the lavas changed upwards to less viscous, dark, fine-grained andesite flows which are thinner and more widespread than the porphyritic flows; but sedimentation continued essentially unchanged in the topographically lower areas. As the local volcanic activity diminished, the upper portion of the depression filled with volcaniclastic sediments (Steven and Lipman, 1976). This upper sequence of thin andesite flows grading upwards into volcaniclastic units has been termed the Henson Formation by Burbank and Luedke (1963).

The sedimentary units of the Burns and overlying Henson Formations are essentially indistinguishable (Steven and Lipman, 1976), leading to a very complex stratigraphic relationship between the upper units of the intracaldera fill. Although both volcanic assemblages are present in upper Cunningham Gulch, the present study did not demand differentiating between them.

Localized rhyolitic flows, south of the Pride of the West mine (on the east side of Cunningham Gulch), appear to represent thick (near vent ?) accumulations of domes of post-collapse lavas that grade laterally, in some places, into sequences of fine-grained volcaniclastic rocks. These volcaniclastic rocks had not previously been reported in the area, although they are a common constituent of intracaldera fill sequences (Steven and Lipman, 1976). The localized rhyolitic flows were mapped by Cook (1952) as part of the Eureka Rhyolite, but, from their limited areal extent and association with adjacent volcaniclastic units, it is reasonable to include them within the Burns Formation.

On the west side of Cunningham Gulch in the vicinity of the Highland Mary mine, a dark, fine-grained andesite flow drapes the topographic wall of the San Juan Caldera and unconformably overlies the San Juan Formation. This andesite flow is probably a unit of the Henson Formation, although it could not be demonstrated that the unit grades upward into volcaniclastic rocks.

QUATERNARY

The present rugged terrain of the San Juan Mountains was carved during several stages of Pleistocene glaciation and recent stream erosion. Quaternary alluvium of Cunningham Creek fills the valley floor and interfingers laterally with talus, accumulating in fans at the base of the steep valley walls. In addition, chaotic landslide debris of Paleozoic sediments appears on the west side of the graben exposures.

STRUCTURE

PRE-TERTIARY

Precambrian

Exposures of the Precambrian Irving Formation in upper Cunningham Gulch generally have east to N70E trends of foliation and compositional banding which probably developed in the Uncompahgran disturbance (1720-1460 mybp) which was accompanied by intense folding and low-to-high grade metamorphism (Barker, 1969). Varnes (1963) noted an abrupt change from regional trends in foliation direction of the Irving Formation within an east trending graben structure located in Upper Cunningham Gulch. He also noted an abrupt change in foliation direction from regional trends on the northern side of this graben, and this apparently represents another structural reorientation (Fig. 17).

Paleozoic

Possible Paleozoic faulting is evidenced by the graben in upper Cunningham Gulch, which was first mapped by Cross et al. (1905) and later by Varnes (1963). This graben contains about 60 m of Paleozoic sediments representing the minimum displacement along the bounding faults. These sediments dip about 30° to the northeast as a consequence of greater displacement along the northern bounding fault. The youngest sediments within

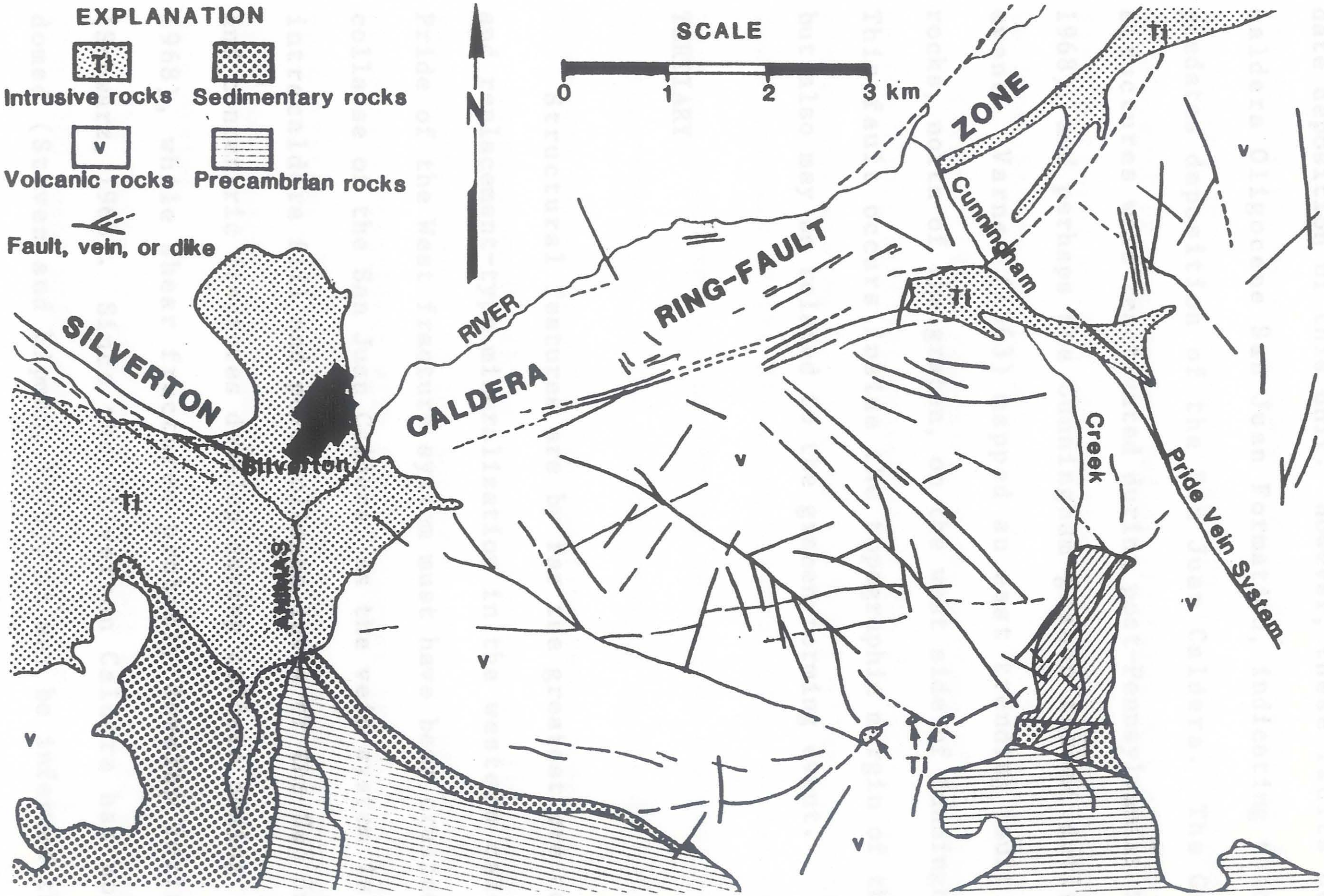


Figure 17. Principal fracture systems of the South Silverton mining area.

The two major systems are: (1) oriented concentrically about the ring-fault zone, and (2) oriented radially about this zone, such as the Pride vein system. Note trend of the intrusion-filled concentric system which crosses upper Cunningham Gulch near the graben, and the orientation of lower Cunningham Gulch which trends radially away from the Silverton ring-fault zone. Also note changes in the foliation direction (ruled pattern) of the Precambrian rocks in upper Cunningham Gulch (modified from Varnes, 1963).

the graben are of Pennsylvanian age, and thus, faulting must clearly postdate deposition of this unit. However, these faults do not cut the pre-caldera Oligocene San Juan Formation, indicating that graben development predates deposition of the San Juan Caldera. The Grenadier Highlands structures were reactivated during post-Pennsylvanian time (Baars and See, 1968), and perhaps the Cunningham graben formed during this structural event. Varnes (1963) mapped an east trending fault cutting Precambrian rocks, north of the graben, on the west side of Cunningham Gulch (Fig. 3). This fault occurs inside the topographic margin of the San Juan Caldera, but also may be related to the graben-forming event.

TERTIARY

Structural features are by far the greatest ore control for both vein and replacement-type mineralization in the western caldera complex. The Pride of the West fracture system must have been created sometime after the collapse of the San Juan Caldera, as the vein system is hosted within the intracaldera fill and post-collapse lavas of the San Juan Caldera. Radial and concentric fractures develop during caldera doming (Smith and Bailey, 1968), while shear fractures probably develop during caldera collapse (Schwarz, 1968). Since the Silverton Caldera has not been resurgently domed (Steven and Lipman, 1976), it may be inferred that the Pride of the West radial fracture system either developed during initial doming of the Silverton Caldera or during resurgent doming of the older San Juan Caldera. These two cycles of caldera development occurred within rapid succession of one another and can be considered part of the same volcano-tectonic event. The unique stress environment which was created as the Silverton Caldera collapsed during resurgent doming of the San Juan Caldera, caused the development of spectacular radial fractures and other intricate vein and dike patterns within the southeast and northwest margins of the Silverton Caldera (Steven and Lipman, 1976).

Varnes (1963) recognized three systems of fractures in the South Silverton Mining District southeast of the Silverton Caldera (Fig. 17); (1) a concentric system 2.4-4.0 km (1.5-2.5 miles south of the southern ring-fault boundary of the Silverton Caldera, (2) a system of shear and related tension fractures in the western portion of the district, and (3) a system of shear fractures in the eastern portion of the district, which includes fractures radial to the Silverton ring fault zone.

Cunningham Gulch is oriented north in its upper portion, but the rather sharp bend to the northwest that it makes in its lower portion is strikingly coincident with the northwest trend of the Pride of the West vein system. This coincidence in trend suggests that Cunningham Creek, in the lower portion of Cunningham Gulch, is controlled by this radial fracture system.

The Pride of the West vein-fault system is a complex vein zone up to 30 m (100 feet) wide, composed primarily of 1 to 3 subparallel structures which generally trend north to northwest and dip 50 to 70 degrees west. (Cook, 1952; Varnes, 1963). The veins have a discontinuous nature and branching habit which makes them difficult to trace, especially in the middle portion of the mine (Varnes, 1963). Apparently, normal faulting took place along this fracture zone and opened up tension fissures at high angles between individual faults (Varnes, 1963). These steep tension fractures were the most favorable sites for mineral deposition, being generally wide and more continuous, especially in the northern part of the mine, where mineralization took place only within these fractures (Cook, 1952; Varnes, 1963). In the southern portion of the mine, however, the structural control changes so that the faults themselves are mineralized. Perhaps the faults in the northern portion of the mine were sealed off from mineralizing solutions by impermeable zones of fault gouge which are present within some barren structures today. Varnes (1963) cited banding, cross-cutting veinlets, and breccia cemented by vein material as evidence suggesting that movement along the faults continued during and after mineralization and that mineralization took place in several stages, accompanied by movement along the vein walls.

The veins are convex to the east (Fig. 18) and change strike from about N30W to N30E from north to south along the vein system (Cook, 1952). This geometry appears to have been locally controlled by the wall of the San Juan Caldera, the shape of which is also convex to the east in this portion of Cunningham Gulch. Apparently, a contact between the hosting volcanics and Precambrian rocks is present at the southern end of the third mine level (Fig. 18), and the Pride vein may have propagated along this contact during its formation. However, Cook (1952) and Varnes (1963) noted that contacts with the Precambrian exposed in the mine are vertical to approximately 70 degrees, contain numerous gougy slip planes, and in places appear as recemented pre-mineralization shear zones. Thus, it is uncertain

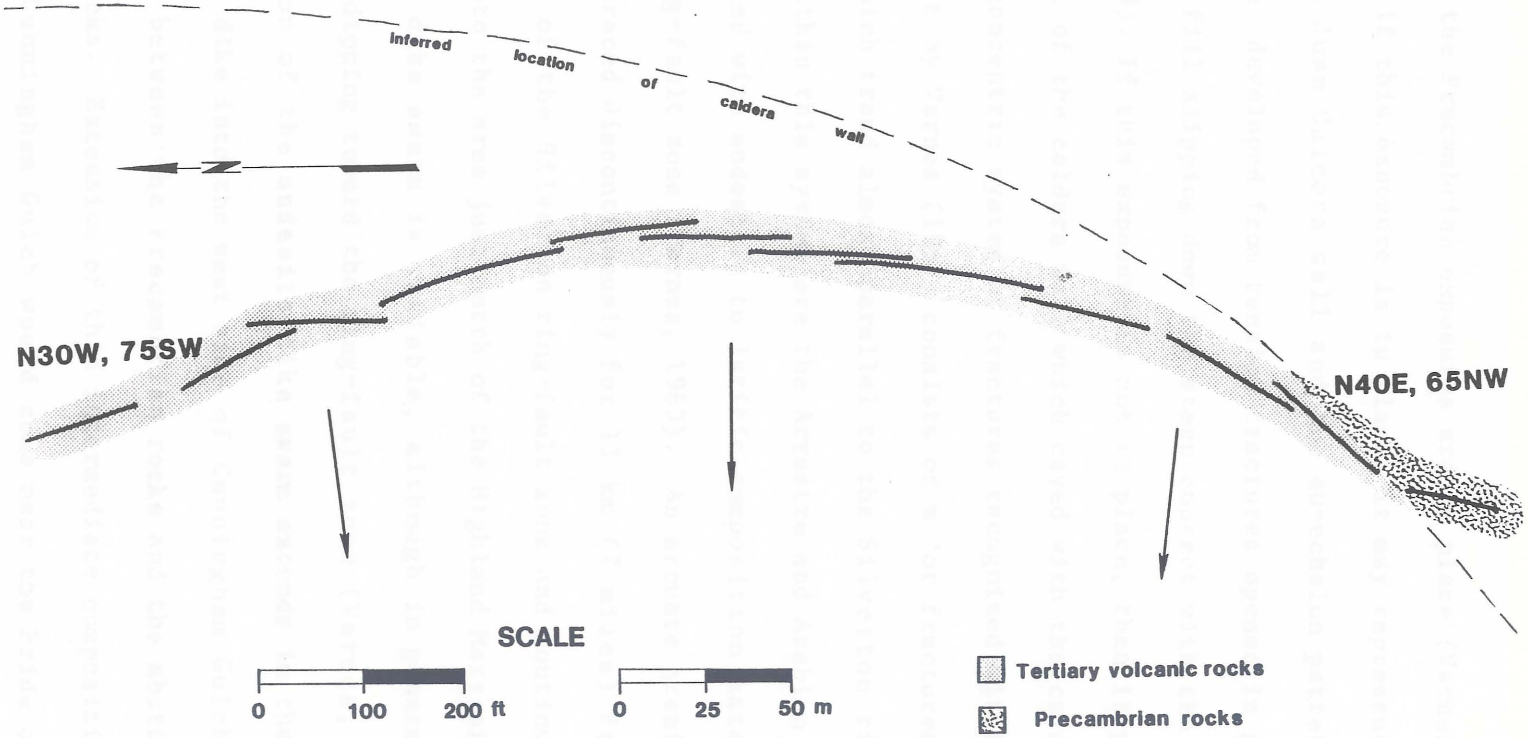


Figure 18. Generalized fracture pattern on the third level of the Pride of the West mine

Note the localized contact of the hosting volcanics with Precambrian rocks. If this Precambrian exposure is in place, it may represent the lower portion of the San Juan Caldera wall which extends to the east of the vein system. The arcuate nature and en echelon pattern may have been influenced by this contact, perhaps by tension fractures opened in response to the caldera-filling volcanics slipping down the caldera wall in the direction of the arrows (modified from Cook, 1952).

whether the Precambrian exposures are in place (Varnes, personal communication). If this exposure is in place, it may represent the lower portion of the San Juan Caldera wall and the en-echelon pattern of fracture systems may have developed from tension fractures opened in response to the intracaldera fill slipping down the steep contact with the San Juan Caldera wall (Fig. 18). If this exposure is not in place, then it probably represents a fragment of the caldera wall which caved with the caldera-collapse breccia.

The concentric system of fractures recognized within the South Silverton District by Varnes (1963) consists of major fractures and dike-filled fissures which trend almost parallel to the Silverton ring-fault zone (Fig. 17). Within this system are the Arrastre and Arabian Boy dike swarms which are filled with andesitic to latitic composition material and dip toward the ring-fault zone (Varnes, 1963). An arcuate granite porphyrydike swarm can be traced discontinuously for 11 km (7 miles) from the southeastern portion of the Silverton ring-fault zone and continuing across Cunningham Gulch into the area just north of the Highland Mary mine (Fig. 17). The dip of this dike swarm is variable, although in general is near vertical to steeply-dipping toward the ring-fault zone (Varnes, 1963). An eastward extension of the andesite dike swarm extends in the form of a northeast-trending dike into the west side of Cunningham Gulch at the approximate contact between the Precambrian rocks and the abutting intracaldera volcanic rocks. Extension of this intermediate composition arcuate dike swarm across Cunningham Gulch would come near the Pride of the West mine while also following the approximate configuration of the San Juan Caldera topographic rim. The position of these arcuate dike swarms near the termination of Precambrian exposures, which are structurally downdropped into the caldera, suggests they are controlled by pre-existing ring fractures related to the structural development of the San Juan Caldera. A deep-seated fracture system, such as the ring-fault zone, would be a likely conduit for intermediate composition magma to rise from the underlying batholith. In addition, these fractures would dip toward the interior of the caldera and thus correspond to the observed dip of the intermediate composition dikes. The granite porphyry-filled structures were apparently not open during filling of the intermediate composition dikes and were thus probably created and filled with available material during resurgence of the San Juan Caldera.

Thus, it appears that the structural control of ore deposition at the Pride of the West mine is not just simple filling of a radial fracture, but in fact mineralization was probably focused at the intersection of this radial fracture and older deep-seated concentric fractures of the San Juan Caldera ring-fault zone. In addition, the proposed fault intersection may help to explain the curvature of the Pride of the West vein system as a manifestation of a propagating radial fracture curving to intersect an older San Juan ring-fault at a right angle. If these hypotheses are correct, mineralization in upper Cunningham Gulch has taken place in an area with a complex structural history in which the structural fabric is closely related to the development of the nested calderas.

MINERALIZATION

INTRODUCTION

Major mining districts of the San Juan volcanic field from which significant lead, zinc, copper, gold, and silver ores have been produced are closely associated with calderas, but only about a third of the calderas are significantly mineralized (Steven et al., 1974; Steven and Lipman, 1976). Most known ore occurs in veins that filled or replaced fracture walls that formed during different caldera cycles, and all calderas with associated mineralization had complex post-subsidence histories involving recurrent intrusion and extrusion of magma along the ring-fracture zones and related grabens (Steven et al., 1974; Steven and Lipman, 1976). The extent of post-subsidence igneous and structural activity is especially important since ore deposition was associated with calderas which had the longest and most complex late histories (Steven et al., 1974). This relationship agrees well with the suggestion by Smith and Bailey (1968) that mineralization is generally associated with terminal stages of the caldera cycle. However, the genetic relationship of mineralization with an individual caldera cycle is generally tenuous, and the calderas principally provided structures that controlled later igneous intrusion and hydrothermal activity (Steven and Lipman, 1976).

The western San Juan Caldera complex had a very complex history, and several of the calderas host major mineralization. The two older isolated calderas (Lost Lake, Ute Creek) show little evidence af hydrothermal activity (Doe et al., 1979). However, the other four calderas (Uncompahgre, San Juan, Silverton, and Lake City) show evidence of extensive hydrothermal activity (Doe et al., 1979) and have major ore deposits which, as of 1968, had produced more than a half billion dollars worth of gold, silver, copper, lead, and zinc (Burbank and Luedke, 1968) About ninety percent of this production has been from veins, with the remaining ten percent from associated replacement deposits.

Several distinct periods of mineralization have taken place within the western San Juan Mountains, extending over an interval of about 15 my in later Tertiary time (Lipman et al., 1973). Most ores are too young to be a part of the caldera cycles, further indicating that caldera-related structures served principally to guide later intrusions and hydrothermal activity (Lipman et al., 1976). Some of these intrusions were emplaced late in the caldera cycle, but most mineralization is related to significantly younger intrusions (Doe et al., 1979). Mineralization-related intrusions in the South Silverton District were emplaced about 12 my later than the formation of the Uncompahgre, San Juan, and Silverton Calderas (Fig. 19) and are compositionally similar to the highly silicic Sunshine Peak Tuff, the eruption of which led to the collapse of the Lake City Caldera at 22.5 mybp (Mehnart et al., 1973). Most of these intrusions occurred within a narrow belt extending a few kilometers north of Lake City, then westward and southward for at least 6.5 km through many mineralized areas to Cunningham Gulch (Doe et al., 1979; Fig. 17). Scattered intrusions within this belt

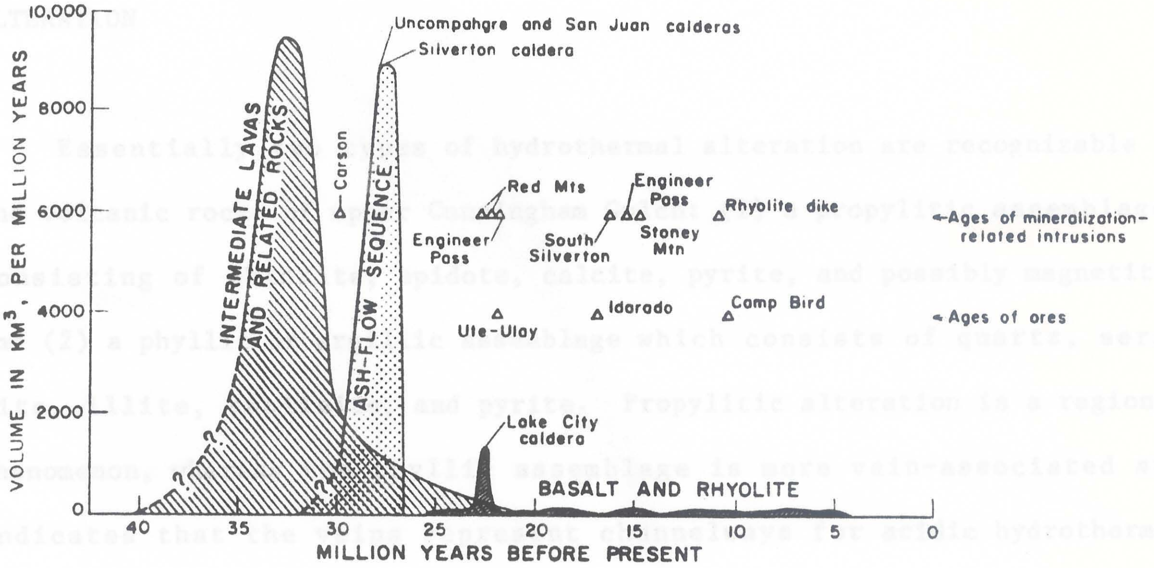


Figure 19. Summary of petrologic type, volume, and timing relationships between volcanism and mineralization in the western San Juan Mountains.

Note the ores are much younger than the ash-flow volcanism (Lipman et al., 1976).

have been dated between 15 m.y. and 22.5 m.y. (Lipman et al., 1976a). Apparently, major mineralization was episodic within this time span as determined by K-Ar dating of adularia in replacement ore in the Idarado mine at 17 m.y. (Doe et al., 1979) and from the Camp Bird vein at 10.5 m.y. (Lipman et al., 1976; Fig. 19).

ALTERATION

Essentially two types of hydrothermal alteration are recognizable in the volcanic rocks of upper Cunningham Gulch: (1) a propylitic assemblage, consisting of chlorite, epidote, calcite, pyrite, and possibly magnetite, and (2) a phyllic or argillic assemblage which consists of quartz, sericite, illite, kaolinite, and pyrite. Propylitic alteration is a regional phenomenon, whereas the phyllic assemblage is more vein-associated and indicates that the veins represent channelways for acidic hydrothermal fluids responsible for this type of alteration (Fig. 20).

Regional propylitic alteration mostly preceded, but in part continued with the period of ore deposition at the Silverton Caldera (Burbank, 1960). This alteration event affected many cubic kilometers of volcanic rock throughout and beyond the caldera (Burbank, 1960) and, within the upper Cunningham Gulch area, pervasively attacked the volcanic units, imparting a greenish coloration to them.

Propylitic alteration effects are apparently much more pronounced within the intermediate composition lavas and breccias of the San Juan Formation, and consequently, within the landslide breccia material as well.

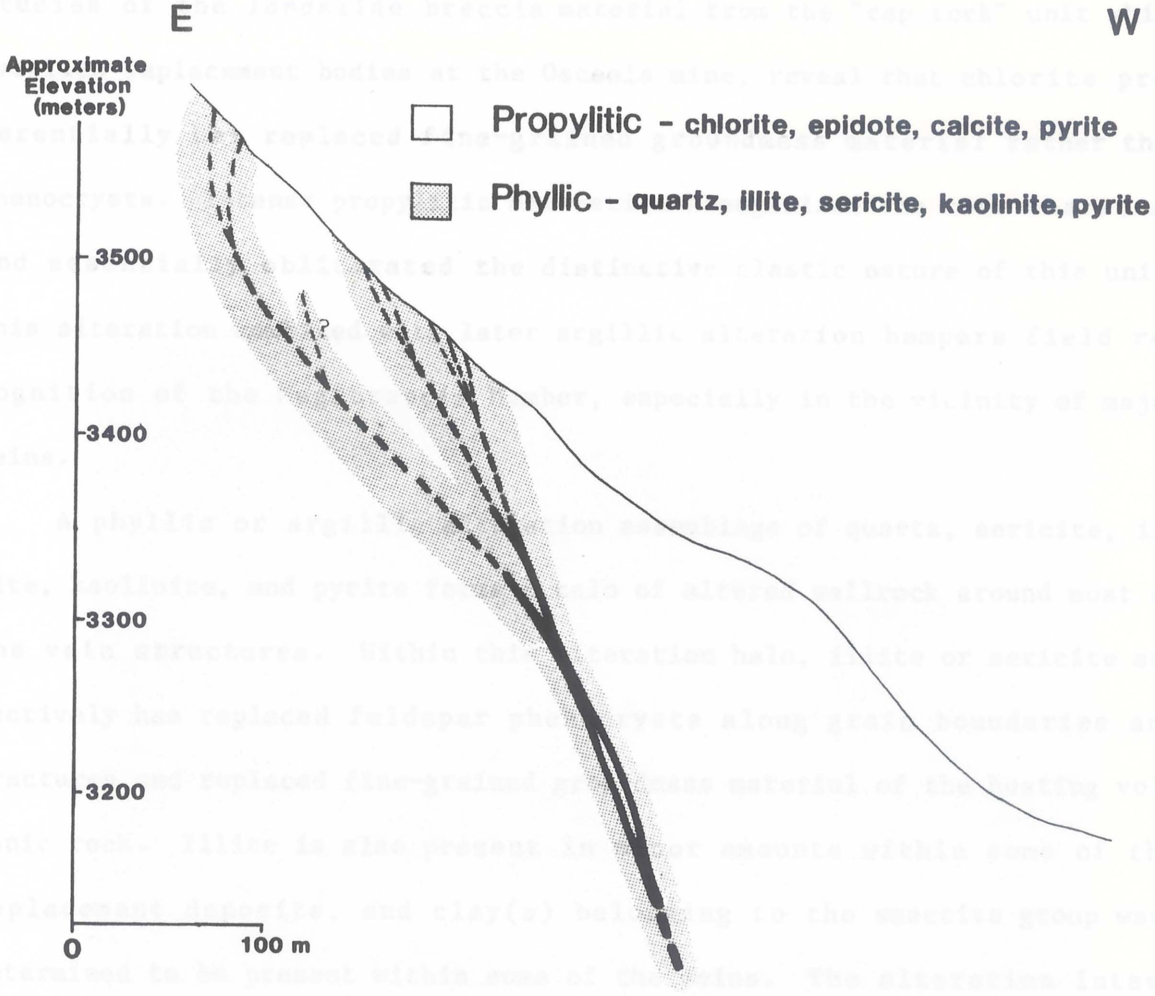


Figure 20. Alteration assemblages enveloping the Pride vein system.

Two distinct assemblages are present: (1) a district-wide propylitic assemblage which widely affected the volcanic section, most intense within remnants of the pre-caldera intermediate composition volcanics, and (2) a vein-associated phyllic or argillic assemblage which envelopes individual veins to varying widths. Configuration of the Pride vein system is, in part, diagrammatic and, in part, derived from surface and underground maps by Cook (1952). Note the typical increasing upward complexity of the vein system.

studies of the landslide breccia material from the "cap rock" unit which overlies replacement bodies at the Osceola mine, reveal that chlorite preferentially has replaced fine-grained groundmass material rather than phenocrysts. Intense propylitic alteration homogenized the rock character and essentially obliterated the distinctive clastic nature of this unit. This alteration combined with later argillic alteration hampers field recognition of the Megabreccia Member, especially in the vicinity of major veins.

A phyllic or argillic alteration assemblage of quartz, sericite, illite, kaolinite, and pyrite forms a halo of altered wallrock around most of the vein structures. Within this alteration halo, illite or sericite selectively has replaced feldspar phenocrysts along grain boundaries and fractures and replaced fine-grained groundmass material of the hosting volcanic rock. Illite is also present in minor amounts within some of the replacement deposits, and clay(s) belonging to the smectite group were determined to be present within some of the veins. The alteration intensity increases inward from this halo toward the vein until the wallrock is totally silicified adjacent to the vein. Cooper et al. (1980) noted that the halo of vein-associated alteration is characteristically about five times wider than the veins themselves. An intense yellow-orange limonitic or jarositic stain often accompanies the vein-associated alteration and is particularly evident adjacent to exposed veins (Fig. 21). This stain, resulting from the oxidation of pyrite, has long been an indicator to prospectors that metallic concentrations may be nearby and at least indicates

Figure 21. Surface exposure of a Pride vein.

This vein, comprised of quartz with about 5% combined sphalerite, galena, and pyrite, is about 0.7 m wide, whereas the composite width with the alteration halo is about 3 m. Exposure is located just below the fifth level portal of the Pride of the West mine.

that hydrothermal activity has been active in the area, utilizing the fracture as a fluid passageway. Cooper et al. (1980) determined the Cu, Fe, Pb, and Ag contents of samples of unmineralized volcanic wallrocks along a 6-meter traverse away from the Osceola vein. The rapid decrease in metal content within wallrock material indicates that major fluid flow was confined to the veins, with lesser fluid passage controlled by fracture porosity.

Thorough examination of surface outcrops in upper Cunningham Gulch did not reveal the presence of mineral assemblages such as alunite, cristobalite, or siliceous residue indicative of the upper portion of a hydrothermal system (Buchanan, 1981). Absence of these materials, even at the highest elevations within the area, suggests that the exposures record the effects of fluid action within the lower portion of an extinct hydrothermal system whose uppermost portion has been removed by erosion.

VEIN DEPOSITS

The Pride of the West vein system generally trends north to northwest with a steep westerly dip (Cook, 1952). The veins have a roughly systematic variation in their strike, ranging between about N30°W to N30°E from northwest to southeast along the greater than 400 m length of the vein system. The Pride vein system is up to 30 m (100 feet) wide and is mineralized for over 425 m (1400 feet) along strike and for over 275 m (900 feet) along dip; economic concentrations of metals occur discontinuously along the vein system, essentially within ore pods (Cook, 1952). The structural style changes along this arcuate network of veins. In the northern portion of the mine, metals are concentrated exclusively within steep tension gashes (possibly opened in response to normal faulting caused by the host rock slipping down the caldera wall), whereas , in the southern portion of the mine, the related normal faults are also mineralized (Varnes, 1963). The veins are absent in the transition zone between these two structural styles, as they are elsewhere in the mine, due to their discontinuous nature and common habit of splitting and horsetailing (Varnes, 1963).

The individual veins of the Pride system are highly variable in nature as is typical of many epithermal vein systems in which the complexity of veins tends to increase upwards (Buchanan, 1981). The Pride veins pinch and swell, as well as bifurcate and converge irregularly as they locally change strike and dip both horizontally and vertically along the vein system, producing a rather complex geometric configuration. Individual vein widths average 0.5 to 2.5 m (2 to 8 feet) and characteristically have sharp contacts with the wallrock (Fig. 22). The veins have no true walls in many places, but rather false walls of thin slabs of barren country rock concealing other veins (Varnes, 1963). The vein fillings are dominated by quartz gangue and the base metal sulfides galena (some argentiferous), sphalerite, chalcopyrite, and pyrite, often occurring in discrete sequential or crustiform bands of different composition. The amount of sulfides contained in the veins is highly variable with combined sulfides reaching as much as 60 percent locally. The banding indicates several periods of mineralization from fluids of changing composition accompanied by movement

Figure 22. Underground exposure of a Pride vein.

Note the sharp contact between volcanic wallrock (V) and vein matter which demonstrates crustaform banding. Quartz (Q) was the first mineral to be deposited (hammer point) and the interior vein matter tends to form pods of metallic minerals such as galena (ga). Also note the lack of argillic alteration adjacent to this vein. The extent and intensity of argillic alteration tends to increase upwards within the vein system. Exposure located on No. 1 level of the Pride of the West mine.

of the vein walls. Varnes (1963) noted cross-cutting vein relationships and brecciated-recemented vein material at the Pride of the West mine, indicating that movements along the veins were active during mineral deposition. In several localities within the Pride of the West mine, post-ore movement is suggested by barren quartz or calcite-filled veins which crosscut older vein or replacement sulfides. Some of these late-stage barren quartz veinlets contain trace amounts of pyrite, indicating that the fluid composition was still compatible with sulfide deposition, but that the main stage of ore formation had ceased by this time.

At several localities in both the Pride and Osceola mines, zones of intense brecciation and silicification are present. At the entrance to the March adit of the Osceola mine, the breccia fragments within one of these zones consist of both sulfide material and unreplaced silicified carbonate. The fragments are cemented by barren quartz, suggesting that the brecciation and silification at this locality postdated sulfide deposition.

The veins tend to change orientation abruptly upon intersecting carbonate blocks with a control apparently exerted by the contact between the carbonate and volcanic host. This contact is often fissile and thus a likely zone to relieve stress. Movement along this contact is indicated by numerous gougy slip planes and by the local development of pinnate fractures suggesting normal displacement along the contact (Fig. 23). The abrupt ending and horse-tailing of some veins within the Pride of the West mine may be the result of an encounter with a carbonate block. An analogous phenomenon on a smaller scale is shown by quartz-filled veinlets within volcanic host ending abruptly at the volcanic-carbonate contact and is

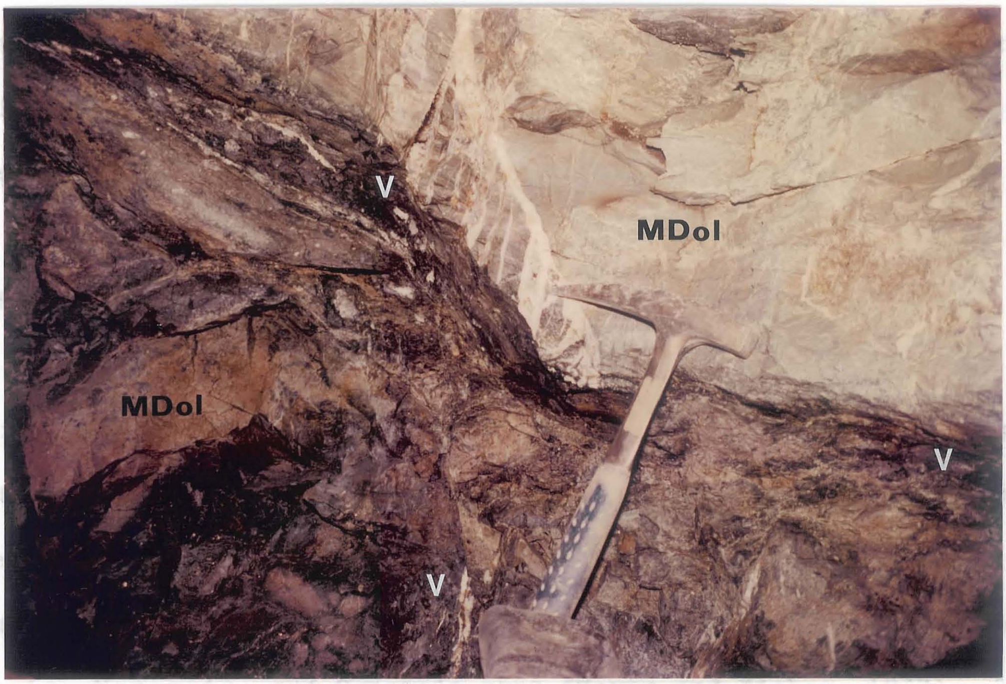


Figure 23. Contact between unreplaced carbonate block and hosting volcanic rock.

Quartz-filled pinnate fractures suggest normal movement along this zone of preferential weakness sometime after incorporation of the block (MDol) into the chloritized volcanic host (V). Note the abundant breccia fragments of carbonate engulfed within the volcanic rock near this contact. Exposure is underground at the Osceola mine.

caused by the contrast in dilatency between these materials.

In the southern portion of the Pride No. 1 level workings, several zones of pink and blue-green fault gouge (0.2 to 0.5 m wide) are present in the back of the drift. These faults appear to be post-mineralization in origin, as they are barren of sulfides but locally contain quartz and calcite within 0.3 to 0.6 m vugs. These vugs represent open space created by post-sulfide fault movement and associated brecciation.

REPLACEMENT DEPOSITS

Mid-Tertiary replacement-type ore deposits are present at several localities in the western San Juan Mountains. These deposits are associated with either base-metal veins or intrusions related to development of the caldera complex and are hosted within a variety of sedimentary rocks of Paleozoic, Mesozoic, and Cenozoic ages (Mayor and Fisher, 1972). The replacement deposits at the Pride and Osceola mines occur only where metal-bearing veins intersect the isolated carbonate blocks which were incorporated into the intracaldera fill of the San Juan Caldera. No replacement deposits are present where barren quartz veins intersect these carbonate blocks. The mineralogic composition and replacement textures vary greatly within these carbonate bodies. The mineralogic composition is controlled by the composition of the mineralizing fluids which utililzed the veins as passagewaysto chemically favorable sites of deposition. The replacement textures appear to be controlled by features related to the depositional and diagenetic character of the host carbonate strata.

Most of the replacement deposits consists of an assemblage of sphalerite, galena, chalcopyrite, and pyrite in a gangue of quartz with or without pyroxmangite. This assemblage is closely analogous to the bulk composition of the veins at the Pride and Osceola mines. In addition, chlorite and illite are present in several of the replacement deposits. A replacement body exposed in the glory holes of the Osceola mine contains massive magnetite, hematite, pyrite, and chlorite (Fig. 24A), locally with quartz and pyroxmangite (Fig. 24B). This replacement body is in the vicinity of a small (2 to 5 cm) magnetite-bearing vein. Recognition of the fact that most chlorite was deposited early, during regional alteration which continued into the phase of ore deposition (Burbank, 1960), tends to suggest that chlorite magnetite replacement deposit also formed temporally early in the mineralization event. Locally, this Fe-rich assemblage has replaced the Fe-rich karstified breccia zone at the contact with the Molas Formation at the top of the Leadville carbonate block (Fig. 25).

The replacement textures, which are present in both the sulfide and oxide metallic assemblages, vary from a massive variety to the "zebra" texture which consists of metallic bands alternating principally with quartz gangue. The massive texture is generally characterized by coarse sulfide crystals and massive white quartz with or without pyroxmangite, occurring in an irregular fashion which is in sharp contrast to the well-banded nature of the zebra texture. The massive and banded replacement texture are not always separate and distinct, but often closely associated in the same exposure (Fig. 25), where zebra laminations may terminate into zones of massive-type replacement (Fig. 26). However, some zones consist

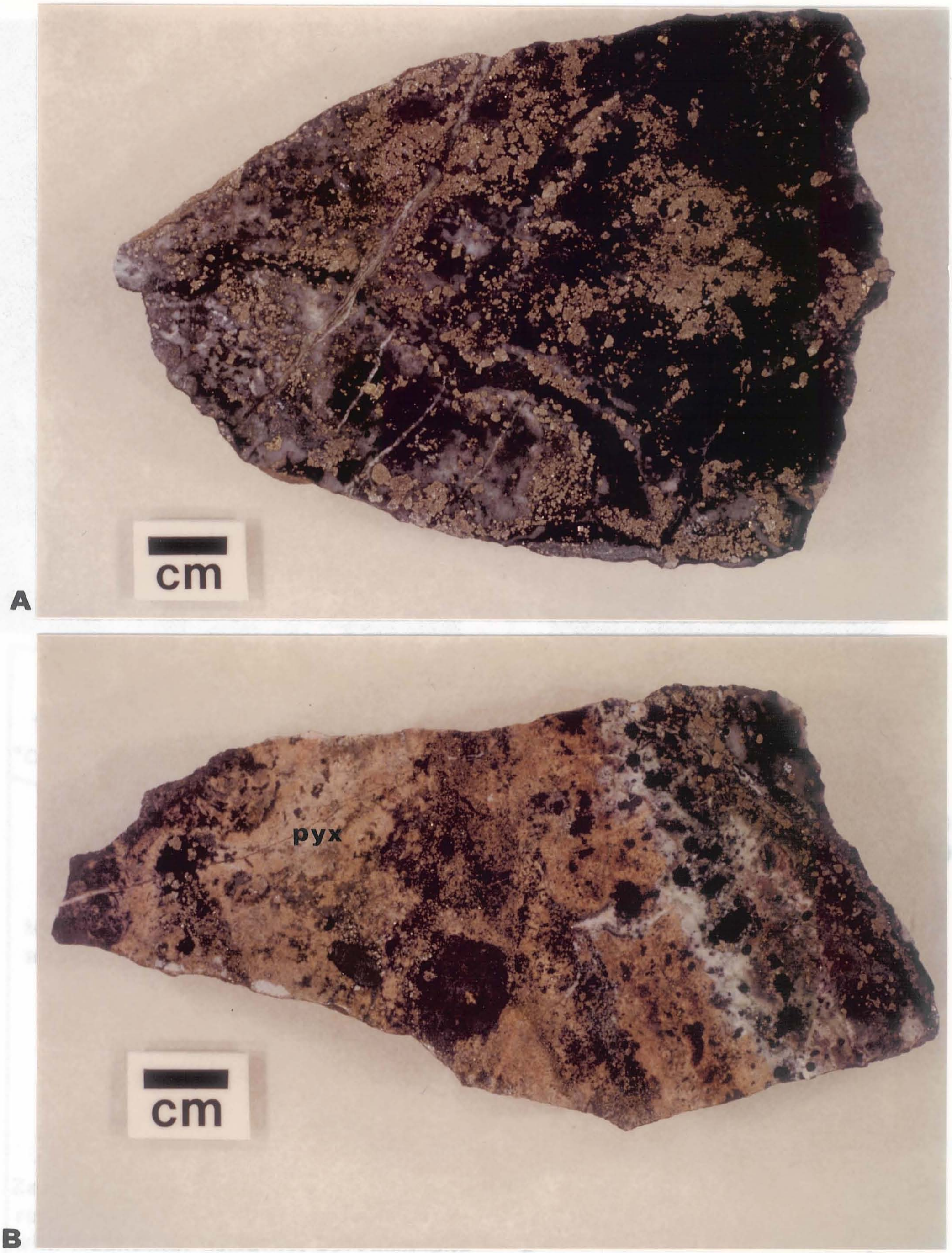


Figure 24. Massive magnetite, hematite, pyrite replacement minerals.

Note quartz and chlorite gangue in (A) as compared with pyroxmangite (pyx) in (B). This iron-rich assemblage tends to be associated with the Molas Formation regolith at the contact between the main replacement body and the hosting volcanics. Samples are spacially separated by only a few meters in a glory hole of the Osceola mine.

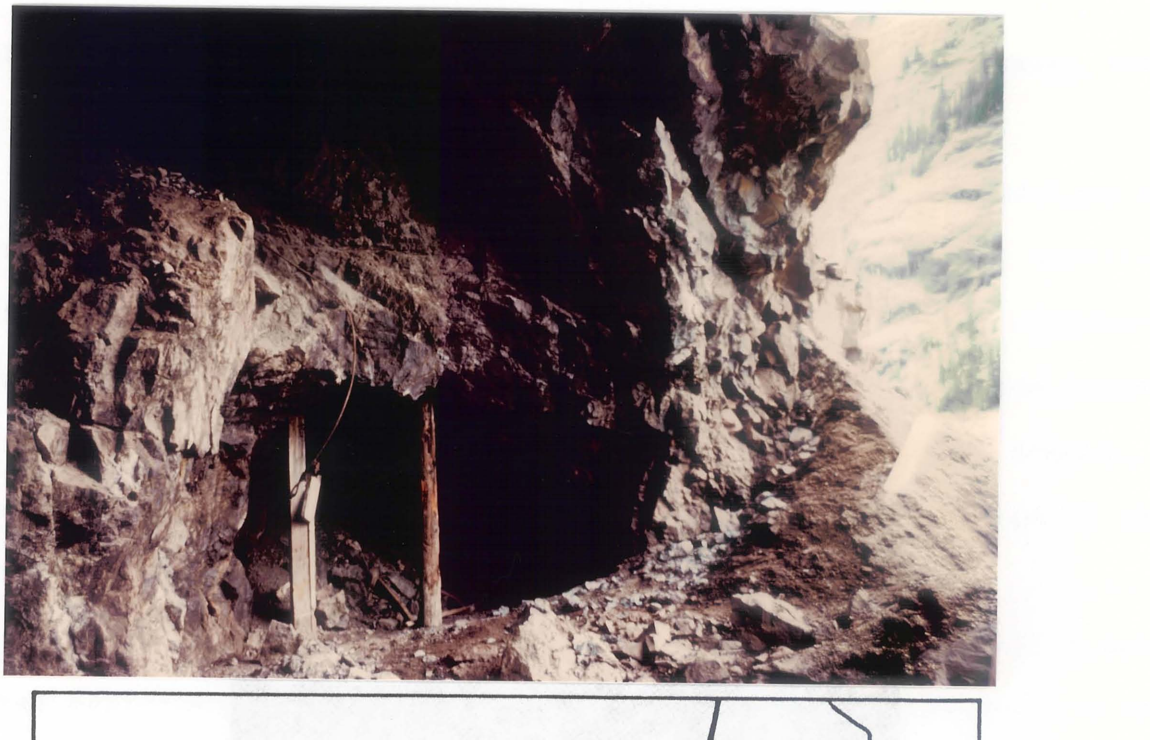


Figure 25. Glory hole left from the mining of a mineralized carbonate block at the Osceola mine.

Note close spatial relationship between massive- and zebra-texture replacement, and an underlying silicified zone. Also note karstified limestone fragments at contact with the hosting volcanics (Tsmm) and the similarity in replacement mineralogy with the intersecting vein structure. Camera orientation: south.

Figure 26. Association between zebra and massive replacement textures.

Note zebra laminations (lower right) terminate into massive replacement texture. This phenomenon of terminating zebra bands may be due to a lack of host rock preparation, such as incomplete creation of open space developed during dolomitization of the Leadville Formation. Metallic minerals in both replacement types of this specimen are sphalerite, galena, and pyrite. Gangue minerals are quartz (Q) and pyroxmangite (Pyx). Sample from the Pride of the West mine dump.

only of zebra banding with little or no massive variety, and likewise, many areas of replacement ore consist exclusively of the massive type.

Ransome (1901) first noted the presence of this unusual banded ore at the Pride of the West mine although neither he nor Varnes (1963) observed this texture in place because of limited exposure. Although unreplaced limestone is exposed in the study area, both on the surface and underground, exposures of the zebra replacement ore are not common. However, a few exposures of zebra ore were examined underground at the Pride of the West mine and at the glory holes of the Osceola mine.

The underground exposure is located in a small room driven off a sublevel approximately 10 m above the main haulage level, and adjacent to the Regulator vein. The ore is composed of base metal sulfides in a dominantly quartz gangue and is mostly of the massive type, although a distinct zone of zebra texture is present. Trace amounts of pyroxmangite occur in the zebra-bands, but moderate amounts form the gangue of the massive-type replacement ore. The Regulator vein which intersects this replacement body contains a similar mineral assemblage including pyroxmangite and probably represents the feeder structure which guided mineralizing fluids to this locality. Rocks within this room are highly fractured and unstable from blasting, leaving in-place exposures unreachable. Inspection was limited to viewing the mine face from a distance of about 5 m and collecting of unoriented samples from the drift floor. An estimated 60 to 70 thousand metric tons of ore averaging 5-6% Pb, 5-6% Zn, 1 oz./ton (34 ppm) Ag, and generally 0.03-0.035 oz./ton (1-1.2 ppm)Au have been removed from this body

(Fetchenhier, personal communication, 1981). The zebra bands are strikingly horizontal and continuous over the entire 5 m^2 area of the exposure. A 3-m thick zone of massive silicified carbonate consisting of coarse interlocking quartz crystals and minor pyrite lies directly below the zone of replacement ore.

The other major exposure of zebra texture is located in a glory hole at the Osceola mine (Fig. 25). Although not as extensive as the exposure at the Pride of the West mine, it is more accessible and consequently more revealing about its origin. Here, zebra-banded material is present in two pillars about 5 m apart and consists of interbanded magnetite and hematite, minor sulfides, and gangue minerals. One of the exposures contains exclusively quartz gangue, whereas the other contains abundant pyroxmangite. Massive type replacement concentrations also occur within these exposures and again a zone of massive silicification at least 2 to 3 m thick is present below the mineralized zone. The spatial relationship of these silicified zones to the replacement ore suggests a stratigraphic control. In addition, the zebra-bands in one of these pillars trend roughly parallel to a band of chert nodules, inferred to correspond to bedding, and further suggests the texture is related to stratification. It appears that certain stratigraphic horizons within the Leadville Formation are preferentially mineralized in a banded fashion while others are either relatively featureless or only silicified and essentially devoid of metallic constituents.

In hand specimen, the zebra-texture typically appears as regularly spaced, alternating, subparallel to undulose bands of gangue and metallic minerals (Fig. 27). The metallic bands are generally 0.5 to 5 mm wide,

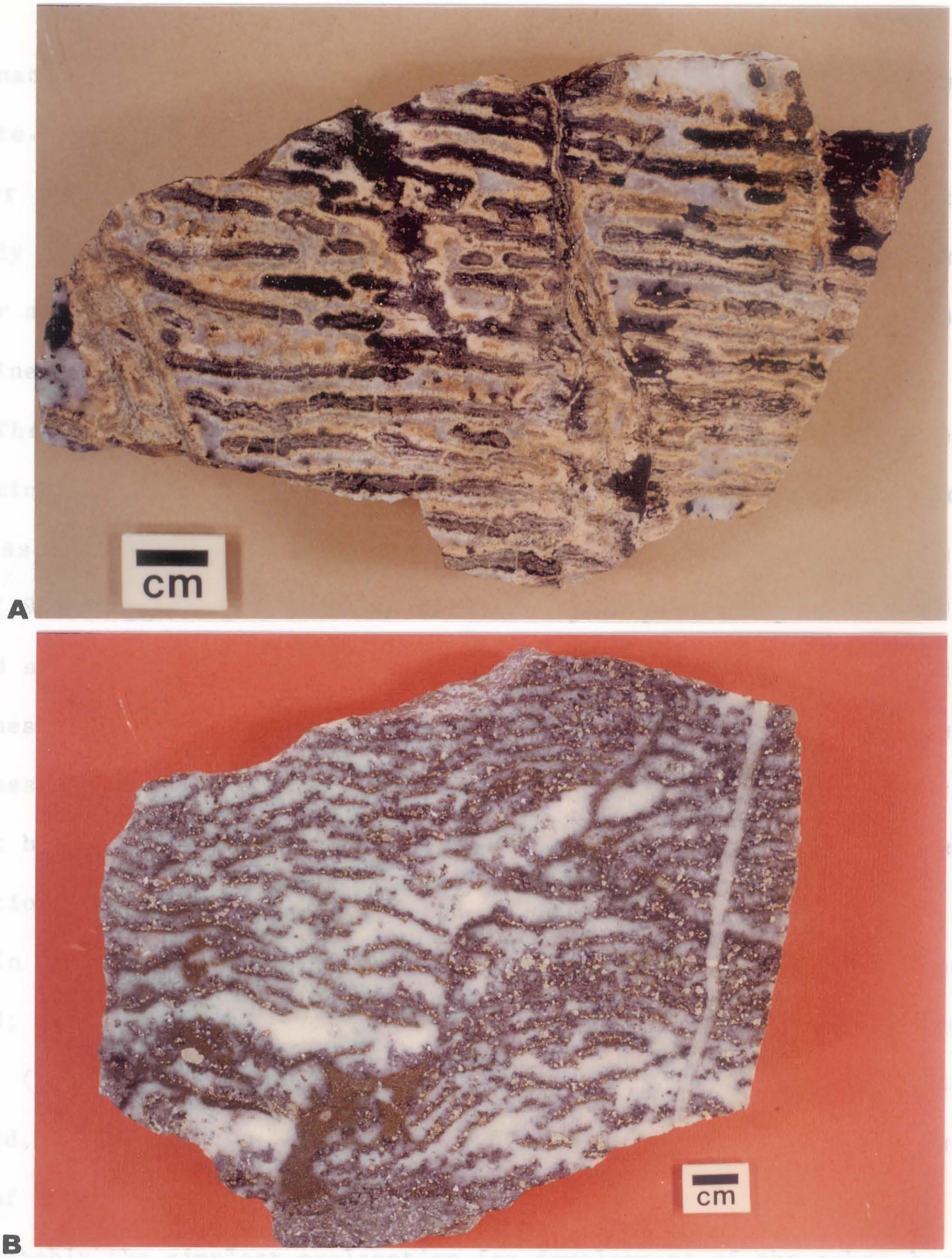


Figure 27. Banded nature of the zebra ore.

(A) The metallic bands consist of magnetite and hematite (dark) and the gangue is pyroxmangite and quartz. Note the metallized tectonic fractures.
(B) Zebra bands consist of galena, sphalerite, chalcopyrite, and pyrite in quartz gangue. Note the post-mineralization quartz-filled veinlet. Samples from the Osceola mine.

alternating with slightly larger (1 to 8 mm wide) bands of quartz or pyroxmangite. The metallic bands usually consist of sphalerite and galena with lesser amounts of chalcopyrite and pyrite, but magnetite and hematite are locally present. At higher magnification, the metallic bands no longer appear as continuous laminae, but as coalesced crystal aggregates of metallic minerals along a particular zone in the quartz (Fig. 28).

The origin of this texture has long been a subject of conjecture, and determination of its origin has been hampered by the pervasive replacement process which has obliterated all signs of precursor carbonate material. Cook (1952) suggested a chemical diffusion-precipitation process in fluid-filled space, analogous to the formation of Liesegang rings. He based this hypothesis on observation of zebra samples which had curved banding and a progressive increase in gangue mineral band thickness. This type of process cannot be refuted and may indeed be responsible, at least in part, for the formation of the zebra bands.

In this study, evidence of substantially curved banding was not detected; only minor curvature which gives the impression of wavy laminae was found (Fig. 29). A slight change in the thickness of the gangue bands was noticed, but attributed to variations in the distance between and orientation of permeable layers in the precursor rock.

Probably the simplest explanation for development of the zebra banding involves preferential fluid flow along zones of enhanced permeability, controlled by the lithologic character of the host rock. Available evidence suggests the zebra texture originated from replacement of a primary depositional fabric, such as stromatolitic laminae of the Leadville Formation.

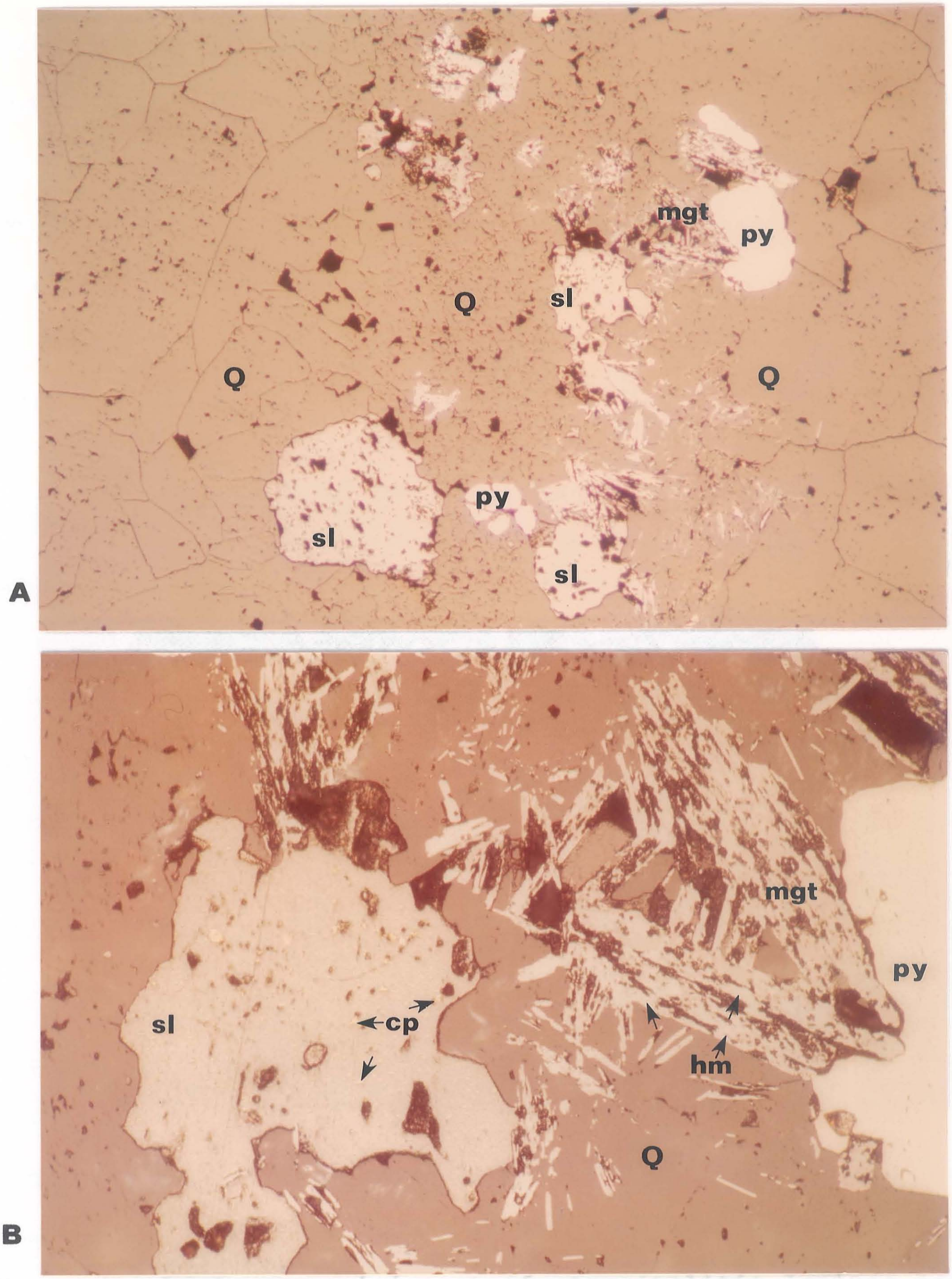


Figure 28. Discontinuous nature of a zebra band.

(A) Note metallic band (oriented north-south) appears as discontinuous patches of metallic minerals in quartz (Q). Long dimension is 4.5 millimeters. (B) Close-up of photo A. Note bladed aggregate of hematite (hm) mostly replaced by magnetite (mgt), being rimmed by later pyrite (py). Sphalerite (sl) contains numerous inclusions of chalcopyrite (cp). Long dimension is 1.1 millimeters. Photos taken in reflected light. Sample #S-12.

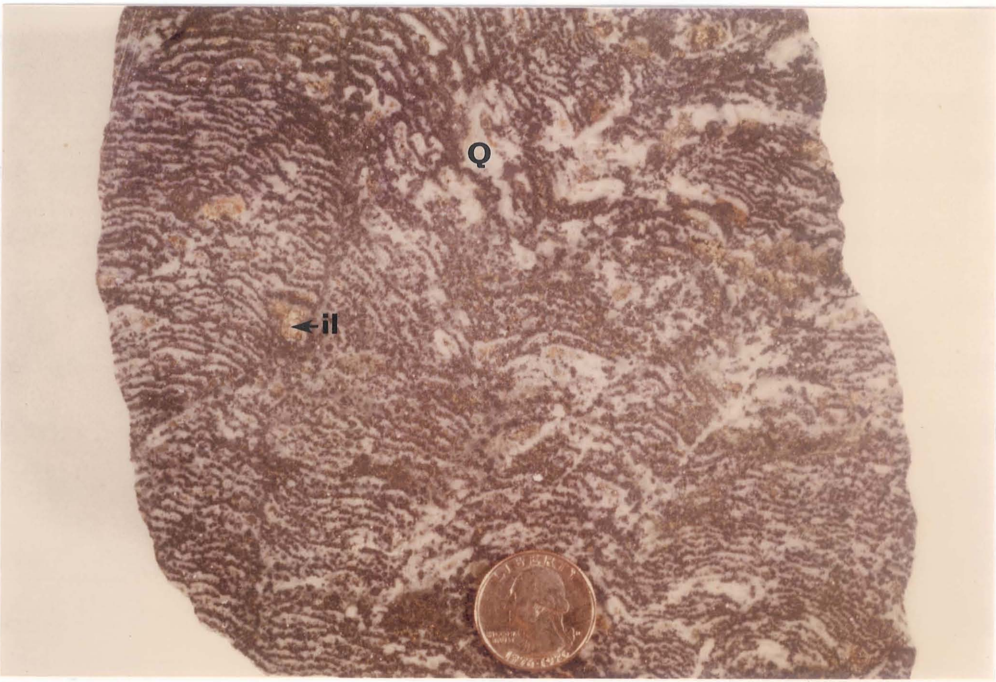


Figure 29. Undulose nature of zebra bands.

Note zebra bands are reminiscent of stromatolitic laminae and the scale of banding is similar to that of the zebra-dolomite texture (c.f. Fig. 8). The metallic bands consist of sphalerite and galena alternating with quartz gangue (Q). Late stage open space voids are now filled with fine-crystalline calcite and illite (il). Sample from the Pride of the West mine dump. Diameter of coin is 2.4 cm.

These stromatolitic laminae were subjected to diagenetic modifications, including dolomitization (Price, 1980), which enhanced the permeability along these laminae to produce the observable open space of the "zebra dolomite" texture (Fig. 8). Mineralizing fluids later encountered the carbonate blocks by way of feeder vein structures and spread laterally along these zones of enhanced permeability to react with the chemically favorable host; microfractures provided local bypasses between laminae (Fig. 30).

Since quartz was apparently the first mineral precipitated in the veins, and since the replacement mineral assemblage reflects that of the feeding vein, it is likely that the first fluids to encounter the carbonate blocks were saturated with quartz. The replacement process probably began with dissolution and rapid replacement of carbonate with microcrystalline quartz, followed by precipitation of megaquartz in fluid-filled space along the most permeable zones. Sulfides and other metallic minerals were precipitated in the available open space about the terminated quartz crystals, leaving the sulfides in a discontinuous banded array of deposition sites. Precipitation of megaquartz continued and overgrew the metallic minerals.

The intertidal depositional environment of the Leadville Formation resulted in the local development of stromatolitic laminae, but a more homogeneous carbonate sediment was the dominant product. Perhaps the precursor for the massive type of replacement ore did not possess a banded depositional fabric or was not subjected to the necessary diagenetic modification which enhanced the laminar permeability of the zones. Other

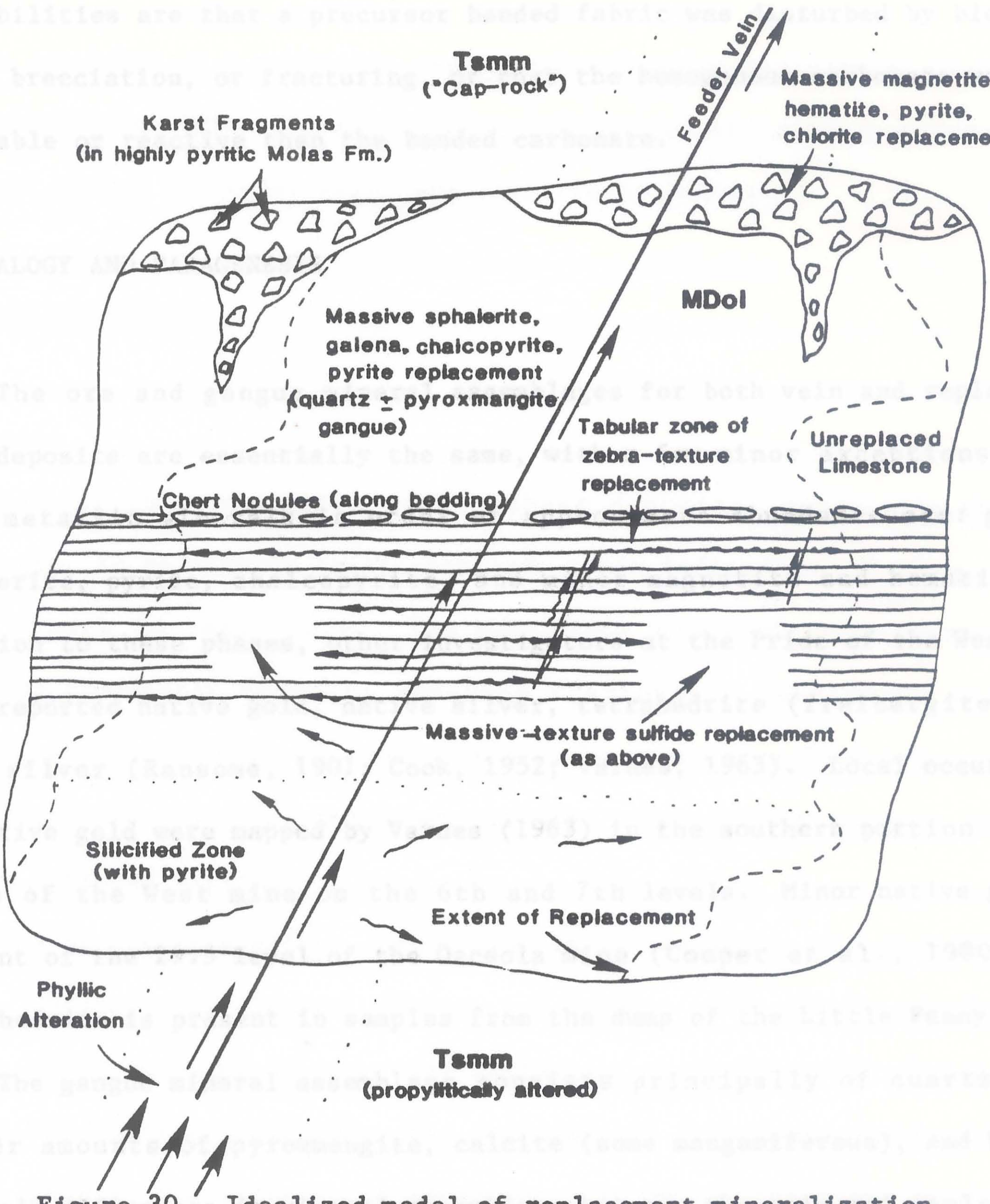


Figure 30. Idealized model of replacement mineralization.

Major flux of mineralizing fluid is directed upward along intersecting feeder vein. Encounter with carbonate block rapidly adds CO_3^- to the system, decreasing solubilities of quartz and base metals, causing deposition of massive quartz at base of block followed by base-metal replacement. Upon encountering banded zone of enhanced permeability, solution spread laterally with local bypass provided by fractures. Lack of available sulfur and metals results in incomplete deposition in available open space, leaving metals in discontinuous bands. Replacement process was aided by damming effect of volcanic caprock.

possibilities are that a precursor banded fabric was disturbed by bioturbation, brecciation, or fracturing, or that the homogenous carbonate was more permeable or reactive than the banded carbonate.

MINERALOGY AND PARAGENESIS

The ore and gangue mineral assemblages for both vein and replacement type deposits are essentially the same, with a few minor exceptions. The main metallic minerals in order of approximate abundance are: galena, sphalerite, pyrite, chalcopyrite, and minor magnetite and hematite. In addition to these phases, other investigators at the Pride of the West mine have reported native gold, native silver, tetrahedrite (freibergite), and ruby silver (Ransome, 1901; Cook, 1952; Varnes, 1963). Local occurrences of native gold were mapped by Varnes (1963) in the southern portion of the Pride of the West mine on the 6th and 7th levels. Minor native gold is present of the 29.5 level of the Osceola mine (Cooper et al., 1980), and tetrahedrite is present in samples from the dump of the Little Fanny mine.

The gangue mineral assemblage consists principally of quartz, with lesser amounts of pyroxmangite, calcite (some manganiferous), and barite. The only difference in mineral assemblage between the vein and replacement deposits is that calcite in barren veins is coarse crystalline, whereas the minor amount of calcite in the replacement deposits tends to be finely crystalline (perhaps representing unreplaced or remobilized original carbonate). In addition, hematite and magnetite tend to occur dominantly within replacement deposits. The only observed magnetite-bearing vein is in the vicinity of a magnetite and hematite-bearing replacement deposit at the Osceola mine (Fig. 25) and further illustrates the common mineral assemblage shared by feeder veins and replacement bodies.

Metallic Minerals

Sphalerite

Much of the sphalerite within these deposits, especially the vein sphalerite, is relatively coarse-grained, again indicative of slow, unimpeded growth in open space. The sphalerite occurs often as twinned crystals and frequently contains numerous fractures. Sphalerite from the Pride and Osceola mines is typically a light amber or yellow color, but is also zoned with a darker, red-brown variety. Sphalerite appears to have locally replaced pyrite.

Much of the sphalerite, especially in darker zones, has what has been called "chalcopyrite disease" (Barton and Bethke, 1977; Craig and Vaughn, 1981), which appears as numerous inclusions of chalcopyrite disseminated through the hosting sphalerite. The chalcopyrite inclusions typically decrease in size and increase in abundance near sphalerite grain boundaries, and many tend to be aligned along well-defined fracture planes and crystallographic axes. However, the chalcopyrite does not appear to occupy discrete growth zones within the sphalerite crystal. Many of the chalcopyrite inclusions appear to be roughly spherical, while others are distinctly rod-like.

Although this texture appears to represent an exsolution phenomenon, experimental studies by Wiggins and Craig (1980) and Hutchison and Scott (1980) have shown that chalcopyrite will not dissolve in sphalerite in significant amounts to produce exsolution below temperatures of 500°C. Considering the much lower temperatures of crystallization for this deposit (200 to 312° C), temperature-dependent exsolution is probably not the means by which these intergrowths form. This texture has been suggested to result from epitaxial chalcopyrite growth during the sphalerite formation or from replacement as copper-rich fluids reacted with the sphalerite after formation (Craig and Vaughn, 1981). This texture may result from simultaneous precipitation of chalcopyrite through sphalerite growth.

Chalcopyrite

Chalcopyrite forms crystals as well as inclusions within sphalerite and commonly has been remobilized into fractures and grain boundaries within more brittle sulfides. This remobilization is probably a result of post-depositional tectonic movement and tends to complicate the recognition of the precise paragenetic position of chalcopyrite within the depositional sequence. Overall, chalcopyrite is a minor constituent of the deposits, but still a source of recoverable copper.

Galena

Galena is the most important economic mineral at the Pride and Osceola mines. This mineral dominates the base-metal assemblage of the deposits and is often argentiferous (Cook, 1952). The galena is present mostly in a cubic habit, especially where it has grown into vugs where the crystals may be up to one centimeter in size. However, fine-crystalline galena also occurs. Some galena crystals show a marked curvature to the alignment of cleavage pits on polished surfaces. The curvature of crystals may be attributed to later tectonic readjustment.

Hematite and Magnetite

Hematite and magnetite are restricted in occurrence mainly to the replacement body exposed in the glory holes of the Osceola mine. Within this deposit, magnetite and hematite comprise a significant portion of the massive-type replacement and as well represent the main metallic constituent of the zebra texture present at this locality. The magnetite and hematite intimately occur together, with a dominantly bladed habit which is characteristic of hematite (Fig. 30). Thus, to retain the crystal habit, it appears that these blades were deposited originally as hematite, and magnetite has replaced portions of the hematite blades. This order of replacement is contrary to the common sequence expected in replacement controlled by a change of oxidation state, as hematite usually replaces magnetite with an increase in fO_2 (Craig and Vaughn, 1981). Therefore, the replacement of hematite by magnetite suggests a period of decreasing fO_2, probably accompanying sulfide deposition, which allowed the more reduced species to become stable.

Non-metallic Minerals

Quartz

Quartz comprises the vast majority of the gangue mineral assemblage for both vein-and replacement-type deposits and is ubiquitous throughout these deposits. Quartz commonly occurs as well-terminated crystals which apparently grew uninhibited in open space as vein or vug fillings. These crystals commonly exhibit a well-banded growth texture which is often of an oscillatory nature, consisting of alternating zones of clear and cloudy, or "milky" quartz. This cloudy variety of quartz contains abundant fluid inclusions which impart a white coloration to these zones, in contrast to the otherwise clear, fluid inclusion-poor zones. Apparently, these alternating bands represent fluctuations in the growth rate of the quartz, with clear quartz representing relatively slow crystal growth in a well-ordered crystal structure and fluid inclusion-rich quartz representing periods of rapid crystallization which resulted in numerous crystal imperfections containing trapped fluids.

Pyroxmangite

Pyroxmangite is a minor constituent in the gangue assemblage of veins and is absent from nearly all productive veins at the Pride of the West mine. This light pink to tan manganese silicate mineral is more common within the replacement deposits and exhibits a fine crystalline habit. The pyroxmangite present at the Pride and Osceola mines was identified by Cooper et al. (1980) by X-ray diffraction analysis.

Pyroxmangite is a difficult mineral to place in the paragenesis of the deposits. Within the replacement deposits, some pyroxmangite appears to have been precipitated with quartz which accompanied early ore deposition. However, pyroxmangite-bearing veinlets also crosscut sulfide-bearing zebra laminations and fill late stage open space in some replacement samples. This indicates that some pyroxmangite was deposited after the bulk of sulfide deposition. In addition, EDS analysis reveals that some calcite which was clearly deposited late in the paragenetic sequence is manganiferous, indicating that manganese was present in late-stage mineralization fluids. Burbank and Luedke (1961), in a comparison of deposits about the Silverton Caldera, noted that rhodonite gangue follows early quartz and the bulk of the base-metal sulfides. Also, pyroxmangite is a common constituent of ore-bearing veins at the Sunnyside mine (Eureka district, Silverton Caldera), where it has also been documented to follow base and precious metal deposition (Casadevall and Ohmoto, (1977).

Calcite

Calcite within the mine area occurs in three habits: (1) rhombohedral, (2) scalenohedral, and (3) a fine-crystalline variety. The age relationships between these three varieties of calcite are not clearly discernable as they are not commonly found together, but they all are probably late in the overall scheme of mineralization. The fine-crystalline variety generally is manganiferous and occurs mainly within the gangue of the replacement deposits. The rhombohedral calcite is most common as late-stage vein fillings which cross-cut main stage ore and gangue minerals. The scalenohedral crystals are usually found growing within open space voids upon late-stage quartz, mostly in the vicinity of replacement deposits. This variety of calcite may be younger than the rhombohedral variety and may represent deposition from local $CaCO_3$-rich ground water perhaps enriched from dissolution of unreplaced carbonate blocks or from calcite in the propylitic alteration assemblage.

Barite

Barite is a minor constituent of some veins of the No. 1 level of the Pride of the West mine. A single barite rose which grew on a substrate of apparent late-stage quartz and scalenohedral calcite indicates that barite was the last hydrothermal mineral deposited.

Paragenetic Sequence

Major quartz deposition, accompanied by minor pyrite, preceded and followed main ore-stage deposition, although quartz and pyrite apparently were deposited discontinuously throughout the mineralizing event. The hematite and magnetite apparently were deposited early in the sequence along with some pyroxmangite, the deposition of which continued into the early phases of sphalerite deposition. The main ore-stage minerals were deposited in the approximate order of sphalerite, chalcopyrite, and galena, although it is emphasized that deposition of these phases overlapped locally (Fig. 31). Post-sulfide silicification (and brecciation) was followed

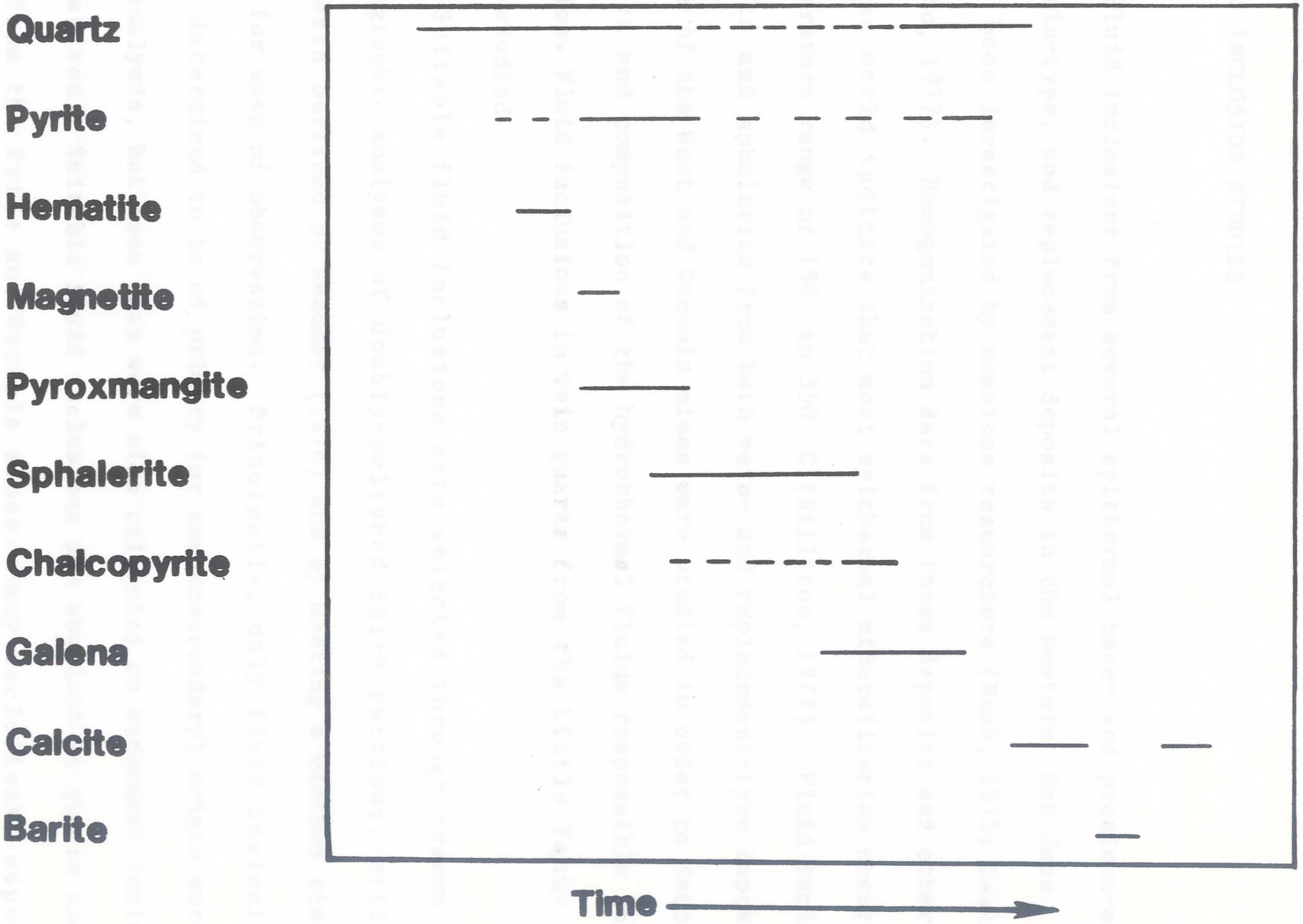


Figure 31. Generalized mineral paragenesis chart of ore and gangue minerals for vein and replacement deposits.

by deposition of minor calcite and lesser barite during the waning stages of the hydrothermal system.

FLUID INCLUSION STUDIES

Fluid inclusions from several epithermal base- and precious-metal vein, breccia-type, and replacement deposits in the western San Juan Mountains have been investigated by numerous researchers (Nash, 1975; Casadevall and Ohmoto, 1977). Homogenization data from these deposits and other districts of the world indicate that most epithermal mineralization occurred over a temperature range of 150 to 350 C (Sillitoe, 1977). Fluid inclusions in quartz and sphalerite from both vein- and replacement-type deposits at the Pride of the West and Osceola mines were studied in order to determine the nature and composition of the hydrothermal fluids responsible for mineralization. Fluid inclusions in vein quartz from the Little Fanny mine were also studied.

Suitable fluid inclusions were selected through transmitted light petrographic analyses of doubly-polished thick sections, utilizing the criteria outlined by Roedder (1976) and by meeting a minimum size requirement for ease of observation. Principally, only fluid inclusions which were determined to be of primary (or pseudosecondary) origin were selected for analysis, but some data were also collected on secondary inclusions for comparison. Suitable fluid inclusions are abundant in quartz and sphalerite from the Pride and Osceola mines. Many inclusions, especially in quartz, are within well-defined growth zones trapped at crystal boundaries which provide good evidence of primary origin. Fluid inclusions within sphalerite averaged about 15 to 18 microns in the long dimension and were generally larger than those in quartz, which averaged about 6 to 10 microns in the long dimension. Vapor bubble diameter averaged 2 to 3 microns in sphalerite as compared to 1 to 2 microns in quartz.

All observed inclusions from both vein- and replacement-type deposits are simple two-phase, liquid and vapor inclusions with no daughter minerals (Fig. 32). Furthermore, all observed inclusions are liquid-rich inclusions with at least a 3:1 apparent liquid-to-vapor ratio. Lack of vapor-rich inclusions indicates that none of these fluid inclusions represent trapped steam, and thus boiling did not occur during deposition at these levels within the hydrothermal system.

Homogenization temperatures were determined for over 160 fluid inclusions, and equivalent total salinity values were determined from freezing point depression analysis for over 40 inclusions (Fig. 33 and Appendix I). Homogenization temperatures for all inclusions ranged between 200 and 323 C with the exception of two inclusions which had not homogenized at 375 C; these two anomalous values were interpreted to be inclusions that had probably leaked or necked down.

Homogenization temperatures for primary and pseudosecondary (?) inclusions ranged between 200 and 312°C (mean 243° C)and between 214 and 323° C for secondary inclusions. The secondary inclusions studied were along well-defined planes in both quartz and sphalerite, and, in general, homogenized at consistent values within each plane. These values usually fell well within the observed range for primary inclusions and suggest that

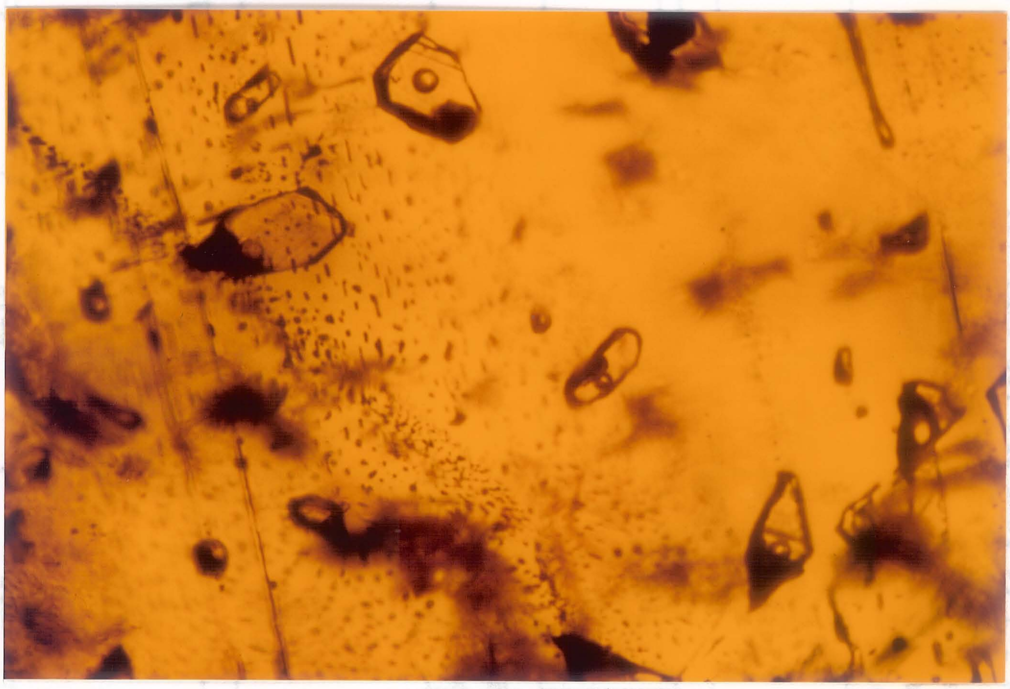


Figure 32. Transmitted light photomicrograph of amber sphalerite.

Note two-phase fluid inclusions, some of which occasionally have negative crystal shape (top center). Tiny dark blebs are "chalcopyrite disease". Sample #S-12 from a replacement deposit at the Osceola mine. Long dimension is 250 microns.

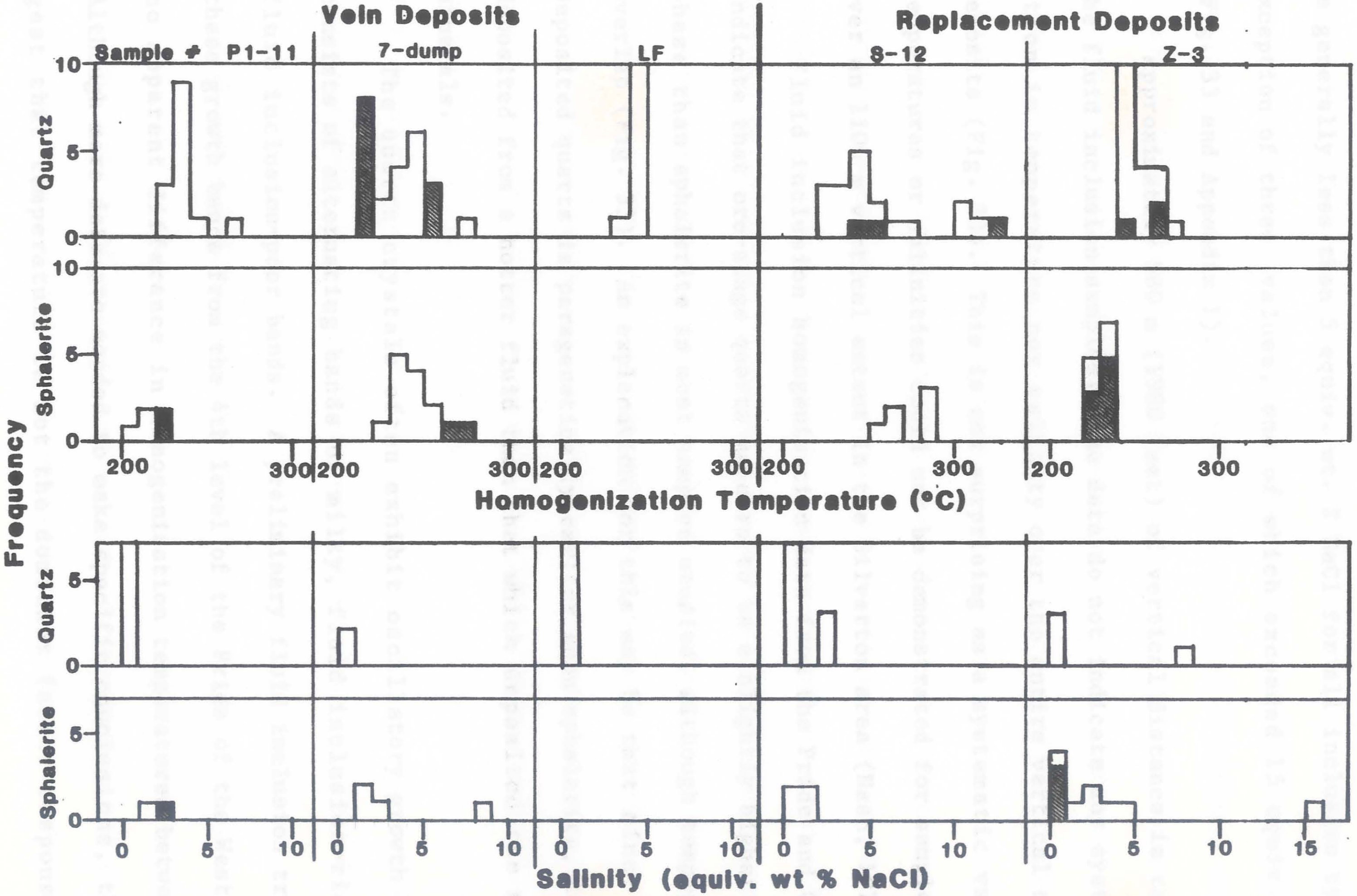


Figure 33. Fluid inclusion histograms for individual samples.

Sample #pl-11 is from the No. 1 level, and Z-3 is from the 1st sublevel of the Pride of the West mine. Sample 7-dump is from the 7th level dump of the Pride of the West mine. Sample LF is from Little Fanny mine dump. Sample #S-12 is from a glory hole at the Osceola mine. Ruled pattern represents data from secondary inclusions.

formation of secondary inclusions from a sealed fracture plane took place when the trapped fluid was a homogeneous phase. Salinity was determined to be generally less than 5 equiv. wt. % NaCl for all inclusion types with the exception of three values, one of which exceeded 15 equiv. wt. % NaCl (Fig. 33 and Appendix I).

Approximately 580 m (1980 feet) of vertical distance is represented by the fluid inclusion samples. The data do not indicate any systematic variation in temperature nor salinity over the entire vertical extent of the deposits (Fig. 33). This is not surprising as a systematic varitaiton in temperatures or salinities could not be demonstrated for samples from veins over an 1100 m vertical extent in the Silverton area (Nash, 1975).

Fluid inclusion homogenization data from the Pride and Osceola mines indicate that ore-stage quartz appears to be a slightly higher temperature phase than sphalerite in most samples studied, although temperature ranges overlap (Fig. 33). An explanation for this may be that since the bulk of deposited quartz is paragenetically earlier than sphalerite, it was perhaps deposited from a hotter fluid than that which deposited the metallic ore minerals.

The quartz crystals often exhibit oscillatory growth banding which consists of alternating bands of milky, fluid inclusion-rich and clear fluid inclusion-poor bands. A preliminary fluid inclusion traverse across these growth bands from the 4th level of the Pride of the West mine showed no apparent difference in homogenization temperatures between band type. Although more data are needed to make specific conclusions, the data suggest that temperature is not the dominant factor responsible for the banding. The milky bands may represent zones of rapid crystallization versus relatively slow growth of the clear bands.

The relative low salinity of the fluids, high temperatures of homogenization (>200°C) and lack of vapor-rich inclusions, indicate that the total pressure (hydrostatic + lithostatic) of the system was great enough to inhibit fluid boiling. Using the boiling curve for a brine of 5 equiv. wt. % NaCl (Haas, 1971) and assuming boiling conditions slightly above the elevation of the Little Fanny mine (quartz homogenization temperature 240° C), a minimum depth of mineral precipitation of approximately 350 m is indicated. Since the Pride and Osceola mines are about 400 m below the level of the Little Fanny mine, a minimum depth of about 800 m for these deposits is suggested. A pressure correction may be applied to the homogenization temperatures to yield a closer approximation of the temperature of mineral deposition. Nash (1975) determined that, in general, a fluid inclusion pressure correction of +25°C is appropriate for deposits in the western San Juan Mountains. Cooper et al. (1980) determined that a pressure correction of approximately +30°C is appropriate for the Osceola deposit. Thus, a pressure correction of +25°C to +30°C for the Cunningham Gulch area lifts the range of entrapment temperature to about 225 to 340°C.

FLUID ORIGIN AND METAL TRANSPORTATION

The origin of hydrothermal mineralizing fluids and their contained metals has been the subject of continued research on ore deposits. Stable isotope studies indicate that fluids in most epithermal systems are dominantly of meteoric origin but may contain a minor magmatic component (Taylor, 1974). As well, oxygen and hydrogen isotopic studies of ore and gangue minerals from the San Juan Mountains indicate the fluids were composed of dominantly meteoric water (Doe et al., 1979). However, it has been suggested that up to about 5 percent magmatic contribution to the ore fluids would go unnoticed (White, 1974) because of dilution from mixing with a much greater volume of meteoric water.

Isotopic composition of leads in galenas from the San Juan Mountains appears to reflect the Precambrian basement rather than the volcanic host rock (Lipman and Doe, 1978; Doe et al., 1979). These data suggest that deeply circulating meteoric water scavenged lead from upper crustal Precambrian rocks. However, galenas from the Summitville District have a lead isotopic composition similar to that of the hosting volcanics rather than that of the underlying basement (Doe et al., 1979). These data indicate that lead was leached from a variety of rock types that occur in the San Juan Mountains. Thus, it has been assumed that other metals in the hydrothermal fluids also originated largely in this manner.

Metals were probably transported as either chloride or sulfide complexes existing within the hydrothermal fluid. Separation of metals into precious and base metal-rich zones roughly corresponding to a boiling level (Buchanan, 1981) may have been, in part, caused by a change in the dominant complexing agent (White, 1981) from Cl^-, in the lower base metal zone, to HS^- in the precious metal zone. Fluid inclusion data (Sillitoe, 1977) also suggest that fluids depositing base metals are somewhat more saline (>2 equiv. wt. % NaCl) than those which deposit precious metals (<2 equiv. wt. % NaCl).

MINERAL ZONATION

Burbank (1933), through his work in the Arrastre Basin, noted a zonal distribution to the kind of ores present in the northwesterly fissures. Immediately adjacent to the Silverton Caldera ring fault zone, the ores contain some specularite and are characterized by base metal sulfides of chalcopyrite, galena, and sphalerite in quartz and chlorite with local free gold associated with chalcopyrite. Within some fissures 1.5 to 3 km southeast (toward Cunningham Gulch), the ores also contain base metals, but argentiferous tetrahedrite (freibergite) becomes abundant in ores with barite, rhodochrosite, and manganiferous calcite in the gangue (Burbank, 1933). In this area, gold is less important and silver more important, with quartz and calcite still farther southeast from the fault zone (Burbank, 1933). This zonation agrees well with the observed mineral assemblages at the Pride of the West mine area and, in some respects, is analogous to the vertical zonation observed in epithermal deposits. The Pride of the West mine area falls within the silver-dominant zone of Burbank and within the zone where Mn-bearing minerals (pyroxmangite and Mn-bearing calcite) occur as gangue constituents.

Available assay data (Table 1) indicate that the replacement deposits at the Osceola mine are, in general, lower grade in terms of precious metal content than vein ore of the Pride or Little Fanny systems. The bulk of these replacement deposits are located at lower elevations and to the northwest of the Pride vein ore, but essentially along the same radial fracture system. Assay data for the Pride of the West mine indicate that high grade gold- and silver-bearing ore was removed from a large zone on the 3rd, 4th, and 5th levels in the southern portion of the mine, and that, below these levels, the ore is low in precious metals and high in base metal content. Production data from the Little Fanny mine, located approximately 400 m above the southern portion of the Pride of the West mine and apparently along the same radial fracture system, indicate that this mine contained very high grade silver ore with grades up to 50 oz./ton (1700 ppm; Table 1). Thus, in a gross sense, this zonation suggests that the Ag content of the ores tends to increase to the southeast and upwards within the mineralized system, although the high grade ore at the Little Fanny mine may be, in part, due to the supergene enrichment.

The amount of calcite in the Pride vein systems increases to the south, as Burbank (1933) noted for the district as a whole. A vein structure (now controlling a creek drainage) along a southeastern extension of the Pride radial fracture system is filled with barren coarse-crystalline rhombohedral calcite. This vein is about 1.5 km south of the Pride of the West mine and is up to 7.5 m (25 feet) wide. No sulfides were discovered in this vein, but it illustrates the great lateral extent of the Pride vein system, as well as the increasing amount of calcite gangue in this direction.

This zonation of mineral assemblages from northwest to southeast may represent a component of lateral fluid flow during the mineralization event. The changes in the observed mineral assemblages along the vein system roughly correspond to their relative solubilities in solution (e.g., Ag>Pb>Fe, Vaughn and Craig, 1978), and may represent precipitation from a cooling, chemically evolving fluid flowing dominantly upward through the vein system, but with a lateral component toward the southeast. If this hypothesis is correct, it implies fluid flow away from the Silverton Caldera structural margin. For the Creede deposit, a similar direction of fluid flow, away from the Creede Caldera, was documented by Barton et al. (1977).

COMPARISON WITH OTHER EPITHERMAL SYSTEMS

Recent detailed studies of hydrothermal ore deposits and modern ancient geothermal systems indicate that epithermal precious and base metal deposits are the fossil equivalents of high-temperature geothermal systems (e.g., White, 1981; Buchanan, 1981; Wetlaufer et al., 1979; Henly and Ellis, 1983). Active systems like Broadlands, New Zealand, and Steamboat Springs, Nevada, are similar to fossil systems in their content of rare elements, temperature range, pressure, fluid composition, isotope relationships, and mineralogy of ore, gangue, and alteration minerals. These active systems show a depth zonation of "epithermal" chemical elements with Au, As, Sb, Hg, Te, B, and some Ag, being selectively concentrated near the surface. In contrast, much Ag and base metals, probably along with Se, Te, and Bi, preferentially precipitate at somewhat greater depths and higher temperatures (White, 1981). Applying this concept of metal zoning with depth to epithermal deposits, suggests that some gold-rich deposits form at relatively shallow depth and low temperatures, and that these may grade downward into deposits enriched in Ag and base metals. These deposit types may be separated by a relatively barren zone, perhaps resulting from changes in the dominant complexing agent from Cl^- in deeper parts of the system to HS^- (White, 1981). Base-metal sulfides seem to be deposited preferentially in the deeper, more saline parts of active geothermal systems; other metals, such as Hg, Sb, Mn, W, and sometimes Au and Ag, more commonly are enriched in the typically less saline upper parts (Wetlaufer et al., 1979). This agrees well with fluid inclusion data from epithermal deposits which indicates that base metals typically are deposited from higher salinity solutions than precious metals (Sillitoe, 1977).

Buchanan (1981), in a comparative study of over 60 epithermal precious metal deposits, demonstrated a well-defined vertical zonation of the veins, from a lower high-temperature base-metal zone to an upper low-temperature precious metal zone, separated by a level of episodic fluid boiling (Fig.34). In addition, he recognized variations in alteration and gangue mineral assemblages. Buchanan (1981) noted that the level of fluid boiling does not remain constant in time nor space due to: (1) irregularities in paleotopography causing local differences in the elevation of boiling, (2) non-uniform isotherms and isobars (Ellis and Mahon, 1977), as well as (3) the superimposed effects of fracture self-sealing and re-fracturing, which can allow boiling at depths much greater than allowed under hydrostatic

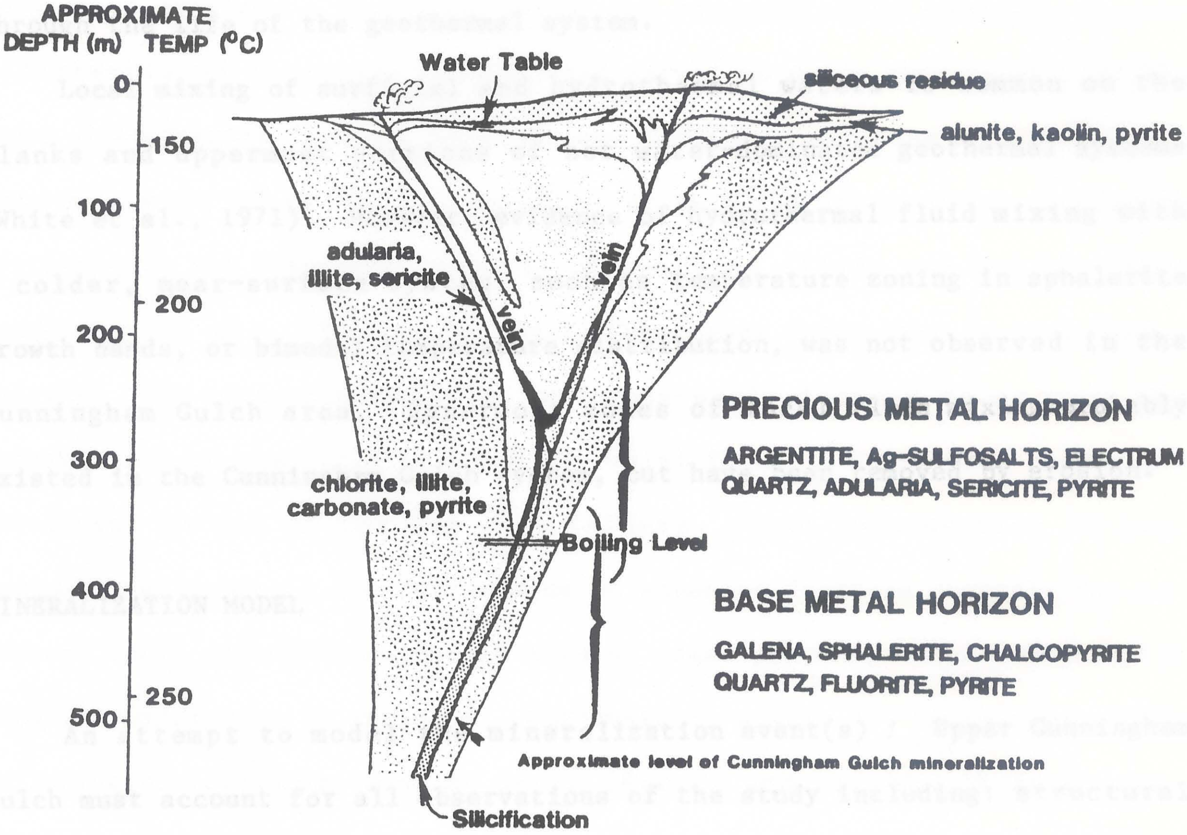


Figure 34. Generalized diagram of an epithermal vein. Note vertical changes in alteration assemblages and separation of precious and base metal horizons. The observed alteration assemblage, dominant base metal content of the veins, and fluid inclusion homogenization temperatures indicate that the ore deposits in upper Cunningham Gulch formed within the lower portion of a fossil geothermal system (modified from Buchanan, 1981).

conditions. Thus, fluctuation of the boiling level can result in vertically extensive overlap between base and precious metal mineralization through the life of the geothermal system.

Local mixing of surficial and hydrothermal waters is common on the flanks and uppermost portions of hot water-dominated geothermal systems (White et al., 1971). However, evidence of hydrothermal fluid mixing with a colder, near-surface system, such as temperature zoning in sphalerite growth bands, or bimodal temperature distribution, was not observed in the Cunningham Gulch area. Uppermost zones of local fluid mixing probably existed in the Cunningham Gulch system, but have been removed by erosion.

MINERALIZATION MODEL

An attempt to model the mineralization event(s) in Upper Cunningham Gulch must account for all observations of the study including: structural setting, nature of the spatially related vein and replacement deposits, nature and composition of the fluid responsible for alteration and mineralization, and spatial and temporal relationships of the mineral assemblages. Useful insights into ore deposit genesis can be derived from the joining of chemistry and fluid flow into a single predictive model (Cathles, 1981). The chemical alteration (mineral zoning, vein halos, etc.) that hydrothermal fluids have produced in ore deposits are the best record we have of the past history of fluid movement (Cathles, 1981).

Structural setting is most important to concentration of metals in the area, which are largely hosted within a caldera-collapse breccia. The nested San Juan and Silverton Calderas underwent a complex structural history which provided a favorable guide for significantly younger, highly differentiated intrusive magmas, and served to guide associated mineralizing hydrothermal fluids. Calderas are commonly the sites of geothermal systems, some of which are located at or near the intersection of fissure systems with the structural margins of calderas (Ellis and Mahon, 1977; Wetlaufer et al., 1979). The Upper Cunningham Gulch area is just such a setting; here mineralizing fluids were apparently focused at or near the intersection of the Pride of the West radial fracture system and the buried structural margin of the San Juan Caldera. This intersection of deep seated fractures is not only a zone of enhanced fracture porosity for increased fluid circulation, but is also an ideal place for heat (and metal?) supplying magmas to be emplaced. Mathematical models of the thermal regime following pluton emplacement at depth (Norton and Knight, 1977; Norton, 1982) have provided valuable insights into fluid circulation paths in freely convecting hydrothermal systems. Norton and Knight (1977) developed a model for a pluton of 920°C emplaced into host rock with permeability of 10^{-11} cm^2 (or 3 md). The configuration of the fluid circulation cells in these models may be used to yield a gross approximation of the fluid circulation path responsible for mineralization in the Cunningham Gulch fossil geothermal system (Fig. 35).

A highly differentiated stock responsible for driving the hydrothermal system in Cunningham Gulch is postulated at shallow depths below the gulch area. The gross scale of available gravity data over the western San

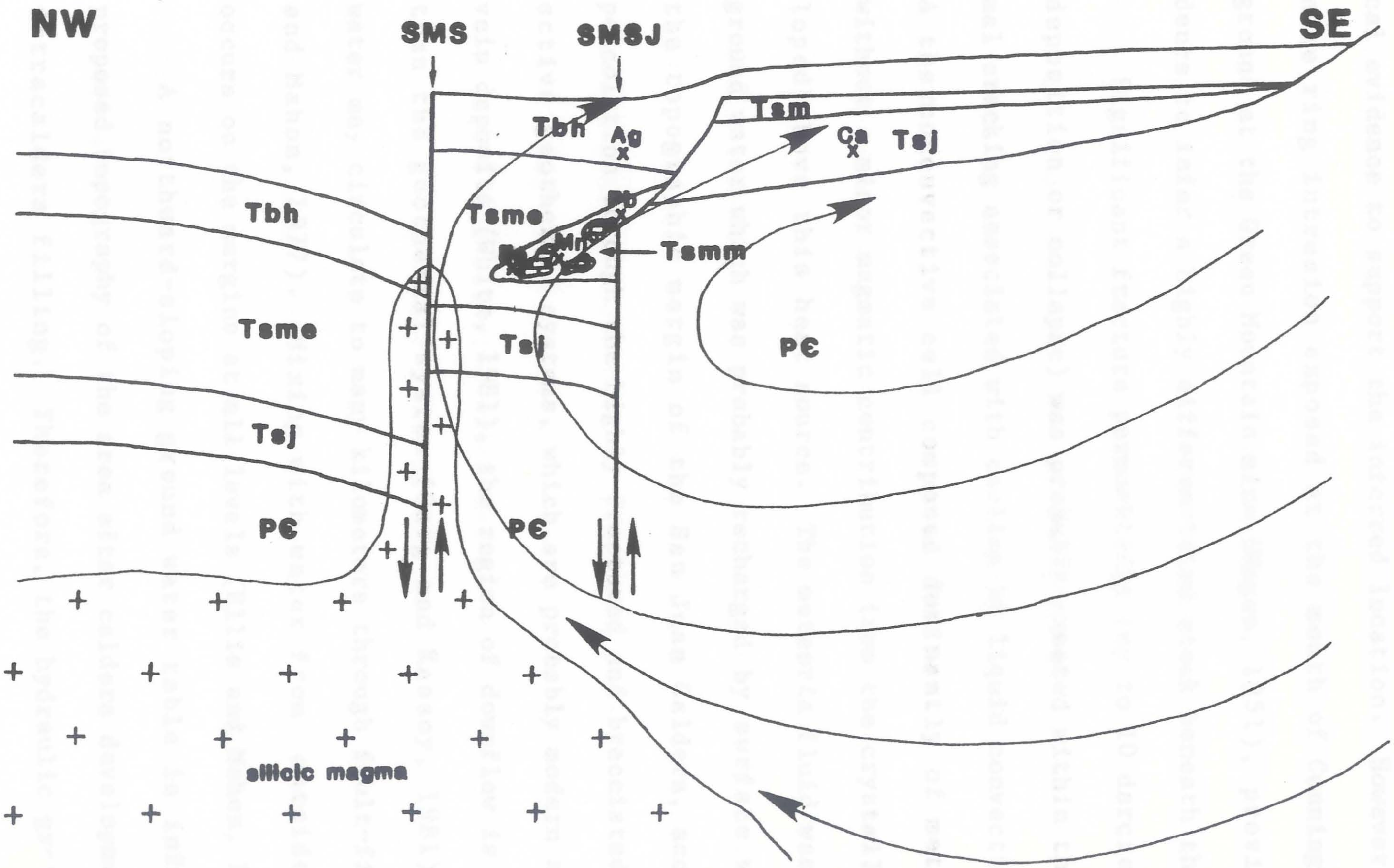


Figure 35. Schematic northwest cross-section of the southeastern margin of the nested San Juan and Silverton Calderas.

Hydrothermal fluids driven by thermoconvection (curved path lines) were focused dominantly upward within the nested structural margins of the San Juan (SMSJ) and Silverton (SMS) Calderas. Mineral zonation along the Pride vein system (plane of cross-section) indicates a component of lateral fluid flow towards the southeast. $\underset{x}{\text{Fe}}$ indicates elemental anomaly location. For explanation of other symbols, see Fig. 3.

Juan Mountains (Plouff and Pakiser, 1972) precludes any detailed geophysical evidence to support the inferred location. However, the quartz monzonite ring intrusion exposed at the mouth of Cunningham Gulch and underground at the Green Mountain mine (Hagen, 1951), provide reasonable evidence to infer a highly differentiated stock beneath this area.

Significant fracture permeability (up to 10 darcies prior to mineral deposition or collapse) was probably created within the intrusion by thermal cracking associated with cooling by liquid convection (Cathles, 1981). A thermoconvective cell composed dominantly of meteoric water, with or without a minor magmatic contribution from the crystallizing stock, developed above this heat source. The meteoric fluid was largely supplied by ground water which was probably recharged by surface waters flowing down the topographic margin of the San Juan Caldera, accompanied by downward percolation through the highly fractured and brecciated country rocks. In active geothermal systems, which are probably modern analogs to epithermal vein deposits (White, 1981), the region of downflow is considerably larger than the geothermal system (Garg and Kassoy, 1981), and local meteoric water may circulate to many kilometers through fault-fissure systems (Ellis and Mahon, 1977). Mixing with water from outside the thermal system occurs on the margins at all levels (Ellis and Mahon, 1977).

A northward-sloping ground water table is inferred to reflect the proposed topography of the area after caldera developments and subsequent intracaldera filling. Therefore, the hydraulic gradient in the area was probably directed northward, i.e. toward the structural margin of the Silverton Caldera and the proposed heat source. Fractured rock of 3 md permeability (a conservative value for fractured igneous rock) could sustain rapid flow rates of about 1 km per year (Garg and Kassoy, 1981).

When heated, the fluid became less dense and began to rise within the highly fractured and brecciated country rocks. The heated fluid was out of equilibrium with the subsurface rocks and began to react chemically. Because the solubility of most chemical species in an aqueous solution increases with increasing temperature, the concentration of most metallic species increased in the circulating acidic hydrothermal fluid. During this process, a major component of the metals was probably derived through prograde leaching of the country rocks, as documented for the origin of lead in western San Juan deposits (Doe et al., 1979). Major upward fluid flux was probably concentrated along the deep-seated fractures of the Silverton ring-fault zone, as major upflow routes are commonly through the same faults and fissured zones caused by the intrusion of the magma. However, the ring-fault zone of the Lake City Caldera was not everywhere a major conduit for hydrothermal fluids, but was so in areas near ring intrusions (Larson and Taylor, 1983). Since a ring-fault intrusion is present at the mouth of Cunningham Gulch, it is reasonable to assume that this region was a major upflow conduit. Ring intrusions also drive small convective systems (ex. northern boundary of the Lake City Caldera; Larson and Taylor, 1983), and perhaps the ring intrusion at the mouth of Cunningham Gulch was a great enough heat source to drive a local hydrothermal system responsible for mineralization in the area. Additional upflow routes may have been provided by the deep-seated fracture system of the buried San Juan Caldera structural margin. In highly fractured terrane, fracture induced, anisotropic porosity and permeability are usually much greater than permeability in pore space (up to 400 md in high level porphyry copper deposits, Garg and Kassoy, 1981) and, consequently, the fluid is strongly focused along the highly permeable fracture zones (Cathles, 1981). Thus, in addition to major upward flux, the hydrothermal fluid was probably channeled along the Pride of the West radial fracture system.

As the metal-charged mineralizing fluids continued to circulate within the conduit provided by the fracture network, ore was deposited in structurally and chemically favorable sites, such as steep tension fractures and low pressure areas within dilatant zones at the Pride of the West mine and the carbonate blocks at the Osceola mine. Fluid inclusion studies indicate mineralization took place below the level of fluid boiling in the lower portion of a fossil geothermal system, within the temperature range of 200 to 320 C. The chemistry of the mineralizing fluid evolved through time in response to wallrock reactions, local changes in pH, and chemical changes as minerals were deposited and removed from the fluid. The fluid was probably initially saturated with quartz and deposited a great amount of this mineral before the chemical environment evolved to allow deposition of the metallic minerals. Quartz deposition largely occurred in response to decreasing temperature and hydrostatic pressure, rather than a change in pH conditions because the solubility of silica in aqueous solutions is essentially independent of pH (Barnes, 1979).

Upon encounter with the carbonate blocks, the fluid spread laterally along zones of increased permeability with minor cross-flow provided by fractures. The lateral movement of fluid within the karstified limestone may have been aided by the relatively impervious volcanic "caprock" which surrounds the carbonate blocks. The acidic (Barnes, 1979) hydrothermal fluid reacted with the carbonate and rapidly added $CO_3^{=}$ to the fluid. This reaction increased the solubility of calcite (Barnes, 1979), and consumed hydrogen ions which resulted in a rise in pH (Vaughn and Craig, 1978). The increase in pH caused an increase in the activity of $S^{=}$ ions which decreased the solubility of the sulfides (Vaughn and Craig, 1978) and resulted in precipitation of the metallic minerals.

The sequence of mineral deposition from a chemically evolving fluid is manifested in a zonation of mineral assemblages both vertically and horizontally within the vein system. The recognizable mineral zonation occurs with respect to Fe, Mn, Pb, Ag, and Ca. Although Fe, Mn, and Ca are all retrograde soluble cations, Mn is more soluble than Fe in the Eh-pH range of the water stability field (Roy, 1980). As well, Pb is much more mobile than Fe under a wide variety of temperatures, pressures, and geological condition (Vaughn and Craig, 1978), and Ag^{+} is more stable than Pb^{++} in chloride complexes at 25 C (Helgeson, 1964). Thus, it is reasonable to assume that the more mobile cations would remain in solution longer, and, consequently, would tend to be displaced further along the flow path.

These elemental properties are in agreement with the observed zonation from northwest to southeast along the Pride vein system. An Fe-rich assemblage of hematite, magnetite, and abundant pyrite occurs only at the

Osceola mine in the replacement deposits. This Fe-rich assemblage is associated with abundant chlorite deposited early in the alteration event which mostly preceded ore deposition, further substantiating that the Fe-rich assemblage also formed early. In the southeastward direction along the vein system, this assemblage overlaps with a Mn assemblage present as pyroxmangite in both replacement and vein deposits at the approximate area between the Pride and Osceola mines. Continuing in this direction, pyroxmangite is no longer present and gives way to abundant galena which accounts for the bulk of the mined metal at the Pride of the West mine. The silver content of the ores increases vertically upward within the system at this locality as evidenced by the high grade silver ore recovered at the Little Fanny mine, approximately 400 m above the Pride deposit. Also, although less well defined, the silver content tends to increase from northwest to southeast along the vein system, as the replacement deposits are characteristically of lower silver grade than the Pride vein ore. Continuing in a southeasterly direction along the vein, calcite becomes an increasingly important mineral and completely fills a barren 10 m wide vein exposed on Green Mountain along an extension of the Pride vein system. This mineral assemblage zonation is interpreted as representing components of both upward and lateral fluid flow along the vein system from northwest to southeast, away from the structural margin of the Silverton Caldera and the proposed heat source (Fig. 35).

Hot-water dominated systems have a high potential for self-sealing by means of deposition of principally SiO_2 in outlet channels where temperatures decrease most rapidly (White et al., 1971). This mineral deposition complicates the original permeability of the system, and the tendency of the fault zone to become blocked with precipitated solids is counteracted by mechanical fracturing (Garg and Kassoy, 1981). Evidence of violent mechanical hydro-fracturing accompanied by SiO_2 deposition is present in a few localities in the mines as post ore-stage silicified hydrothermal breccia bodies. These intense, late events finally gave way to waning of the hydrothermal system and late-stage deposition of calcite. Extinction of the mineralization phase is marked by minor deposition of barite, representing the last mineral to be deposited.

EXPLORATION CONSIDERATIONS

Vein Deposits

The greatest control on vein-type mineral deposits in Upper Cunningham Gulch is structure. Exploration for these deposits requires detailed structural analysis supplemented by available chemical and mineralogic data. On a regional scale, the strongest veins of the Pride radial vein system follow a well-established trend, and most undiscovered veins which were created during the same volcano-tectonic event will probably continue to be discovered on this trend. Available assay data indicate the vein deposits are generally higher grade in terms of precious metal content than the replacement deposits, and that the Ag content of the vein material increases upward and southeastward along the vein system (Table 1). Thus, in general, exploration for high grade silver ore should be concentrated at higher elevation within the southern portion of the vein system.

Ore grade concentrations in hydrothermal vein systems commonly occur at the intersection of veins. This area is a focus of fluid flow and increases the possibility of mineral concentration from ore-bearing solutions. From analysis of vein trends on the surface at the Pride of the West mine area, it appears that the vein on which the Schneider open pit occurs and the vein on which the Little Fanny mine is hosted intersect in the area between the Schneider open pit and the Little Fanny mine. Both of these areas contained relatively high-grade precious-metal ore. This area of vein intersection is a likely target for a vein-type deposit and should be further explored.

Ore-bearing veins can pinch and die before reaching the surface (Buchanan, 1981). Non-outcropping ore shoots high within a hydrothermal system may be prospected by means of a low pH assemblage of alunite, sericite, illite, kaolinite, montmorillonite, or any of the kaolin minerals which form a cap or halo around individual ore shoots (Buchanan, 1981). If this assemblage is detected when prospecting at highest elevations within the area, a follow-up geochemical exploration program utilizing pathfinder elements such as As, Sb, Hg, Tl, and B may prove useful. However, geochemical exploration within the lower portion of a hydrothermal system, such as proposed for the Cunningham Gulch area, direct analysis for base and precious metals may be the best indicator of economic concentrations.

A geochemical traverse for a few metallic elements in the volcanic wallrock adjacent to the Osceola vein (Cooper et al., 1980) determined that the content of Fe, Pb, and Ag drops off rapidly away from the vein, whereas

Mn and Cu essentially show no variation. This trend is not systematic enough to be a useful exploration guide without additional data. However, the silicification halo developed about the Osceola vein has replaced up to 80 percent of the wallrock for up to about 1.5 m away from a 0.5 m vein, and thus increases target width by a factor of 6X (Cooper et al., 1980). This relationship generally holds true for many other veins in the area, although all veins with silicification halos do not necessarily host metals. Extent of the silicification halo is a function of vein permeability, wallrock permeability (related to fracture density), and volume of fluid flow rather than simply vein width. However, wider veins and vein intersections act as greater fluid flux conduits and are generally good exploration targets.

An extensive fluid inclusion study within the area may prove useful to assess areas which have undergone favorable geologic conditions to concentrate precious versus base metal minerals. Homogenization temperatures and salinities may be used to predict temperature and pressure of formation (and thus depth) within the hydrothermal system, as well as help identify areas of local fluid boiling and zones of local fluid mixing. Since isotherms fluctuate in both time and space over the life of a hydrothermal system (Ellis and Mahon, 1977), this complicates the simplified concept of base and precious metal horizons (Buchanan, 1981) and may result in complex overlapping mineralized zones.

Outside the San Juan Caldera structural margin at the Green Mountain and Highland Mary mines, ore is hosted largely within Precambrian gneiss of the Irving Formation. Inside the San Juan Caldera structural margin, these

Precambrian rocks were structurally dropped to an elevation in the hydrothermal system where they most likely host only base metals. Potential for metals hosted within Precambrian rocks should not be overlooked, especially outside the San Juan Caldera structural margin where these rocks remained at great enough elevation during the mineralization event to potentially host significant concentrations of precious metals.

Replacement Deposits

All of the carbonate blocks investigated are hosted within the Megabreccia Member emplaced as a caldera-collapse breccia and dominantly are comprised of intermediate composition volcanics of the San Juan Formation. Carbonate blocks exposed on the surface lie at about the same elevation (Fig. 3), near the contact with the underlying rhyolitic ash-flow tuff of the Eureka Member. Exploration efforts for replacement deposits should be concentrated within the megabreccia unit in the vicinity of metal-bearing veins. Carbonate blocks may also occur in an erratic spatial array anywhere within the caldera-collapse breccia because they were incorporated as megaclasts within mud-flow breccias of the San Juan Formation. The caldera-collapse breccia exists only inside the topographic rim of the San Juan Caldera, as the caldera wall was the source for this material. Exploration efforts for mineralized carbonate blocks within the intracaldera fill should be concentrated within the San Juan Caldera topographic boundary, near the basal contact of the Megabreccia Member in the vicinity of metal-bearing veins.

From a local exploration standpoint, an important criterion is the extent of the megabreccia unit beneath Green Mountain. Precambrian rocks are present on the first and third levels of the Pride of the West mine, and, if these exposures are in place, represent precaldera floor on which the Tertiary volcanics were deposited, indicating there is no potential for carbonate replacement bodies at or below this level to the east or south beneath Green Mountain. However, it is uncertain whether these Precambrian rocks are in place (Varnes, personal communication, 1982). If not, they also represent fragments which caved from the San Juan Caldera wall, and thus carbonate blocks may be present as well.

The carbonate blocks were originally incorporated within the San Juan Formation mudflow breccias, and the possibility of discovering mineralized carbonate blocks within in-place San Juan Formation outside the San Juan Caldera margin cannot be overlooked. This hypothesis is supported by the presence of carbonate blocks near the Precambrian contact, within the San Juan Formation of the present-day caldera topographic wall in Stony Gulch. Thus, it is possible that carbonate blocks (mineralized?) may be discovered essentially anywhere within the early Oligocene intermediate composition volcanics, but probably near the Precambrian contact and near the San Juan Caldera topographic wall. Mineralized blocks are to be expected only where intersected by a metal-bearing vein.

Cook (1952) field-tested a magnetometer exploration program for vein deposits with no apparent conclusions. However, a field magnetometer survey may be useful in exploring for mineralized replacement bodies due to the large tonnages involved. This technique may be especially useful for replacement bodies which contain significant amounts of hematite and magnetite, because of the great contrast in magnetic susceptibility between these deposits and the hosting volcanic rocks. The high Fe-bearing bodies are intimately associated with the more valuable sulfide replacement deposits. Thus, the coincidence of structural trend and localized magnetic anomaly is a good place to discover mineralized carbonate blocks and should be followed up with directional drilling. This method should first be tested over areas of known replacement bodies and the data compared with that of barren ground in the area.

SUMMARY AND CONCLUSIONS

Epithermal mineralization in Cunningham Gulch occurs within the Tertiary volcano-tectonic setting of the Western San Juan Caldera complex. The principal mines are located outside the structural margin of the Silverton Caldera and just inside the topographic margin of the larger and earlier-formed San Juan Caldera. Ore bodies are hosted within the intracaldera fill of the San Juan Caldera. The major ore host is the Megabreccia Member of the Sapinero Mesa Tuff; this unit originated as a caldera-collapse breccia which caved from the oversteepened wall of the San Juan Caldera, in response to caldera collapse.

Ore deposition was preceded by regional propylitic alteration and was accompanied by vein-associated quartz-sericite-illite-kaolinite-pyrite alteration and silicification. Mineralization may have been concentrated at the intersection of the Pride of the West radial fracture and the buried ring fracture zone of the San Juan Caldera.

Two types of ore deposits occur in the Pride area: (1) vein deposits and (2) carbonate replacement deposits. Vein deposits occur along an arcuate system of fractures radial to the nested calderas; this trend was apparently controlled by the shape of the San Juan Caldera wall. Economic concentrations occur discontinuously for over 275 m vertically and 425 m along the vein system. Vein deposits contain a greater concentration of precious metal than do the carbonate replacement deposits.

The carbonate replacement deposits consist of large blocks of the Mississippian Leadville Formation which are selectively replaced adjacent to metal-bearing feeder veins. The carbonate blocks were incorporated into mudflow breccias of the Tertiary San Juan Formation (32.1 my), and later emplaced (28 my) to their present structural position within a caldera-collapse megabreccia. Where a banded precursor carbonate fabric was present, the pervasive replacement process produced an irregularly banded "zebra" texture, dominantly composed of alternating bands of sulfides and quartz.

Deposition of quartz preceded base-metal mineralization in a general paragenetic sequence of sphalerite, chalcopyrite, and galena, although chalcopyrite may have been deposited contemporaneously with sphalerite. A zonal distribution to the mineralogic assemblages along the Pride of the West vein system suggests a component of lateral flow away from the structural margin of the Silverton Caldera. Fluid inclusions from vein-and replacement-type quartz and sphalerite indicate a 200 to 312°C (225 to 340° C, pressure corrected) range of precipitation from fluids containing generally <5% equivalent salinity.

The ore deposits in Upper Cunningham Gulch represent mineralization within the lower portion of a fossil geothermal system. This conclusion is supported by: (1) the proximity of the deposit to the subvolcanic basement with a thick overlying volcanic sequence at the time of mineralization (at least 800 m), (2) the high base-metal content of the ore, (3) the precious metal content is Ag-dominant and the Ag content increases upwards within the system, (4) the quartz-illite-sericite-kaolinite-pyrite alteration assemblage and lack of high-level alteration products, (5) lack of evidence for boiling in the system.

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VITA

James F. Hardwick, Jr. was born in Wichita Falls, Texas on September 9, 1955, the son of Patricia Ade and James Fredrick Hardwick. Following his 1974 graduation from Abraham Lincoln High School, Denver, Colorado, he entered The University of Colorado at Boulder, Colorado. After one semester at the university, he worked as a roughneck in Ft. Stockton, Texas, after which he re-entered school and received the Bachelor of Arts degree, with a major in Geology, in December, 1978. As a geologist, Mr. Hardwick worked with the Minerals Division of Conoco, Inc. in San Antonio, Texas, for a period of one year, and entered the graduate school of The University of Texas at Austin, Department of Geology in January 1980.

While attending the University of Texas at Austin, he held several positions as a Teaching and Research Assistant in the Department of Geology, as well as summer positions with Chevron Resources of Golden, Colorado, and Union Oil Co. of California. In November of 1982, he left graduate school to work for Gulf Oil Corporation in Houston, Texas, and returned to finish his thesis in the fall of 1983.

Mr. Hardwick was an active participant in the Society of Economic Geologists'(SEG) 1982 Field Conference on the relationship between mineralization and development of the San Juan volcanic fields. He presented the preliminary results of this study at the 1982 Annual

Meeting of the Geological Society of America in New Orleans, Louisiana. Mr. Hardwick is an Associate Member of the Society of Economic Geologists and a member of the Geological Society of America and the American Association of Petroleum Geologists.

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APPENDIX I

Fluid Inclusion Data

Measurement of the homogenization and freezing point temperatures were made on an adopted U.S.G.S. gas-flow heating/freezing stage (Fluid Inc.). Calibrated according to techniques discussed by Roedder (1976).

Vein-type Deposits

Sample #	Mineral	Inclusion Type	T-Homog.(C)	T-Freeze(C)	NaCl equiv. wt. %
7th dump	qtz	P	244	+0.7	0
	"	P	240		
	"	P	241		
	"	P	244	+0.7	0
	"	P	234		
	"	S?	254		
	"	S?	255		
	"	S?	256		
	"	P	227		
	"	P	227		
	"	P	227		
	"	P	242		
	"	P	233		
	"	P	234		
	"	P	244		
	"	P	214		
	"	P	234		
	"	P	200		
	"	P	201		
	"	P	201		
	"	P	215		
	"	S?	214		
	"	S?	214		
	"	P	214		
	"	S?	214		
	"	S?	215		
	"	S?	214		
	"	P?	276		

Sample #	Mineral	Inclusion Type	T-Homog.(C)	T-Freeze(C)	NaCl equiv. wt. %
	sphal.	P	239		
	"	P	242		
	"	P	253		
	"	P	250		
	"	P	249		
	"	P	236		
	"	P	236	-5.0	7.85
	"	P	221	-1.5	2.56
	"	P	232	-0.7	1.22
	"	P	236	-0.6	1.05
	"	P	241		
	"	P	238		
	"	S	273		
	"	S	262		
P 1-11	qtz	P	233		
	"	P	235		
	"	P	232		
	"	P	233		
	"	P	232		
	"	P	232		
	"	P	229		
	"	P	228	0	0
	"	P	233	-0.4	0.70
	"	P	244	0	0
	"	P	263	-0.3	0.53
	"	P	234	0	0
	"	P	235	-0.4	0.70
	"	P	228		
	sphal.	P	218	-0.8	1.39
	"	P	206		
	"	P	222		
	"	S	226	-1.4	2.4
	"	P	212		
LF	qtz	P	247	0	0
	"	P	235		
	"	S	241	+0.2	0
	"	P	240	+0.1	0
	"	P	240	0	0
	"	S	240	0	0
	"	P	242	0	0
	"	P	242	0	0
	"	P	241	0	0
	"	P	241	0	0
	"	P	241	0	0

Replacement-type Deposits

Sample #	Mineral	Inclusion Type	T-Homog.(C)	T-Freeze(C)	NaCl equiv. wt. %
Z-3	qtz	P	268		
	"	P	269		
	"	P	243		
	"	P	258		
	"	P	251		
	"	P	245		
	"	S	263		
	"	S	247		
	"	S	265		
	"	P	246		
	"	P	245		
	"	P	250	+0.6	0
	"	P	255		
	"	P	270	-0.4	0.70
	"	P	241		
	"	P	248		
	"	P	241		
	"	P	241	-4.8	7.58
	"	P	245	-0.3	0.53
	sphal.	P	233	-2.7	4.48
	"	P?	239	-11.6?	15.6
	"	S	233		
	"	S	228		
	"	S	237		
	"	S	238		
	"	P	228	-1.9	3.21
	"	P	225	-1.2	2.06
	"	P	225	-1.7	2.89
	"	S	226	+0.6	0
	"	S	225	+0.6	0
	"	S	235	+0.6	0
	"	P	---	-0.7	1.22
	"	P	---	-0.2	0.35
S-12	qtz	P	279		
	"	P	300		
	"	P	303		
	"	P	312		
	"	S	323		
	"	P	---	-1.3	2.23
	"	P	---	-1.3	2.23
	"	P	---	-1.4	2.40
	"	P	240	0	0

Sample #	Mineral	Inclusion Type	T-Homog.(C)	T-Freeze(C)	NaCl equiv. wt. %
	qtz	P	239	0	0
	"	P	242	0	0
	"	P	222	-0.3	0.53
	"	P	222		
	"	P	228	0	0
	"	P	240	0	0
	"	P	235	0	0
	"	P	234		
	"	P	258		
	"	P	241		
	"	S	249		
	"	S	257		
	"	P	262		
	sphal.	P	269	-0.6	1.05
	"	P	253	-0.5	0.87
	"	P	268		
	"	P	210?		
	"	P	280	-0.3	0.53
	"	P	282	0	0
	"	P	283		