

GEOLOGICAL CHARACTERISTICS OF THE SUMMITVILLE MINE AND THEIR ENVIRONMENTAL IMPLICATIONS

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INTRODUCTION

The Summitville mine, located in the southeastern San Juan Mountains of southwest Colorado (Fig. 1), has received considerable attention as a result of environmental problems related to mining activities. Summitville Consolidated Mining Company, Inc. (SCMCI), a subsidiary of Galactic Resources of Canada, operated an open-pit gold mine at Summitville (Fig. 2) during the period from 1985 to 1992. Environmental remediation was underway by SCMCI when the mine was abandoned in December, 1992, and SCMCI declared bankruptcy. The Environmental Protection Agency (EPA) took over the mine site under Superfund Emergency Response authority, and intensified remediation efforts. Summitville was added to the Superfund National Priorities List in May, 1994. The EPA continues to monitor the site and treat acid- and metal-rich waters emanating from the mine. The EPA has plugged the major acid-mine drainage sources (the Reynolds and Chandler adits), and has moved several waste piles back into the open pit including the Cropsy waste dump, Beaver mud dumps, and Cleveland Cliff tailings. Cyanide solutions in the heap leach pad were also treated by the EPA.

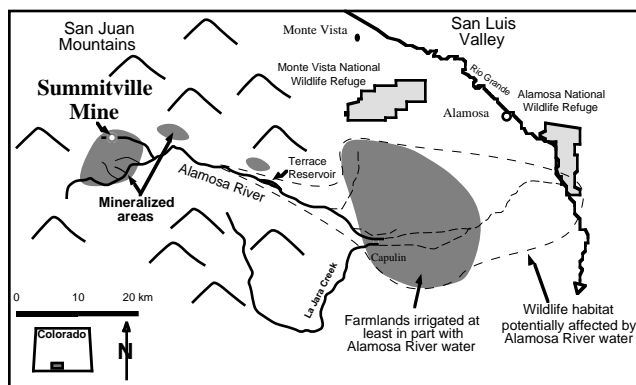


Figure 1. Location of the Summitville mine, Alamosa River, and adjacent San Luis Valley, SW Colorado.

Concerns remain about the possible short- and long-term adverse effects to the environment resulting from the abandoned mining operations. Geologic characteristics

of the Summitville mine are an important control on the generation of acid drainage, the dominant long-term environmental problem at the site. A thorough understanding of the environmental geology of the Summitville gold-silver-copper deposit is necessary to: (1) develop the most effective remediation strategies for the Summitville site, and (2) help predict, mitigate, and remediate potential environmental problems at future proposed mine sites with similar geologic characteristics. This paper summarizes the geologic characteristics of the Summitville mineral deposit and their effect on the environment. Most of the conclusions in this paper were drawn from Gray et al. (1994) and Plumlee et al. (1995a). Additional geologic descriptions of Summitville are provided in Steven and Ratté (1960), Perkins and Nieman (1982), Stoffregen (1985; 1987), Gray et al. (1993), and Gray and Coolbaugh (1994).

GEOLOGIC CHARACTERISTICS

The processes that formed the gold-silver-copper deposit at Summitville also directly relate to the generation of both natural and mining-related acid drainage from the site. Summitville is located in the southeastern portion of the mid-Tertiary San Juan volcanic field, a thick section of volcanic rocks composed in its lower portions of andesitic volcanics and related rocks erupted from numerous stratovolcanoes, and in its upper portions of andesitic to rhyolitic ash flow sheets erupted from numerous calderas (Steven and Lipman, 1976).

South Mountain Volcanic Dome

The Summitville deposit is hosted by the South Mountain volcanic dome (Figs. 3, 4) and formed about 22 million-years ago as a direct result of the magmatic processes that generated the dome (Steven and Ratté, 1960; Perkins and Nieman, 1982; Stoffregen, 1985, 1987; Rye et al., 1990; Gray and Coolbaugh, 1994). The volcanic dome is composed of quartz latite lavas that contain abundant silica and coarse grained crystals of feldspar. The quartz latite lavas were extruded from a narrow feeder zone



Figure 2. Aerial view of the Summitville mine in 1991 looking southwest (photo by IntraSearch, Inc.)

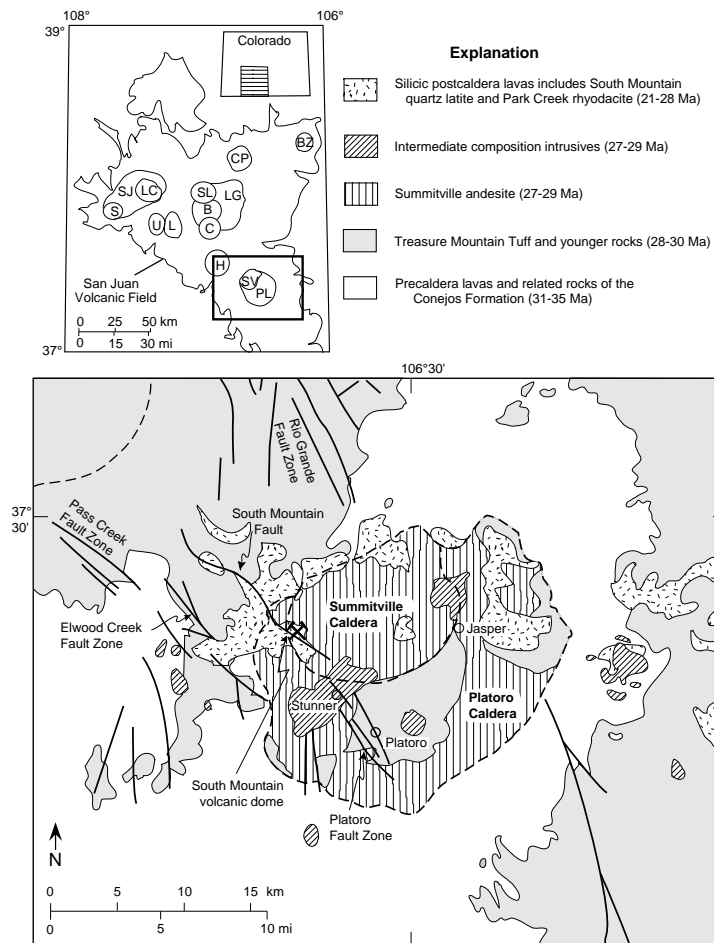


Figure 3. Location map showing the outline of the San Juan volcanic field and calderas within the field (generalized from Lipman, 1975). Age data are from Steven et al., (1967), Lipman et al. (1970), Lipman (1975), Mehnert et al. (1973), and Perkins and Nieman (1982). Calderas shown are abbreviated: B-Bachelor, BZ-Bonanza, C-Creede, CP-Cochetopa Park, H-Mount Hope, LC-Lake City, LG-La Garita, L-Lost Lake, PL-Platoro, S-Silverton, SJ-San Juan, SL-San Luis, SV-Summitville, and U-Ute Creek. Inset figure geology modified from Lipman (1975) and Steven and Lipman (1976). X - Location of the Summitville deposit. Reprinted from Gray and Coolbaugh (1994).

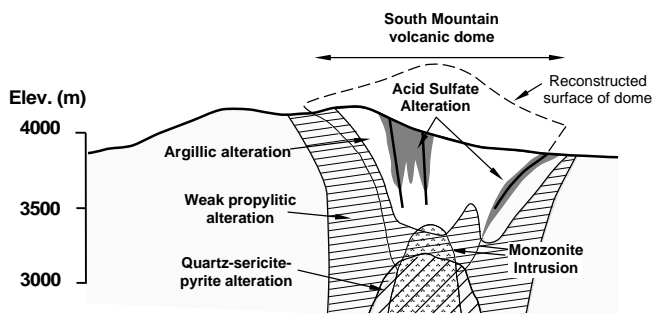


Figure 4. Generalized cross section of the South Mountain volcanic dome showing the geology and distribution of altered rocks. Modified from Perkins and Nieman (1982) and Enders and Coolbaugh (1987). Reprinted from Plumlee et al. (1995a).

(Steven and Ratté, 1960) and pushed outward to form a typical mushroom-shaped silicic lava dome (Fig. 4). Rocks along the contact between the dome lavas and surrounding andesitic lavas were brecciated, creating a zone of higher permeability that is an important control on groundwater movement at the site.

Formation of the Summitville Deposit

As part of the volcanic dome-forming process, additional magmas were intruded into the area beneath the dome. As these magmas crystallized, they released hot gases rich in sulfur dioxide. The gases rose along fractures in the quartz latite volcanic dome and eventually condensed in the upper portions of the dome, producing fluids rich in sulfuric acid that extensively leached and altered the quartz latite to an advanced argillic alteration assemblage (Fig. 4). The greatest amounts of leaching resulted near fractures and left only silica and pyrite in the rock; this alteration zone is called the vuggy silica zone because of the well-formed voids left by the removal of large feldspar crystals (Fig. 5). Progressive neutralization of the acidic gas condensates outward from the vuggy silica zones altered the quartz latite to successive quartz-alunite, quartz-kaolinite, clay (containing illite, montmorillonite, and pyrite), and propylitic (containing chlorite, pyrite, and some calcite) assemblages (Fig. 6). The propylitically altered rocks are rare in the open pit area, but are more common south and east of the mine.

The advanced argillic alteration event was important in the formation of the Summitville deposit because it provided open-space porosity for subsequent sulfide and gold deposition. The advanced argillic rocks are also environmentally significant because these rocks have a greatly reduced capacity (as compared to fresh, unaltered quartz latite) to consume acid in natural and mine drainage. Propylitically altered rocks contain minor amounts of carbonate minerals that can help neutralize acid water; however, the propylitically altered rocks are in such small amounts in the Summitville open pit that they likely have

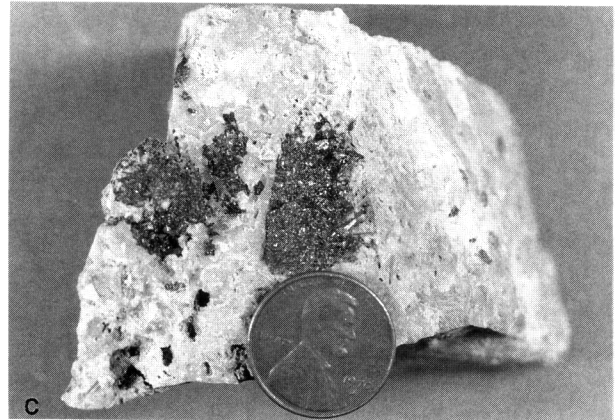
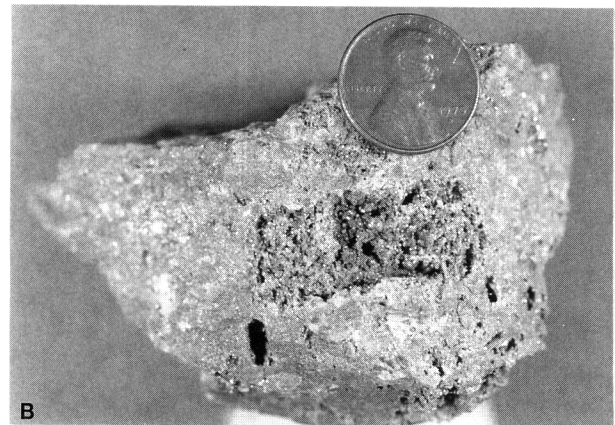
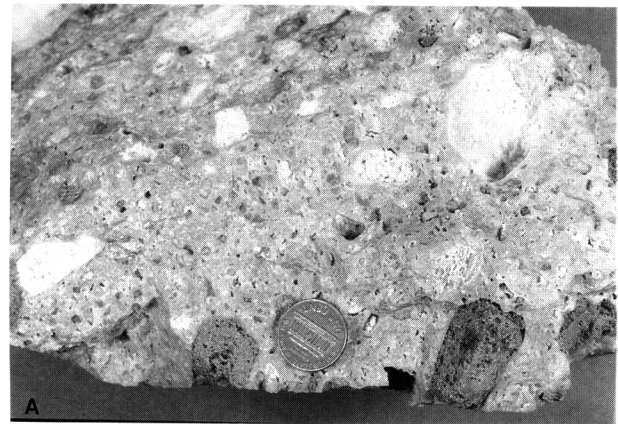


Figure 5. Photos showing pyrite (A and B) and enargite (C) replacing feldspar phenocryst sites in vuggy silica from the Summitville deposit. Sulfide minerals in unoxidized ore zones are responsible for generation of most of the acid waters. From Gray et al. (1994).

had relatively little mitigative effect on acid-mine drainage at the site.

Following the period of intense acid leaching by magmatic gas condensates, Cu- and As-rich sulfide minerals were deposited in the highly altered rocks by hot hydrothermal fluids (about 100-250° C) also derived from crystallizing magmas below the Summitville deposit. Minerals deposited in this assemblage include pyrite,

marcasite, enargite, native sulfur, covellite, chalcopyrite, tennantite, and minor barite, sphalerite, galena, and various phosphate minerals (Stoffregen, 1987; Gray and Coolbaugh, 1994). The greatest amounts of sulfide minerals (generally 1-5 %) are found in rocks altered to vuggy silica and quartz-alunite (Fig. 6) because hydrothermal fluid flow was focused in these highly permeable zones; however, appreciable Cu-As sulfide minerals were also deposited in the other alteration zones. During the final stages of the formation of the mineral deposit, several hydrothermal breccias were generated, in which magmatic fluids were explosively released from depth into the volcanic dome; these breccias also contain minor sulfide minerals. Finally, late-stage sulfide-rich veins were deposited in fractures cutting the highly altered rocks (Gray and Coolbaugh, 1994).

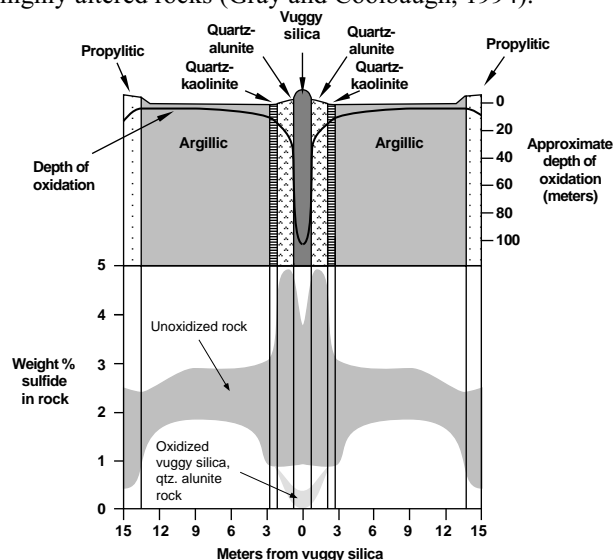


Figure 6. Generalized alteration zoning along from fractures in the South Mountain quartz latite, showing approximate depth of oxidation (upper plot) and ranges of reduced sulfur in weight percent (lower plot). From Plumlee et al., 1995a), based on data from Gray et al. (1994).

Structure

The importance of structures as controls on the distribution of alteration and mineralization zones is illustrated by a map of gold grades of the Summitville mine (Fig. 7); the highest gold grades generally follow the vuggy silica zones of most intense alteration. Vuggy silica zones and coincident gold ore zones radiate outward from the core of the deposit (Enders and Coolbaugh, 1987; Fig. 7). Three northwest fracture trends are present that dip steeply from 65° to vertical. A N30°W ± 20 trend is typified by narrower zones with higher Au grades, such as the Little Annie and Tewksbury zones. A second strong NW structural trend is characterized by N60°W zones that are wider and longer, but have lower than average Au grades; examples are the Highland Mary, Nellie, and Copper Hill zones; these N60°W zones parallel the South Mountain fault on the southwest side of the deposit. A third, less well-

developed NW trend strikes N5-10°W and is typified by the Bonus vein east of the Little Annie vein. These three trends intersected near the center of the deposit to form a large ore body approximately 150 by 400 m, the Highland Mary-Copper Hill zone. In addition, some west-trending arcuate ore zones such as the Dexter vein form concentric structures around the core of the deposit on its northern side (Fig. 7). The radial and arcuate structures probably resulted from emplacement of magmas at depth beneath the dome. The well-developed, N60°W-trending structures probably developed along pre-existing regional fractures that were reopened during the Summitville alteration and mineralization.

In summary, original dome structures focused alteration by magmatic gas condensates. The alteration zones and some later cross-cutting structures have, in turn, greatly influenced post-mineralization groundwater movement and the extent of weathering prior to mining.

ENVIRONMENTAL GEOLOGY

A fundamental environmental concern at Summitville is the presence of abundant sulfide-bearing rocks with the potential to generate highly acidic and metalliferous waters during surface weathering (Fig. 5). Geologic units of environmental concern are all sulfide-bearing rocks (primarily pyrite, marcasite, and enargite) including the highly permeable vuggy silica zones, quartz, alunite and quartz kaolinite zones, and argillic rocks. Volumetrically minor late-stage sulfide-rich veins and hydrothermal breccias are also important, but are considered insignificant acid-generators in comparison to the large volumes of sulfide-bearing vuggy silica, quartz-alunite, quartz-kaolinite, and argillic rocks. Open-pit mining exposed large volumes of sulfide-bearing rocks to weathering. When these rocks weather, the sulfide minerals are oxidized forming sulfuric acid, which then leaches metals from the surrounding rocks, primarily from the sulfide minerals. There is little carbonate or fresh rock to buffer (or neutralize) any acid-rich solutions generated during weathering. Components of environmental concern are rocks in the open pit, heap-leach pad, waste piles, and geologic structures in and around the mine site (Fig. 8). The interaction between these rocks and surface and groundwaters is also important for understanding environmental problems.

Open Pit

The primary environmental problem related to the open pit is the formation of acid- and metal-rich waters. Most of these waters emanate as acid-mine drainage from small seeps in and around the open pit, and larger volumes of effluent from mine adits connected to underground workings, such as the Reynolds adit. Adits and underground workings located at Summitville were

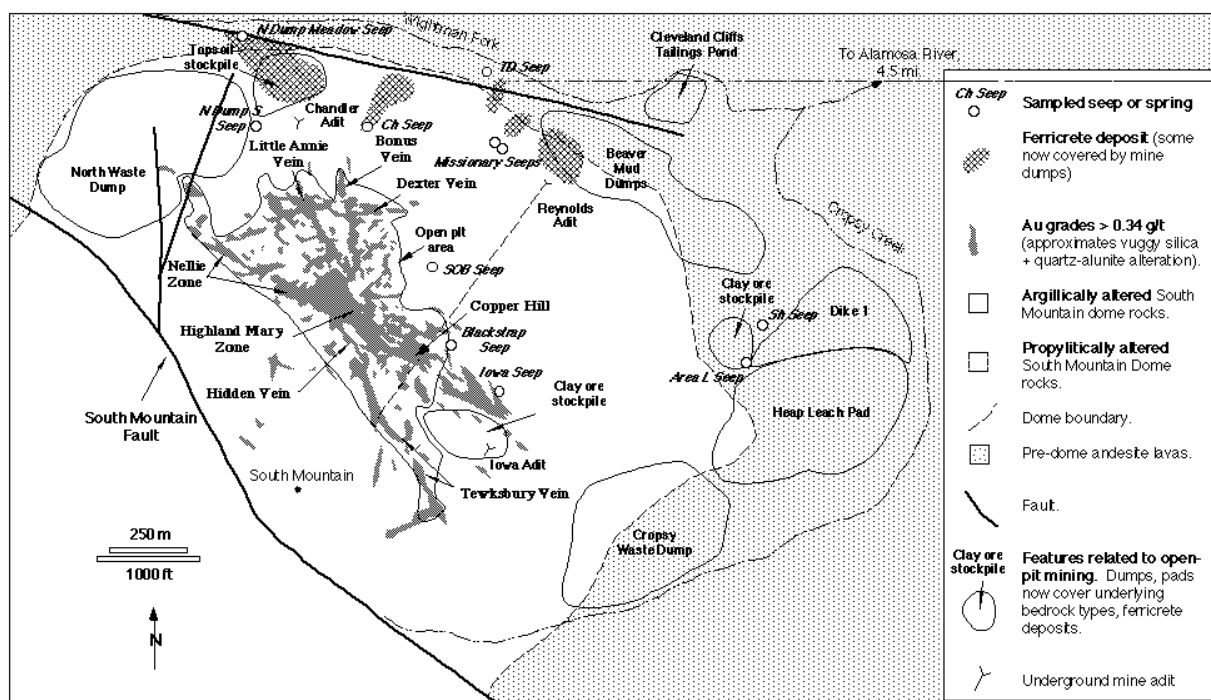


Figure 7. Generalized map of the Summitville mine site showing geologic features (major alteration and ore zones, ferricrete deposits) in relation to past and recent mine features. Also shown are the locations of active seeps sampled for chemical analysis (see Plumlee et al., 1995b). The distribution of argillic and propylitic alteration was taken from a surficial geologic map prepared by Mike Perkins and Bill Nieman for the Anaconda Company in the early 1980's. The distribution of acid sulfate alteration (vuggy silica and quartz alunite zones) is approximated by gold grades greater than 0.34 grams per ton (after Gray and Coolbaugh, 1994). The location of ferricrete deposits is approximate based on distributions observed in aerial photographs taken of the site in 1968 and 1980 by Intra-Search, Inc; many of the deposits are now covered by material from the recent open pit mining operations. Figure from Plumlee et al. (1995a).

developed during early underground mining of high-grade gold zones in the late 1800's and early 1900's (Steven and Ratté, 1960). Acid-mine drainage emanated from the Reynolds adit prior to open-pit mining, but the acidity and metal loadings increased after open-pit mining began (Plumlee et al., 1994).

Formation of metal-rich secondary salts in the open pit and throughout the mine site is also a potential environmental problem because such salts may release metal into surface water when they dissolve (Flohr et al., 1995). Minor pools and puddles of acidic and metalliferous water were observed in the open pit and as these acid waters evaporate during dry periods, they precipitate a complex suite of soluble secondary salts that contain metals and acid in solid form until they dissolve during the next period of rain or snowfall (Plumlee et al., 1995b). Secondary salts were found as surficial coatings on rocks within the open pit and waste dumps, as coatings on fractures in rocks of the open pit walls, and as disseminations within sediments throughout the mine site

(Flohr et al., 1995; Plumlee et al., 1995a). In the area beneath the pit, these salts are abundant near airways that allow for evaporation, such as in and near mine workings and in fractured rock immediately beneath the open pit. Soluble secondary salts are a significant environmental concern at Summitville due to their abundance and the ease with which they can liberate metals and acid into the environment simply by dissolving in surface water.

To remediate environmental problems in the open pit, the SCMCI initiated, and later the EPA continued, reducing the amount of acid-mine waters draining into the Wightman Fork of the Alamosa River by treating some of the waters emanating from the Reynolds adit, and then releasing waters with improved water quality. The EPA then plugged the Reynolds and Chandler adits in 1994, eliminating acid-mine drainage from these sources, which were the major effluents at the mine. In 1995, the EPA filled the open pit with material from several waste piles at the mine site in order to reduce surface oxidation and acid water production in the

open pit. Filling the open pit also reduced the potential for the formation of metal-rich secondary salts in the pit.

Heap Leach Pad

Environmental concerns of the heap leach pad are leaks and seeps of potentially acidic and cyanide-bearing solutions in and beneath the leach pad, and the remaining sulfide-bearing rocks on the leach pad with the capacity to generate additional acidic and metalliferous waters during weathering. The leach pad began to leak into an underground drainage system shortly after being installed. Most of the material added to the leach pad was oxidized, silicified ore. This oxidized ore was encountered at shallow levels of the deposit and contained few sulfide minerals, probably averaging less than one percent by volume. However, as open-pit mining progressed more sulfide-rich ore was encountered and added to the heap leach pad. Some partially oxidized sulfide-bearing ore also was added to the pad during mining.

Precise determinations of the amount of sulfide on the leach pad are difficult, but it is estimated that about 70 percent by volume of the material on the pad is oxidized ore, 25 percent by volume is partially oxidized sulfide-bearing ore, and 5 percent by volume is unoxidized sulfide-rich ore. Therefore, total sulfides in the material on the leach pad probably do not exceed one percent by volume. However, because there is little buffering capacity in the material on the leach pad, rocks contained on the leach pad could generate significant acid during weathering. Conventional agglomeration of ore using lime and cement was not carried out at Summitville. Lime was added to ore as it was added to the leach pad as a pH control of the cyanide solution. This lime may increase the buffering capacity of the heap leach pad, but its long-term buffering capacity is presently unknown.

To remediate environmental problems on the heap-leach pad, SCMCI captured and treated water leaking beneath the leach pad between 1986-1992. The EPA has continued to monitor, capture, and treat waters leaking from the heap leach pad, as well as detoxify cyanide remaining on the heap leach pad. The EPA is also evaluating a procedure to cap the heap leach pad to reduce the amount of surface water flowing into it, and thereby reducing potential acid-water generation from sulfide-bearing rocks located there.

Waste Piles

Waste rocks at the Summitville mine site were located in the Cropsy and North waste piles (Fig. 8). Most environmental mine waste concerns were related to the Cropsy waste pile that was constructed in the relatively small Cropsy Creek, part of the larger Alamosa River (Fig. 1). The SCMCI diverted Cropsy Creek

around this waste pile and constructed a drainage system beneath the waste, but the diversion and drain did not function properly. Flow of spring and surface waters into the Cropsy waste pile reacted with sulfide-bearing rocks producing acidic, metalliferous waters. These waters drained into Wightman Fork and eventually the Alamosa River. In contrast, the North waste pile is a less significant problem because surface and spring waters have been effectively diverted around it, but presently, minor acid drainage emanates from the North waste pile.

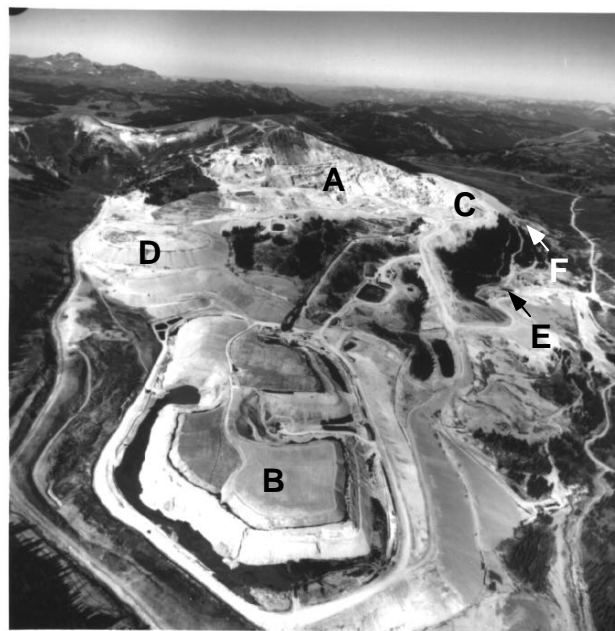


Figure 8. Aerial view of the Summitville mine looking southwest showing open pit (A), heap leach pad (B), north waste pile (C), Cropsy waste pile (D), Reynolds adit (E), and Chandler adit (F) (photo by IntraSearch, Inc.). From Gray et al. (1994).

The majority of waste in the piles is sulfide-bearing and oxidized argillic rocks, with lesser breccia waste (also argillic), and propylitic rocks that are also typically sulfide-bearing. Argillic rocks contain about 2 to 3 volume percent sulfide minerals. Silicified rock was rarely mined as waste, but due to the small-scale nature of some silicified ore zones, as much as 10 volume percent of the waste piles may be silicified rock. Minor amounts (less than 1 volume percent) of sulfide ore minerals should be expected in the dump material due to the composition of the late-stage breccias (Gray and Coolbaugh, 1994) and because minor silicified ore material is in the piles. Similar to the open pit and heap-leach pad, the total amount of sulfide minerals in the waste piles is small; however, acidic waters can form rapidly because of the inability of surrounding rocks to buffer the solutions. As discussed for the open pit, formation of soluble salts in the waste piles also may be

an important factor affecting metal contents and acidity of waters in contact with waste material (Flohr et al., 1995).

To remediate problems associated with the waste piles, the EPA moved the Cropsy waste pile and other wastes (the Beaver mud dumps and Cleveland Cliffs tailings) back into the open pit (Fig. 7). The waste in the open pit was capped and contoured to reduce infiltration of surface waters that may react with sulfide-bearing rocks, generating additional acid waters.

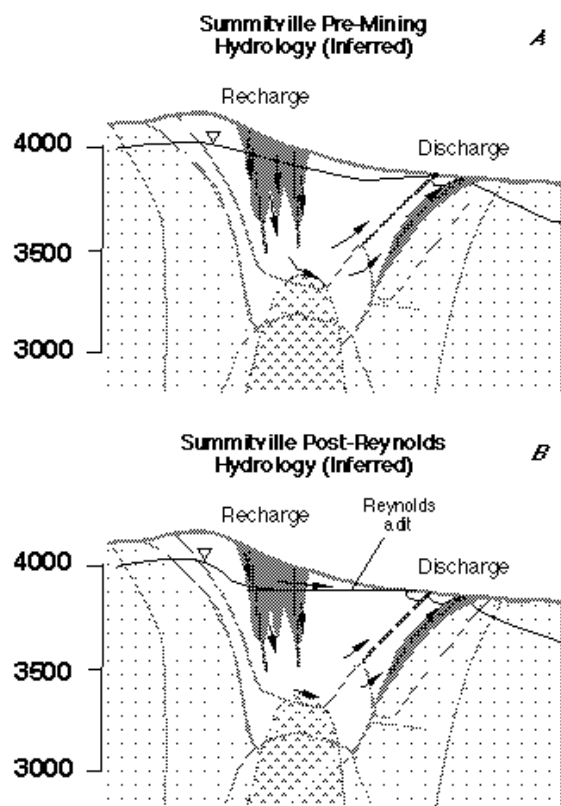


Figure 9. A. Generalized cross section showing inferred hydrology of the Summitville mine prior to underground mining. Solid black line with triangle indicate the water table. Arrows indicate possible groundwater paths. B. Generalized cross section showing inferred hydrology of Summitville resulting from underground mining. Solid black line with triangle indicate the water table. Arrows indicate possible groundwater paths. Flow was reduced from natural discharge points due to increased flow from the Reynolds adit. From Plumlee et al. (1995a).

Structures

Fracture control is an important aspect of many ore deposits, including Summitville. Fracture control was not only important for localizing Summitville advanced argillic alteration and mineralized zones, but is also an important component affecting modern

groundwater hydrology (Fig. 9). The interaction between water and sulfide-bearing rocks along permeable fractures has led to acid-water generation and water-quality degradation and is an important environmental concern at Summitville.

Silicified rocks, most importantly the highly permeable vuggy silica zones, closely follow fractures in the open pit and significantly affect local groundwater flow (Fig. 9). During weathering highly metalliferous and strongly acidic solutions form when surface and groundwaters contact sulfide-bearing rocks, primarily in the more permeable ore zones. These waters flow along the permeable fractures in the deposit. Supergene oxidation to depths of as much as 100 m (300 ft) in highly permeable vuggy silica (Fig. 6) provides evidence of the importance of the interaction of water with permeable fractures.

The location of seeps and springs on South Mountain suggest a relationship between fractures and hydrology at some localities, although many details of the relationship between fractures and groundwater flow remain unresolved. Strong northwest-striking fractures that control the location of mineralized zones in the open pit also appear to control groundwater flow north and south of the ore deposit. A southerly extension of the Nellie-Highland Mary-Iowa zones probably controls the location of springs south of the open pit in Cropsy Creek.

Many ferricrete deposits in and around the mine indicate locations of past and present water seeps. Near the base of South Mountain and northwest of the open pit, a large iron bog or ferricrete deposit was found during drilling; this deposit is located at the projected intersection of the Little Annie vein and Missionary fault (Gray et al., 1993). The deposit is as much as 15 m (50 ft) thick, suggesting that iron-rich groundwaters had at one time passed through the Summitville deposit and surfaced as springs in this area. This area is presently concealed because it is overgrown with vegetation and did not appear to be actively seeping groundwater prior to plugging of the Reynolds adit. Smaller ferricrete deposits are located on the north slope of South Mountain near the Dexter adit, just outside the open pit. These deposits lie along an intersection of northeast-striking fractures in the open pit and the Dexter zone. The location of these seeps and ferricrete deposits suggests that these fractures have influenced groundwater hydrology and that acid drainage existed prior to any mining.

Underground mine workings significantly changed the groundwater hydrology. Adits, crosscuts, and drifts have likely diverted waters away from their normal prehistoric discharge points, possibly explaining why iron bogs northwest of the open pit are no longer active. At one time, the Chandler adit was clearly discharging water because a stand of dead trees and

ferricrete deposits are present near the adit. Prior to open-pit mining and plugging of the Reynolds adit, the Chandler adit was dry, but the younger and topographically lower Reynolds adit has a significant acid-mine drainage discharge, some of which has drained into the Wightman Fork of the Alamosa River (Fig. 1). It is possible that underground mining diverted groundwater flow from the Chandler to the Reynolds workings.

Throughout open-pit mining, acid waters continued to discharge from the Reynolds adit. The water quality of the Reynolds effluent had shown increased metal loadings (e.g. copper) as mining progressed (Golder and associates, 1992; Plumlee et al., 1994). The deterioration of the Reynolds effluent was probably a result of increased surface area exposure of sulfide-bearing rocks, and groundwaters flowing into different fractures. Many of the permeable, oxidized vuggy silica zones were removed as mining continued, resulting in flow of surface and groundwaters into new fractures that were generally less oxidized. In summary, fractures control groundwater flow in the open pit and outside its boundary. Underground workings intercepted these fracture-controlled groundwaters and diverted them to new discharge locations, the most significant of which was the Reynolds workings. Open-pit mining removed zones of oxidized vuggy silica, forcing waters to follow more sulfide-rich fractures, adding to water degradation. Therefore, fractures and underground workings affected the acid-mine drainage location and output. Some of the metal- and acid-rich effluent from Summitville drains into the Wightman Fork of the Alamosa River.

To slow seepage from the mine site, the EPA plugged the Reynolds and Chandler adits, which ceased discharge from these major sources of acid mine drainage, but effectively increased the water table elevation. Sealing these adits resulted in some additional leaks including seeps north of the open pit, along the Missionary fault, and along the volcanic dome contact east of the open pit. Although seep waters are highly acidic and metalliferous, overall the acid and metal concentrations in these seep waters have decreased significantly as a result of the EPA's remediation efforts; however, such seeps are a source of acid and metal that may require long-term monitoring and possibly treatment.

CONCLUSIONS

Altered and mineralized rocks at Summitville contain relatively small amounts of sulfide minerals, generally less than 5 percent. Yet significant acid-mine drainage problems have resulted at Summitville primarily because the surrounding rocks were pervasively altered during hydrothermal processes forming highly

siliceous and argillized rocks with little capacity to buffer acidic waters generated during weathering. Concerns continue because altered and mineralized rocks in the open pit, heap leach pad, and waste piles are exposed to oxygenated waters during surface weathering and have long-term potential to generate additional acid- and metal-rich waters. Subsurface structural control and underground mine workings at Summitville also affect water quality and the location of acid-mine drainage output. Results from Summitville underscore the need for careful geologically constrained acid-generation studies of ore and altered rocks at all potential mine sites, a current practice that was overlooked at Summitville. Economic geology studies of mineralogy, structure, and alteration are a critical initial process in an environmental characterization of a mineral deposit. Thus, economic geologists can play an important role in understanding and predicting unique effects of various types of mineral deposits and resource development on surrounding environments.

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