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GEOLOGIC FRAMEWORK AND ENVIRONMENTAL GEOLOGY OF THE SUMMITVILLE, COLORADO ACID-SULFATE MINERAL DEPOSIT

By

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INTRODUCTION

The Summitville mining district has received considerable attention recently as a result of environmental problems related to mining activities. Summitville Consolidated Mining Company, Inc. (SCMCI), a subsidiary of Galactic Resources, operated an open-pit gold mine at Summitville during the period from 1986 to 1992. Although mining ceased in the fall of 1991, heap leaching continued until the spring of 1992, and remediation efforts began shortly thereafter. The declaration of bankruptcy by SCMCI in December 1992, cast doubt on the short- and long-term remediation efforts at Summitville. In addition, substantial concerns were raised about continued adverse environmental impacts resulting from the abandoned mining operations. Of short term concern is the presence of cyanide- and metal-bearing solutions in the mine's heap leach pond. Acidic, metal-rich mine waters emanating from several sources on the mine site are long-term concerns.

Since the cessation of mining, much attention has focused on the environmental concerns of the Summitville mineral deposit. In order to understand and interpret the environmental aspects of any mineral deposit, it is critical to have an established geological framework for that deposit. From 1987 to 1989, the USGS conducted geological mapping and geochemical studies of the Summitville mineral deposit that provides such a framework. Several government agencies have requested that the USGS provide geologic information on the deposit for ongoing environmental modeling and predictive studies. It is in response to these requests that this report has been created. The open-file report format was selected for release of this information because it is the most rapid means of publication available to the USGS. This report is not intended to represent a compilation of all previous studies at Summitville, but presents geologic data that has an impact on remediation efforts at Summitville. Much of the information presented here was extracted from a forthcoming journal article (Gray and Coolbaugh, in press).

GEOGRAPHY AND HISTORY

The Summitville deposit is located in the southeastern San Juan volcanic field (fig. 1), approximately 20 km (12 miles) east of Wolf Creek Pass and 10 km (6 miles) northwest of Platoro, Colorado. The deposit is located about 11 km (7 miles) northeast of the continental divide at elevations ranging from 3,445 to 3,750 meters (11,300 to 12,300 ft) (Steven and Ratté, 1960). Due to its proximity to the continental divide, the Summitville area receives abundant snowfall, on the order of 1000 cm (400 inches) per year. The deposit is drained by Wightman Fork, a tributary of the Alamosa River.

Placer gold was first discovered at Summitville in 1870, and by 1873 several gold lodes had been located (Raymond, 1877). Rich oxidized gold ore near the surface was the primary objective of the underground mining in the late 1800's, when over 2,940 kg (100,000 oz) of gold were recovered (Steven and Ratté, 1960). Deeper, lower-grade gold ore from the sulfide-rich zone was the focus of underground mining during the 1930's and 1940's. Through 1949, total gold production reached 8,000 kg (257,000 oz) (Steven and Ratté, 1960) from approximately 270,000 metric tons of ore from underground mines. The major commodity was gold, however, minor silver, copper, and lead were also recovered (Steven and Ratté, 1960). Exploration for gold and copper between 1948 and 1983 was conducted by ASARCO that identified the low-grade gold deposit and a deep porphyry intrusive, and Anaconda Copper Co. that defined the bulk-mineable gold resource. From 1986 through 1992, SCMCI operated a low-grade/high tonnage open-pit mine from which approximately 9,250,000 metric tons of ore averaging 1.6 g/t gold (0.047 oz/t) was removed. Between 1986-1992, SCMCI produced approximately 9,400 kg of gold (302,000 oz), which made Summitville the largest producer of gold in Colorado for this period.

Early studies noted the unusual character of the hydrothermally altered rock at Summitville, in which gold was found in highly silicified rock rather than in distinct quartz veins (Endlich, 1877; Raymond, 1877; Patton, 1917). Ironically, many of the ore zones were referred to as "veins" during the early mining (eg. Science vein, Hidden vein, Little Annie vein, etc.); however, typical open-space quartz veins are rare at Summitville. Early workers also described the close association of gold with limonite and enrichment of gold by secondary processes (Endlich, 1877; Hills, 1885; Patton, 1917). Patton (1917) provided the first comprehensive geologic description of the area and also suggested that primary ore deposition must have followed the alteration phase that formed the highly siliceous rock. Steven and Ratté (1960) mapped the surface geology and recognized that the Summitville deposit was hosted in a volcanic dome. They also described the nature of the altered and mineralized rock, and provided a synthesis of the deposit which has served as the foundation for more recent studies of the area. Since that time, various aspects of the Summitville deposit have been described including: models for the genesis of the deposit (Perkins and Nieman, 1982; Stoffregen, 1985; 1987), geochemical conditions of acid-sulfate alteration and mineralization (Stoffregen, 1987), geochemical zoning (Enders and Coolbaugh, 1987), and stable isotope systematics (Rye and others, 1990; Rye and others, 1992).

GEOLOGICAL FRAMEWORK OF THE SUMMITVILLE DEPOSIT

Based on geologic mapping in the open-pit, it is evident that the Summitville deposit was developed during at least six distinct events. These events followed emplacement of the South Mountain quartz latite volcanic dome. The events are defined as 1) early main-stage acid-sulfate alteration, 2) subsequent Cu-sulfide and gold mineralization, 3) widespread hydrothermal brecciation, 4) deposition of volumetrically minor, base-metal-sulfide-bearing barite veins, 5) emplacement of small-scale, local kaolinite matrix breccias, and 6) a final stage of supergene oxidation and secondary sulfide enrichment. Dikes (Tdu) that postdate events 1-5, and in some instances event 6, are widespread in the Summitville open-pit mine (pl. 1), but are generally small and rarely exceed widths of 5 meters (16 ft). These dikes are typically intermediate in composition, unaltered, and are not related to the development of the Summitville deposit.

The Summitville acid-sulfate deposit occupies the mid-level portion of a larger magmatic-hydrothermal system that includes a porphyry environment below and a hot-spring environment at higher elevations (fig. 2). ASARCO drilled two deep holes through the center of the volcanic dome and intersected a quartz monzonite porphyry below the deposit (Enders and Coolbaugh, 1987). The quartz monzonite intrudes the volcanic dome and postdates the quartz latite. The quartz monzonite is altered to sericite and pyrite, and contains pyrite-quartz stockwork veins with trace amounts of chalcopyrite and molybdenite, and pyrite disseminations similar to those in Cu-porphyry environments (Enders and Coolbaugh, 1987). In addition, Summitville acid-sulfate altered rock is similar to advanced argillically altered rock containing alunite and kaolinite observed in the upper portions of some porphyry deposits such as Butte, Montana (Meyer and Hemley, 1967), El Salvador, Chile (Gustafson and Hunt, 1975), North Sulawesi, Indonesia (Lowder and Dow, 1978), and Red Mountain, Arizona (Corn, 1975). Laterally extensive cristobalite and opal that replace quartz latite are found southwest of the acid-sulfate deposit, and likely formed in a hot-spring environment. At a few localities, bedded siliceous sinter (fig. 3) overlies the cristobalite and opal. Some sinter samples contain plant debris, and up to 0.39 ppm Hg, 38 ppm As, 50 ppm Ag, 12 ppm Sb, and 116 ppm Bi (J. Gray, unpublished data). These hot spring deposits may represent surface vents for the fluids responsible for acid-sulfate alteration or fluids that deposited ore at Summitville.

Structure

Structure played an important role in localizing the volcanic dome and acid-sulfate alteration and mineralization at Summitville. As first documented by Lipman (1975), the South Mountain volcanic dome was emplaced near the intersection of the northwest-striking Platoro fault zone and the Platoro and Summitville caldera margins. The Platoro fault zone is part of a larger northwest-striking graben system, the Pass Creek-Elwood Creek-Platoro fault system (Lipman, 1975), that extends northwest from the Platoro and Summitville calderas (fig. 1). In the vicinity of the Summitville deposit, this fault system is expressed as the South Mountain fault (Lipman, 1974). A portion of the north-northwest striking Rio Grande fault zone is also found north of the Platoro-Summitville calderas. Although these fault zones have had long histories of recurrent movement, major displacement along the Pass Creek-Elwood Creek-Platoro and Rio Grande fault zones occurred between 27.8 and 26.7 Ma, contemporaneous with eruption of ash-flow tuffs and caldera collapse (Steven and Ratté, 1965; Lipman, 1975). The Pass Creek-Elwood Creek-Platoro fault zone remains active today, as evidenced by offsets in Quaternary colluvium (SCMCI, unpublished data). Fractures at Summitville are similar in orientation to the Pass Creek-Elwood Creek-Platoro and Rio Grande fault zones, suggesting that preexisting fractures were important for localizing acid-sulfate alteration and subsequent ore formation. Fractures related to the Platoro fault zone have localized mineralized ore not only at Summitville, but also in the nearby Platoro and Stunner districts.

The importance of fractures in ore distribution is shown on the map of gold-ore zones (fig. 4). Fracture control at Summitville is apparent despite a lack of distinct through-going open-space quartz veins. Ore zones are easily recognized because of their highly silicified character forming irregular steeply-dipping pods, pipes, and tabular bodies. Ore zones are often vertically and laterally continuous; individual zones may be traced laterally for up to 500 meters (1600 ft) (Tewksbury zone) and vertically up to 200 meters (650 ft) (Missionary), though changes in strike and dip sometimes make the zones difficult to follow. The distribution of mineralized zones closely follows that of intensely altered acid-sulfate rocks, specifically the vuggy silica, quartz alunite, and quartz-kaolinite zones. Though irregular in detail, individual silicified zones show a pronounced tendency to form along steeply-dipping linear zones similar in orientation to regional faults. The importance of structure is also apparent on a local scale where joints, fractures, faults, and unit contacts mapped in the open-pit parallel regional faults (pl. 1).

In general, mineralized fractures strike northwest. Two strong northwest trends are evident; both northwest striking fractures dip steeply from 65° to vertical. A N30W ± 20 strike is typified by narrower zones with higher gold-grades, such as that of the Little Annie and Tewksbury zones mined underground. The second, characterized by a N60W strike, is wider and more laterally extensive, but is marked by lower than average gold-grades; examples are the Highland Mary, Nellie, and Copper Hill zones. These mineralized zones intersect near the center of the deposit to form a large ore zone approximately 150 by 400 meters (1300 to 2600 ft)(fig. 4). This ore zone, termed the Highland Mary-Copper Hill zone, contained low to average gold-grades of 0.34 to 2.1 g/t (0.01 to 0.06 oz/t). These relationships indicate that where numerous fractures intersect, broad zones of permeability allowed hydrothermal fluids to react with large surface areas of rock, precipitating gold over a wide area. In these areas, such as in the center of the deposit, the result was a large, low-grade gold deposit.

Narrower, but higher grade gold ore zones are present outside the central Highland Mary-Copper Hill zone (fig. 4). Almost all pre-1949 underground production, at grades greater than 10 g/t gold (0.30 oz/t) and averaging about 30 g/t (1 oz/t), came from strong northwest-striking fractures lying outside the central zone. The higher gold grades in this area may have been caused by the channeling of ore-forming fluids into fewer, more confined fractures.

A rough radial pattern of fractures was observed at Summitville, with most fractures striking northwest (fig. 4). The intersection of these fractures near the center gives the deposit this radial appearance (Enders and Coolbaugh, 1987). In addition, less abundant fractures strike approximately due west (eg. the Dexter vein). This westerly fracture pattern is most evident in the northern portion of the deposit, as evidenced by an arcuate feature in silicified ore zones. A weak northeast component is also part of the radial pattern in the central and northern portion of the ore deposit (fig. 4). The radial component and northern arcuate zone at Summitville probably formed during emplacement of the underlying quartz monzonite porphyry. The northwest fractures were probably preexisting regional fractures that were infiltrated by fluids during the Summitville hydrothermal activity.

The strong northwest-strike of mineralized fractures and the postcaldera age of alteration are features that Summitville has in common with most other precious metal districts in the San Juan volcanic field, including, but not limited to, the Creede, Telluride-Sneffels, Animas, and Platoro districts. This distinctly postcaldera control has been related by Dreier (1984) to arching of the San Juan Mountains during rift-related basin and range development. Lipman and Mehnert (1975) suggest that basin and range development began as early as 26 Ma and has continued to the present. The age of Summitville acid-sulfate alteration of 22.4 Ma (Mehnert and others, 1973) slightly overlaps with this period suggesting that alteration and mineralization are related to the onset of basin and range tectonism.

Acid-sulfate alteration

Acid-sulfate alteration was the earliest, most pervasive, and widespread hydrothermal event in the genesis of the Summitville deposit. Hydrothermal fluids responsible for acid-sulfate alteration flowed along preexisting fractures in the volcanic dome. Acid-sulfate alteration was an important precursor stage that provided open-space porosity for subsequent Cu-sulfide and gold deposition (Patton, 1917; Steven and Ratté, 1960; Hayba and others, 1985; Stoffregen, 1985). Along individual fractures, acid-sulfate altered rocks are composed of a central vuggy silica zone, grading laterally outward into quartz-alunite, quartz-kaolinite, pervasive argillic, and propylitic zones.

The central vuggy silica (Tqv, pl. 1), is composed predominantly of silica, with minor anatase, rutile, zircon, and sulfide minerals (Steven and Ratté, 1960; Stoffregen, 1987); mafic mineral and coarse feldspar phenocrysts originally present in the rock were completely dissolved and are now marked by hollow vugs up to 5 cm in size (fig. 5). In the open-pit, the width of individual vuggy silica zones is highly variable from a few centimeters (1 inch) to several tens of meters (100 ft), but is much wider where fractures intersect. Vuggy silica represents silicification through leaching of all the other major-elements, including aluminum (Stoffregen, 1987). Silica was locally mobilized during acid-sulfate alteration, and reprecipitated as fine-grained drusy silica found pervasively throughout the vuggy silica, quartz-alunite, and quartz-kaolinite zones. In addition, relict quartz phenocrysts are sometimes overgrown with silica in the vugs, forming euhedral secondary quartz crystals (fig. 6).

Quartz-alunite zones (Tqa) are found laterally outward from vuggy silica (pl. 1). The quartz-alunite zones are composed of a hard silicified matrix with minor alunite and pyrite; in addition, finely-crystalline white to pink alunite has replaced feldspar phenocrysts. Quartz-alunite zones, which range from a few centimeters (1 inch) to several tens of meters (100 ft) in width, are typically about 3 meters (10 ft) wide. Contacts between quartz-alunite and vuggy silica are usually sharp, but gradational contacts are also found.

The quartz-alunite zones grade laterally into quartz-kaolinite zones (Tqk, pl. 1). Quartz-kaolinite zones have a silicified matrix with minor kaolinite and pyrite, but feldspar phenocrysts have been replaced with kaolinite. The quartz-kaolinite zones are generally narrower than quartz-alunite zones (pl. 1); quartz-kaolinite zones are often too small to form mappable units. Quartz-kaolinite zones reach a maximum thickness of approximately 5 meters (16 ft) and average about 1 meter (3 ft) in the open-pit. The transition from quartz-alunite to quartz-kaolinite zones may be sharp, but more commonly is gradational.

A wide zone of pervasive altered argillic rock (Taa) surrounds the generally narrower silicified zones made up of vuggy silica, quartz-alunite, and quartz-kaolinite zones (pl. 1). Argillic zones consist of nearly complete replacement of feldspar in the quartz latite by kaolinite nearest the silicified zones, followed laterally outward by an illite-dominated zone, and a distal montmorillonite-rich zone. Pyrite is common in the matrix, typically replacing mafic phenocrysts. The contact between the argillic zone and the silicified rock is sharp and distinct. The argillic zone is by far the widest altered rock zone in the deposit, ranging from 5 to 100 meters (16 to 330 ft), and averaging about 30 meters (100 ft). In parts of the deposit, the silicified rock is completely surrounded by large bodies of argillic rock.

The weakest altered rock zone is propylitic (Tpa), which is most distal at Summitville (pl. 1). Propylitic zones consist primarily of chlorite replacing mafic phenocrysts, giving the rock an overall greenish appearance; minor pyrite is common in the matrix, also replacing mafic phenocrysts. Minor montmorillonite and occasional carbonate rims on feldspar phenocrysts are also found. Contacts between the argillic zones and propylitic zones are gradational.

Early breccias

Brecciation at Summitville is complex, but consists of four major types: 1) prealteration breccias that predate development of the mineral deposit, 2) contemporaneous breccias roughly coeval with the formation of the mineral deposit, 3) postalteration hydrothermal breccias and pebble dikes, and 4) late-stage kaolinite matrix breccias. Prealteration and contemporaneous breccias are grouped together as the early breccias (Tbe) on plate 1.

The largest prealteration breccia is up to 60 meters (200 ft) wide and approximately 200 meters (660 ft) along strike (pl. 1, northeast from 51,000N, 99,500E). The breccia contains predominantly angular clasts of quartz latite, Summitville andesite, and Park Creek rhyodacite, ranging in size from less than 0.5 centimeters (0.2 inches) to greater than 1.5 meters (5 ft). The matrix is finely crystalline, weakly argillized, pyritic, and tuffaceous; this breccia is barren of ore. Other prealteration breccias are generally small, typically only a few centimeters (1 inch) to one meter (3 ft) wide, and rarely exceed strike lengths of more than one mine bench (roughly 6 meters); generally, prealteration breccias are small and do not form mappable units. Prealteration breccias are consistent with intrusion breccias described by Sillitoe (1985).

Breccias contemporaneous with acid-sulfate alteration contain angular to subangular fragments, typically vuggy silica or quartz-alunite set in an acid-sulfate altered matrix. Contemporaneous breccias usually contain only one type of altered rock at any locality. Occasionally, contemporaneous breccias contain minor open-space filling of finely crystalline quartz and alunite. These breccias are most consistent with epithermal-type phreatic (hydromagmatic) breccias (Sillitoe, 1985). Contemporaneous breccias probably formed when hydrothermal fluid pressure exceeded confining pressure and explosive release produced brecciation. The resulting brecciated zones then provided pathways for the hydrothermal fluids which generated acid-sulfate altered rock. Thus, contemporaneous breccias, as well as prealteration breccias, may be altered to any type of acid-sulfate altered rock (eg. near 51,500N, 99,500E on pl. 1). Contemporaneous breccias are generally not the primary location of large ore zones at Summitville and are generally small, local units. Prealteration and contemporaneous breccias are easily distinguished from the hydrothermal and late-stage kaolinite matrix breccias, (described later) that postdate acid-sulfate alteration.

Cu-sulfide and gold stage

Early studies of the Summitville deposit recognized that primary sulfide minerals and gold distinctly postdated acid-sulfate alteration (Patton, 1917; Steven and Ratté, 1960). Field observations during open-pit mining support this conclusion. The sulfides typically line or fill open-space vugs and microfractures in vuggy silica (fig. 7), quartz-alunite, and quartz-kaolinite zones. Primary ore minerals include pyrite, enargite, luzonite, covellite, gold, native sulfur, marcasite, barite, and minor hinsdalite, sphalerite, and galena (Steven and Ratté, 1960; Stoffregen, 1987). Native sulfur occurs somewhat sporadically, but is abundant where present. Minor kaolinite is the only gangue mineral observed with the Cu-sulfide mineral assemblages. Gold was deposited with Cu-sulfide minerals, usually as microscopic disseminations. Gold that has been unaffected by oxidation generally contains less than 0.25 weight percent silver (Stoffregen, 1986). Chalcopyrite and tennantite are a deeper sulfide facies of the covellite-enargite-luzonite assemblage, and are observed in drill hole cuttings below 3,400 meters (11,200 ft) elevation (Stoffregen, 1987).

The majority of the gold at Summitville is found in vuggy silica, quartz-alunite, and quartz-kaolinite zones. Gold analyses of exploration drill-core samples indicated that vuggy silica averaged 2.4 g/t gold (0.07 oz/t), quartz-alunite averaged 1.2 g/t gold (0.03 oz/t), and quartz-kaolinite averaged 0.86 g/t gold (0.02 oz/t). Argillically altered rock was rarely above the ore-grade cut-off of 0.34 g/t gold (0.01 oz/t). Propylitic rock rarely contained detectable gold concentrations of 0.03 g/t gold (0.001 oz/t), and constituted only waste rock.

Hydrothermal breccias

Hydrothermal breccias (Tbp) cut acid-sulfate altered rock and ore zones. One large breccia approximately 100 meters (330 ft) in strike length and 10 meters (33 ft) wide is located in the northwest portion of the deposit (pl. 1). A number of smaller, coeval pebble dikes are located throughout the deposit and range in width from a few centimeters (1 inch) to 3 meters (10 ft). Pebble dikes are discontinuous along strike, and often difficult to trace to adjacent benches. Hydrothermal breccias consist of heterogeneous rounded to subrounded clasts of variable size (microscopic to 1 meter (3 ft) in diameter) set in a clay-rich "rock flour" matrix. The matrix also contains fine-grained pyrite, giving the breccias a dark gray color. These hydrothermal breccias unquestionably postdate acid-sulfate alteration and ore formation because clasts of acid-sulfate altered and mineralized rocks are found within the breccia. Occasionally, chalcopyrite has replaced enargite along the rims of some clasts. These hydrothermal breccias also contain rounded clasts of quartz monzonite altered to sericite and pyrite, and highly argillized rock that is probably Summitville andesite.

X-ray analysis indicates that the matrix of these breccias is composed of sericite, illite, and pyrite, with minor amounts of alunite. The presence of a significant sericite matrix component, rounded clasts of sericite-pyrite altered quartz monzonite, and a wide variety of clast rock types, suggest an origin from deep within the deposit (fig. 2). Fine-grained alunite and illite were apparently added to the matrix of the breccia as it cut through acid-sulfate altered rock during emplacement. The hydrothermal breccias contain some mineralized ore clasts; however, these breccias rarely contained gold-grades in excess of the cutoff value of 0.34 g/t (0.01 oz/t) when encountered in the open-pit, and were mined as waste.

Summitville hydrothermal breccias and pebble dikes are similar to porphyry-type phreatic (hydromagmatic) breccias (Sillitoe, 1985) and "intrusive breccia dikes or pebble dikes" commonly observed in Cu- and Mo-porphyry deposits (Gustafson and Hunt, 1975; Wallace and others, 1978; Thomas and Galey, 1982). Diagnostic features include their dike and pipelike forms, inferred depth, substantial clast transport, weak hydrothermal alteration (excluding altered clasts), and ages postdating ore. The mineralogy of these hydrothermal breccias is significantly different than that of the acid-sulfate zones and ores, suggesting that separate hydrothermal fluids formed the earlier acid-sulfate altered rock, ores, and hydrothermal breccias.

Late-stage base-metal-sulfide-bearing barite veins

Deeper levels of the open-pit, approximately 3650 to 3500 meters (12,040 to 11,560 ft) in elevation, exposed a series of sulfide-bearing barite veins. These veins contain galena, sphalerite, pyrite, marcasite, barite, kaolinite, and traces of chalcopyrite. Small amounts of chalcocite and fine-grained covellite are also contained in the veins, but are of probable supergene origin. These veins are quite narrow, typically just a few centimeters (1 inch) to 1 meter (3 ft) wide, sparsely distributed, and because they have short strike lengths, are often discontinuous to the next mine bench or about 6 meters (20 ft) vertically. The base-metal sulfide veins cut the hydrothermal breccias and acid-sulfate altered zones, clearly postdating these units. Samples of the veins contain up to 250 g/t gold (7.3 oz/t).

Veins containing barite, gold, goethite, and jarosite were common in the upper portion of the deposit near the original surface of South Mountain (Stoffregen, 1987). The presence of barite in these high-level oxidized veins suggests that they are equivalents of the deeper level base-metal-sulfide-bearing barite veins. The oxidized barite veins produced occasional specimens with abundant visible gold, containing up to 4500 g/t gold (130 oz/t), as well as the "Gold Boulder of Summitville," currently in the Denver Museum of Natural History, which weighs 51.7 kg and contains 17 percent gold. Oxidized goethite-jarosite-barite-gold-bearing veins are similar to high-grade gold veins described during the early history of the deposit (Hills, 1885; Patton, 1917) and more recently studied by Steven and Ratté (1960) and Stoffregen (1987). Barite from one such vein, collected near the original surface during this study, contains abundant inclusions of gold and pyrite suggesting a hypogene origin. Supergene Fe-oxide and jarosite often coat barite in the veins. The mineralogical similarity of the base-metal-sulfide-bearing barite veins and the shallow oxidized barite veins, suggest the shallow veins were altered by supergene processes.

Late-stage kaolinite-matrix breccias

Late-stage kaolinite-matrix breccias are limited in distribution; however, when grab samples of these breccias were collected in the open-pit they contained high gold-grades, up to 780 g/t gold (25 oz/t). These breccias were observed in 1990 in blasted, intermediate benches that were mined away, and therefore, do not appear on plate 1. Kaolinite-matrix breccias are distinctly younger than, smaller, and easily distinguished from, the hydrothermal breccias (discussed above). Kaolinite-matrix breccias consist of dikes and pipes up to a few meters (10 ft) wide, are discontinuous along strike, and difficult to trace for more than two successive mine benches or approximately 12 meters (40 ft). The breccias contain subangular to rounded fragments of vuggy silica and other altered rocks set in a kaolinite- and iron-oxide-rich matrix. Based on cross-cutting relationships observed in two localities, kaolinite-matrix breccias postdate base-metal-sulfide-bearing barite veins, and represent the youngest hypogene unit at Summitville.

The kaolinite-matrix breccias were first identified by Stoffregen (1985) in drill core and drill hole cuttings. These breccias are possibly also equivalent to microbreccias described by Steven and Ratté (1960), but exact correlations are difficult. The kaolinite-matrix breccias described here are interpreted to be of hydrothermal origin due to the well-rounded shape of some clasts and the argillic, fine-grained nature of the matrix. Fine-grained sulfide minerals, Fe-oxides, and gold in the groundmass could be of either hypogene or supergene origin. The late-stage kaolinite-matrix breccias are most similar to phreatic porphyry-type breccias (Sillitoe, 1985) due to their postore age, size, and matrix and clast composition. However, phreatic porphyry-type breccias are typically barren of ore, whereas the kaolinite-matrix breccias often contain high gold-grades.

Supergene alteration

The effects of supergene oxidation are pronounced at Summitville, reaching depths of up to 100 meters (330 ft) below the original surface. Oxidation generally penetrates to much greater depths in vuggy silica zones than in quartz-alunite, quartz-kaolinite, and argillic zones. The differences in oxidation depth are a function of the permeability, which is greatest for vuggy silica altered zones. The oxidation of argillic zones is typically limited to within 10 meters (30 ft) of the surface.

Oxidized vuggy silica is usually dark brown to red-brown from the presence of geothite. In contrast, jarosite is more common in argillically altered zones, producing a yellow-brown color. Chalcanthite ($CuSO_4 . 5H_2O$) is found locally and probably formed during open-pit mining. The frequent occurrence of greenish scorodite ($FeAsO_4 . 2H_2O$) coatings reflect the weathering of the As-sulfides enargite and luzonite, whereas occasional platy hematite aggregates suggest pseudomorphic replacements of coarse-grained primary covellite. Fine-grained supergene alunite veins are found in the uppermost portions of the deposit and were produced by the destruction of sulfide minerals and wallrock reactions during weathering.

Irregular zones of secondary Cu-sulfides found at the base of the oxidized zone, just above primary Cu-sulfide ore zones at some localities, provide evidence of Cu-mobilization and reprecipitation. Here, fine-grained chalcocite-digenite and covellite are located along microfractures. Primary enargite and covellite are replaced to varying degrees by chalcocite and digenite, and well-developed pseudomorphs of chalcocite after covellite have been observed in these zones. The removal of Cu from the oxidized zone by weathering is supported by Cu concentrations in oxidized silicified rocks of 500 ppm or less, whereas the underlying sulfide-bearing silicified rocks average around 4000 ppm Cu.

Remobilization and enrichment of gold during supergene oxidation is not as clear as it is for Cu, but remobilization of gold is evident locally. Based on microprobe studies of drill-hole cuttings, Stoffregen (1986; 1987) observed consistently finer grain-size and higher Ag concentrations in gold (0.5-3.0 weight percent Ag) from the oxidized zone, compared to gold in the sulfide zone (less than 0.25 weight percent Ag). This supports observations of Hills (1885), and Steven and Ratté (1960), who found unusual intergrown gold-limonite textures suggestive of transport and deposition of gold. Similarly, two analyses of limonite stalactites and stalagmites taken from underground mine workings (Patton, 1917) contain up to 4.1 and 12 g/t gold (0.12 and 0.35 oz/t), respectively, suggesting transport and deposition of gold.

Evolution of the Summitville hydrothermal system

The Summitville Cu-Au-Ag deposit is regarded as a prototype epithermal magmatic-hydrothermal acid-sulfate system characterized by advanced argillically altered rock (Hayba and others, 1985; Rye and others, 1992). Deposit models synonymous with acid-sulfate deposits include enargite-gold (Ashley, 1982) and epithermal quartz-alunite gold (Berger, 1986). Other epithermal acid-sulfate precious-metal deposits include Julcani, Peru (Petersen and others, 1977), El Indio, Chile (Jannas and others, 1988), Goldfield, Nevada (Ransome, 1909; Vikre, 1989), Lake City, Colorado (Slack, 1980), Rodalquilar, Spain (Arribas and others, 1988; Sänger-von Oepen and others, 1989), and Pueblo Viejo, Dominican Republic (Muntean and others, 1990). Characteristics found at Summitville considered diagnostic of such acid-sulfate deposits are 1) temporal and spatial association to an intermediate composition volcanic dome host rock of Cenozoic age, 2) successive altered rock zones of highly silicified vuggy silica, quartz + alunite, and quartz + kaolinite, 3) a high sulfur assemblage that includes enargite, luzonite, covellite, native sulfur, and native gold, 4) a magmatic sulfur source, 5) fluids responsible for acid-sulfate alteration with heavy oxygen isotope signatures indicative of a magmatic component, and 6) a close association with a deeper porphyry environment.

A model for the formation of the acid-sulfate portion of the Summitville deposit was proposed by Perkins and Nieman (1982) that related the alteration and mineralization processes to magmatic activity in the volcanic dome. Thermodynamic modeling by Stoffregen (1985; 1987) clarified the earlier model by showing that an early vapor-dominated phase that produced the acid-sulfate altered rocks was an ascending gas, largely of magmatic origin, that contained appreciable sulfur. Stoffregen suggested that SO_2 produced from a degassing magma disproportionated to form H_2SO_4 and H_2S; the sulfuric acid intensely leached the surrounding quartz latite. Stoffregen also suggested that Cu-sulfides and gold precipitated from a liquid-dominated fluid that followed the magmatic vapor stage. Stable isotopic data for alunite and kaolinite indicate that the hydrothermal fluids producing acid-sulfate altered rocks contained a significant magmatic fluid component that mixed with meteoric water (Rye and others, 1990); thus, confirming Stoffregen's conclusion of a magmatic component in the fluids responsible for acid-sulfate alteration. In addition, Rye and others (1990) established a geothermal gradient ranging from 200°C near the surface, to approximately 400°C in the deep acid-sulfate portion of the deposit, based on sulfur isotope geothermometry of alunite and coexisting pyrite.

A genetic relationship between the quartz monzonite porphyry and hydrothermal activity is suggested by: 1) the radial appearance of mineralized zones near the center and the arcuate zones on the northern edge of the deposit that probably formed during emplacement of the quartz monzonite porphyry, and 2) heavy hydrogen and oxygen isotopic signatures in alunite and ore-stage kaolinite that indicate a large magmatic component in hydrothermal fluids.

Following acid-sulfate alteration and subsequent ore deposition, hydrothermal breccias were emplaced in the deposit. These hydrothermal breccias marked the end of acid-sulfate alteration and mineralization, and signaled the emplacement of a hydrous magma that was barren of ore metals. A deep source for the fluids that produced the breccias is required by the presence of sericite-pyrite altered quartz monzonite clasts and the well-rounded nature of many of the clasts. Quartz monzonite porphyry altered to sericite and pyrite, encountered at approximately 600 meters (2000 ft) below the present surface in drill holes, provides a minimum depth of formation for these hydrothermal breccias.

Late-stage base-metal-sulfide-bearing barite veins cut the hydrothermal breccias in the mid-level portion of the acid-sulfate zone at approximately 300 meters (1000 ft) below the paleosurface. Oxygen isotope compositions in the barite from these late-stage veins suggest a large meteoric water contribution to the hydrothermal fluids that formed these veins (Rye and others, 1990). The gangue mineralogy of kaolinite without alunite suggests that the late-stage hydrothermal fluids at Summitville had a more neutral pH closer to that of adularia-sericite ore fluids (Heald and others, 1987). These base-metal-sulfide-bearing barite veins, may have formed when meteoric waters invaded the cooling intrusive complex, after the intrusion had substantially degassed. The high gold grades in these veins are possibly related to the higher solubilities of Au-bisulfide complexes at more neutral pH and 250°C (Romberger, 1986). Precipitation of barite, base-metal sulfides, and gold probably occurred as the solutions rose and mixed with cooler, more oxidized waters, or boiled, in the upper portions of the system. A similar origin was proposed for the gold-quartz-barite-bearing "Gold Boulder of Summitville" (Cunningham, 1985).

Kaolinite-matrix breccias are the youngest hypogene unit at Summitville, probably formed by late phreatic explosions. Late phreatic explosions may have associated boiling that can induce gold precipitation, which is a possible explanation for the high gold-grades in the Summitville kaolinite-matrix breccias. Together the late-stage base-metal-sulfide-bearing barite veins and kaolinite-matrix breccias made-up much less than 1 percent of the volume of the deposit. As a result of their high gold-grades, these units produced about 5-15 percent of the total gold mined from the deposit.

Textural and chemical evidence indicates remobilization of gold during weathering (Stoffregen, 1986). The overall distribution of gold-grades suggests a moderate degree of gold enrichment during oxidation because gold grades tend to be highest near the premining surface regardless of elevation. The Summitville deposit was particularly susceptible to supergene gold enrichment because: 1) the sulfide-rich mineralogy produced strongly acid supergene waters near the surface, and 2) the gold is not encapsulated in insoluble minerals, thereby allowing easy access to supergene solutions.

ENVIRONMENTAL GEOLOGY

Of primary concern to the environment are sulfide-bearing rocks with the capacity to generate acid and highly metalliferous waters during surface weathering. Nearly all rocks exposed in the open-pit contain some sulfide minerals and the recent open-pit mining has exposed a large volume of these sulfide-bearing rocks (Plumlee and others, 1994). There is very little carbonate or fresh rock to buffer acid- and metal-rich solutions formed on site. Of highest concern environmentally are rocks in the open-pit, the heap-leach pad, and the waste dumps. The relationship of the geology of the Summitville mineral deposit to the local hydrology is also important for understanding environmental problems.

Open-pit

Subsequent to deposit formation, supergene processes oxidized much of the sulfide-rich ore to a depth of approximately 100 meters (300 ft) below the paleosurface in permeable vuggy silica (fig. 8), but oxidation reaches depths of only about 10 meters (30 ft) in argillic zones. Therefore, as mining progressed, more sulfide-bearing rocks with little buffering capacity were exposed. Surface weathering of these sulfide-rich ore zones has led to the production of highly acidic, metalliferous waters.

Geologic units of primary concern environmentally are highly permeable vuggy silica zones with unoxidized sulfide minerals, and all unoxidized argillic rocks that also contain sulfide minerals. Volumetrically minor base-metal-sulfide barite veins and late-stage kaolinite matrix breccias are considered insignificant acid-generators in comparison to the large volumes of vuggy silica and argillic rocks. Vuggy silica rocks contain abundant pyrite, enargite, covellite, marcasite, and lesser chalcopyrite, tennantite, galena, and sphalerite. During open-pit mapping, total sulfides were estimated to average about 1-3 volume percent in vuggy silica. A small subset of five samples of unoxidized vuggy silica collected throughout the deposit were analyzed for sulfide sulfur (S^{2-}) and range from about 0.3 to 3.5 weight percent (averaging about 1.5 weight percent); one sample of oxidized vuggy silica contains less than 0.05 weight percent sulfide sulfur (J. Gray, unpublished data). Unoxidized quartz-alunite and quartz-kaolinite zones contain 0.1 to 4.7 weight percent sulfide sulfur (averaging about 2.4 weight percent).

Argillically altered rocks are by far the most abundant rocks at Summitville, making-up about two-thirds of the rocks in the open-pit (pl. 1). These rocks include quartz latite pervasively altered to clay, all prealteration and postalteration hydrothermal breccias with clay matrices, and late-stage kaolinite-matrix breccias. Pyrite is the most abundant sulfide mineral in argillically altered rocks; during geologic mapping, pyrite in argillic rocks was estimated to vary from about 1 to 3 volume percent. Analysis of five pyrite-bearing argillic rocks collected from the open-pit contain 1.9 to 2.9 weight percent sulfide sulfur. Although sulfide sulfur is probably less than 4 weight percent for most vuggy silica and argillic rocks observed in the open-pit, the large volume of these rocks, coupled with the poor buffering capacity of the rocks of the deposit, suggest that formation of highly acidic, metalliferous waters during oxidation will continue.

As discussed in the supergene alteration section, a number of secondary minerals such as scorodite, chalcanthite, geothite, jarosite, and hematite are present in and around the Summitville open pit. Some of these minerals formed prior to mining as a result of long-term weathering of the ore body. However, abundant secondary minerals are also presently forming due to the oxidation of sulfides exposed by mining. For example, chalcanthite is the most abundant secondary salt identified to date, and forms on the surfaces of mining-related rock debris by evaporation of pit waters during dry periods and redissolves during periods of rainfall or snow melt. Plumlee and others (1994) have proposed that soluble secondary salts are responsible for the observed seasonal increases in acidity and metal content of Summitville mine-drainage waters. Studies are currently underway to characterize the secondary mineralogy at Summitville, and to understand in more detail the roles of these minerals in controlling mine-drainage chemistry.

Leach pad

There are approximately 9,000,000 metric tons of rock presently on the Summitville leach pad (fig. 9). The leach pad began to leak shortly after being installed and these leaks are being monitored. Additional environmental concerns would result if the pad were to leak more severely, rupture, or if the leach water would overflow the containment. In addition to the environmental hazards of any cyanide remaining within or leaking from the leach pad, some of the rocks on the pad are sulfide-bearing ore capable of generating acidic and highly metalliferous waters.

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 volume percent total sulfide. As open-pit mining progressed, however, more sulfide-rich ore was encountered and added to the leach pad. Some partially oxidized sulfide-bearing ore was also 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 volume percent is sulfide-rich ore. Therefore, total sulfides in the material on the leach pad probably does 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 simple weathering.

Waste dumps

Waste dumps at Summitville presently contain over 20,000,000 metric tons of waste rock (fig. 10). The majority of waste in the dumps is argillically altered rock, followed by breccia waste (also argillically altered), and propylitically altered rock. As noted above, argillic rocks contain about 2-3 weight percent sulfide sulfur; sulfide sulfur in propylitic rocks varies from about 0.4 to 2.4 weight percent (J.Gray, unpublished data). Silicified rock was rarely mined as waste, but due to the small-scale nature of some silicified ore zones as much as 10 percent by volume of the waste dumps may be silicified rock. However, the majority of the dump material is composed of argillically altered rock with pyrite. Minor amounts (less than 1 volume percent) of all the ore minerals described above should be expected in the dump material due to the composition of the late-stage breccias and because minor silicified ore material is in the dumps. Similar to the open-pit and heap-leach pad, the total amount of sulfide minerals in the waste dumps 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 may also be important in the waste dumps affecting metal contents and acidity of waters in contact with waste material.

Structural control on the local hydrology

The interaction between rock and water is an important environmental component 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. Vuggy silica, quartz-alunite, and quartz-kaolinite zones contain abundant sulfides, and therefore produce highly metalliferous and strongly acidic solutions upon weathering by surface waters and groundwaters. Supergene oxidation to depths of as much as 300 ft (100 meters) in highly permeable vuggy silica provides evidence of the importance of the interaction of water with permeable fractures.

Fracture control was not only important for localizing acid-sulfate altered and mineralized zones, but is also an most important component affecting modern groundwater hydrology. 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 to be worked out. 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. An extension of the Nellie-Highland Mary-Iowa zones appear to control the location of a spring south of the open-pit in Cropsy Creek; this area currently lies beneath the Cropsy waste dump.

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 (SCMCI, unpublished data). The deposit is as much as 15 meters (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 does not appear to be actively seeping groundwater. Smaller ferricrete deposits are located on the north slope of South Mountain near the Dexter portal, 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 fractures (fig. 4) have influenced groundwater hydrology.

Underground mine workings (see Steven and Ratté, 1960) have also changed the groundwater hydrology. The interception of groundwater with adits, crosscuts, and drifts has 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 portal was clearly discharging water because a stand of dead trees and ferricrete deposits are present near the portal. More recently, the Chandler portal has been dry, but the younger and topographically lower Reynolds portal has a significant acid-mine drainage discharge. It is possible that underground mining diverted groundwater flow from the Chandler workings to the Reynolds workings.

Throughout open-pit mining, acid waters continued to discharge from the Reynolds portal. The water quality of the Reynolds effluent has shown increased metal loadings (eg. copper) as mining progressed (Golder and associates, 1992; Plumlee and others, 1994). The deterioration of the Reynolds portal effluent has probably been due to increased surface area exposure of sulfide-bearing rocks, and groundwaters flowing into different fractures, both a result of open-pit mining. 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 is the Reynolds portal. Open-pit mining removed zones of oxidized vuggy silica, forcing waters to follow more sulfide-rich fractures, adding to water degradation. The effect of fracture control and location of underground workings on local groundwater hydrology should not be overlooked when considering environmental remediation at Summitville.

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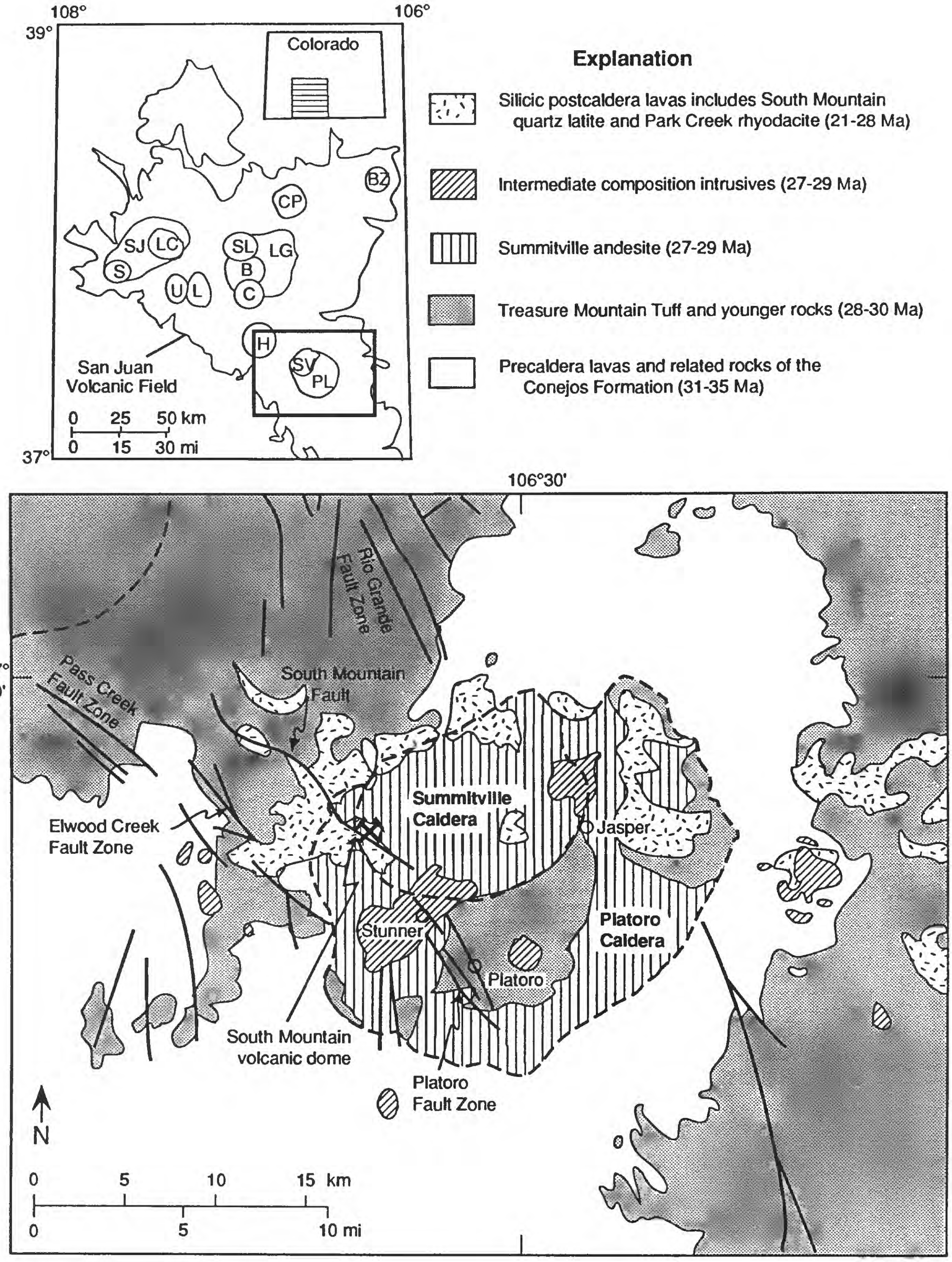

Figure 1. Location map showing the outline of the San Juan volcanic field and calderas within the field (generalized from Lipman, 1975). Age data are from Steven and others, (1967), Lipman and others (1970), Lipman (1975), Mehnert and others (1973), and Perkins and Nieman (1982). Calderas shown are abbreviated: B-Bachelor, BZ-Bonanza, C-Creede, CP-Cochetopa, 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 geology figure modified from Steven and Lipman (1976). ⚒ - Location of the Summitville deposit.

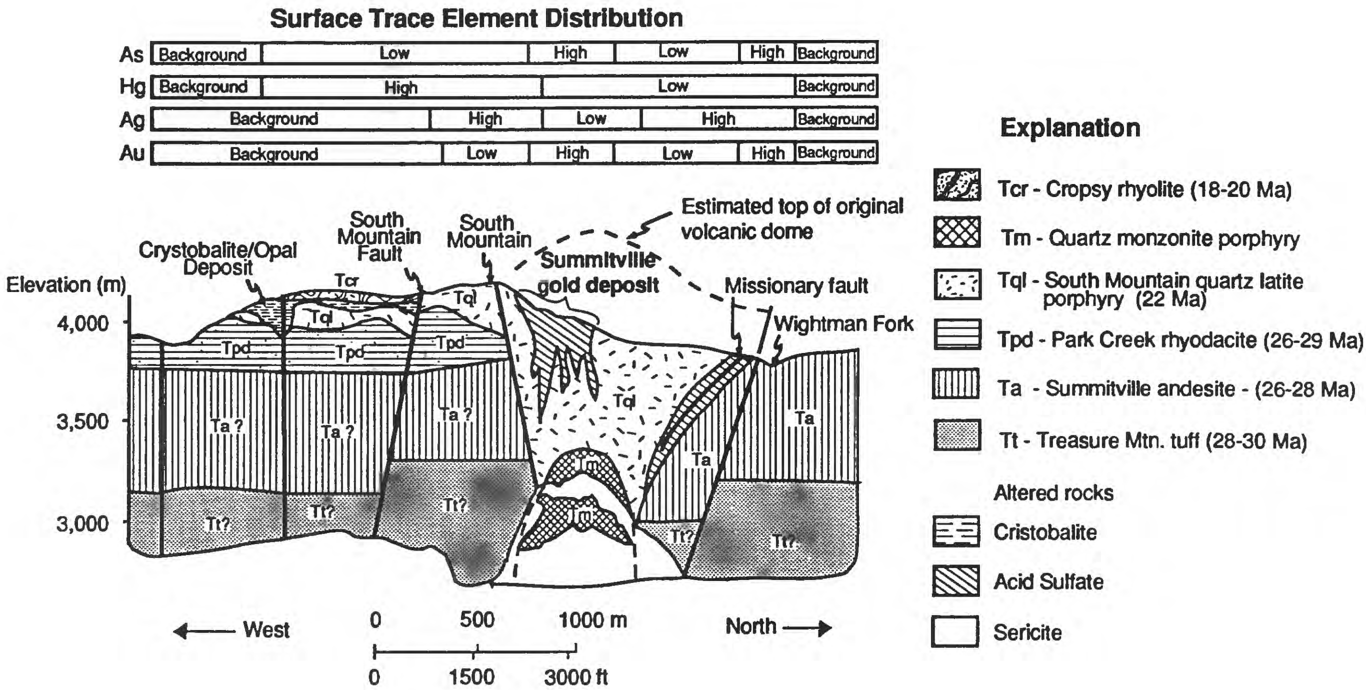

Figure 2. Schematic cross-section of the Summitville area showing the gold-deposit, cristobalite- and opal-bearing hot-springs deposit, and the sericite-pyrite altered quartz monzonite porphyry at depth (modified from Enders and Coolbaugh, 1987).

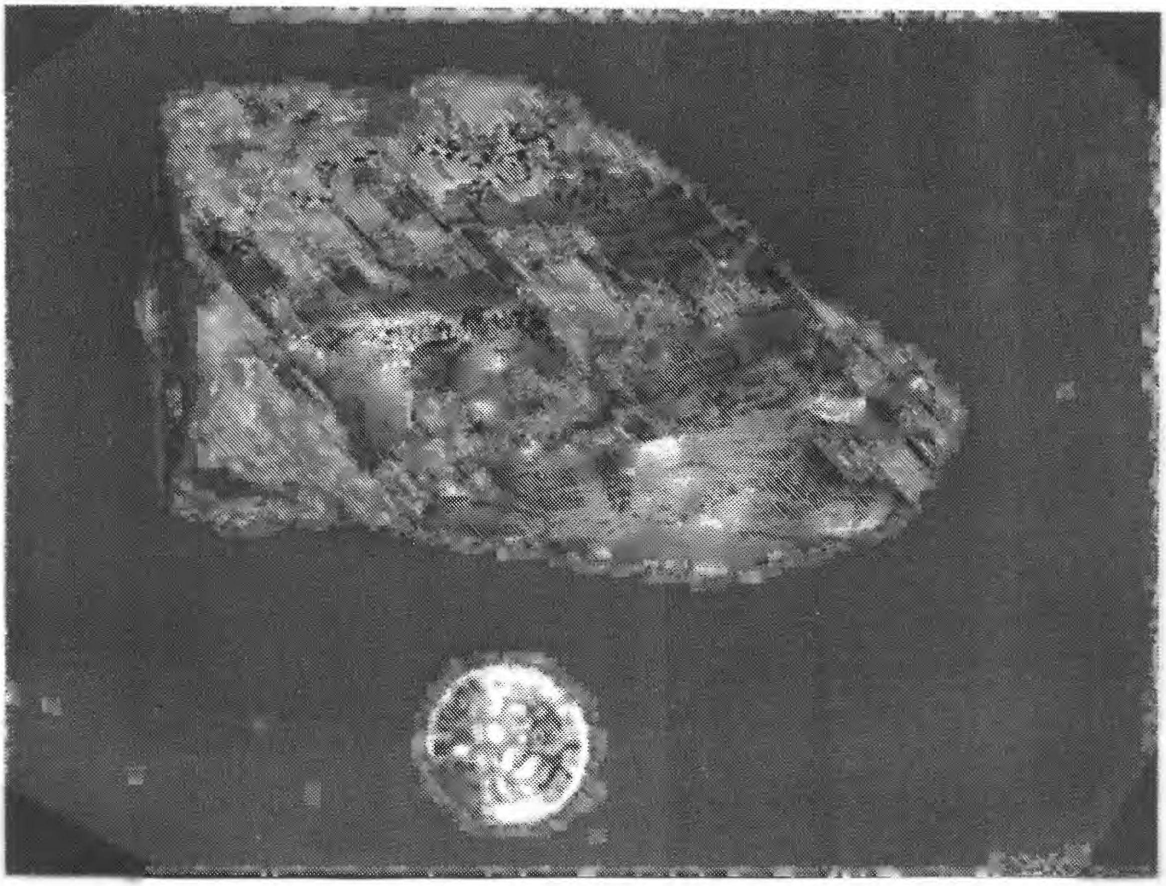

Figure 3. Siliceous sinter from the hot-spring environment at Summitville collected just west of the South Mountain fault. Bedded nature of the sinter suggests surface deposit of silica.

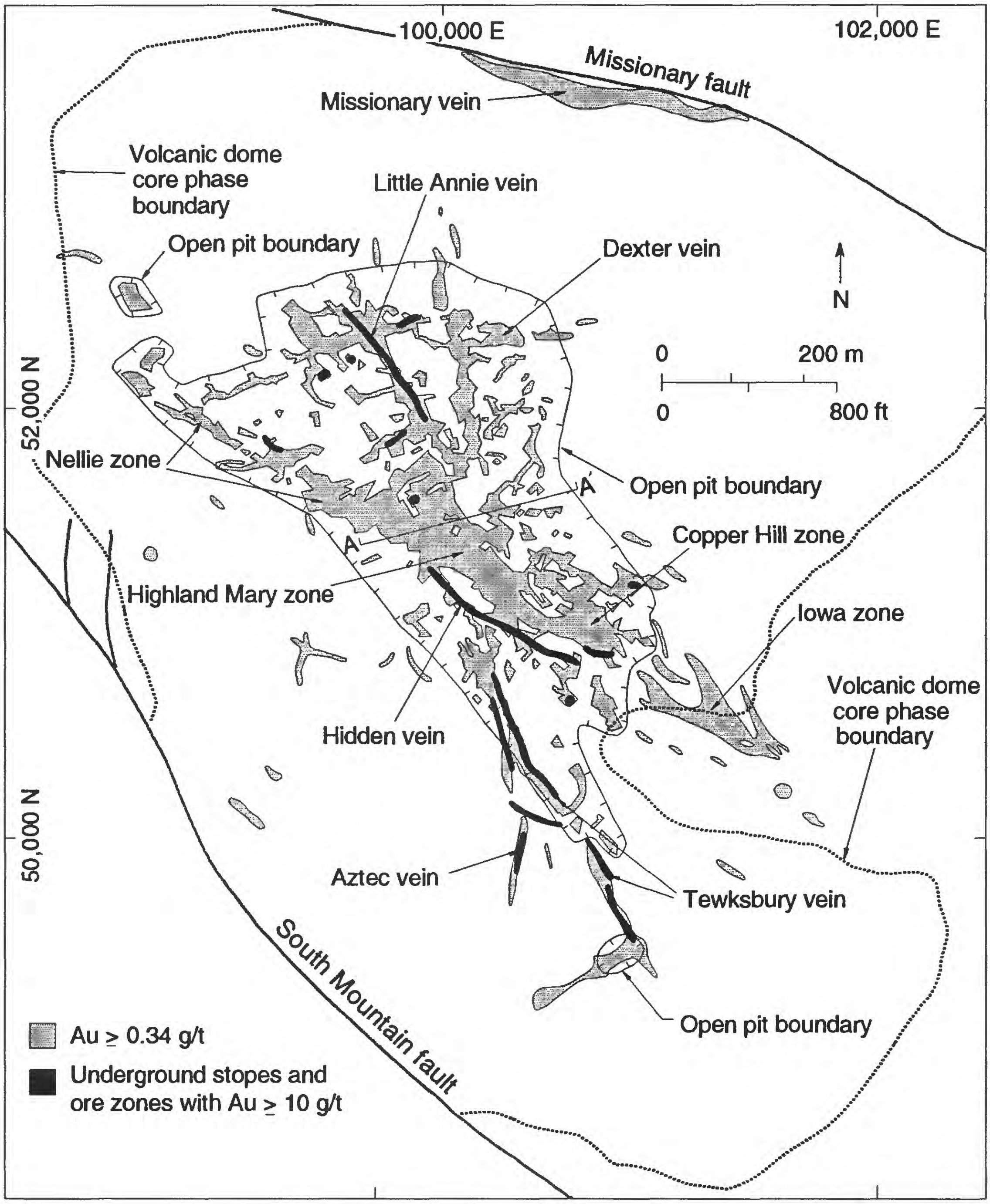

Figure 4. Plan view of ore-grade gold zones. Inside the pit boundary, grades greater than 0.34 g/t gold were based on compilation of the blast-hole ore control maps (SCMCI, unpublished data). Outside the pit boundary, ore zones were based on vertical projections of development drill holes. Ore zones with greater than 10 g/t gold and underground stopes were based on data prior to open-pit mining (Steven and Ratté, 1960), in addition to open-pit blast hole and underground mine data (SCMCI, unpublished data). Volcanic dome core phase boundary plotted from unpublished data from Anaconda Copper Co.

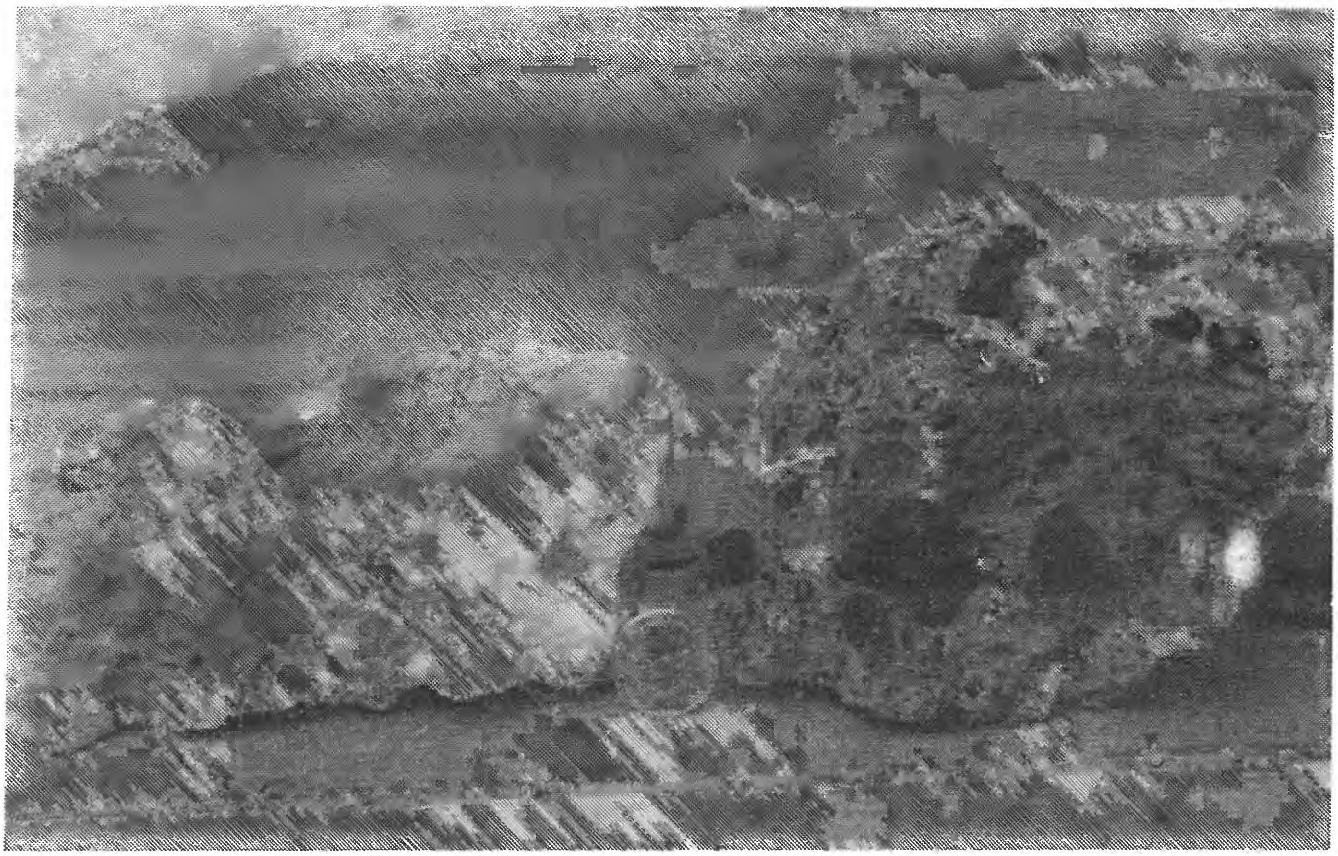

Figure 5. Fresh quartz latite (left) is shown beside a sample of intensely altered vuggy silica (right).

Figure 6. Sample of vuggy silica with euhedral hydrothermal quartz crystal overgrowths on relict quartz phenocrysts.

Figure 7. Sample of coarsely-crystalline covellite filling voids in vuggy silica indicating that the Cu-sulfide stage of mineralization postdates acid-sulfate alteration that formed the vuggy silica.

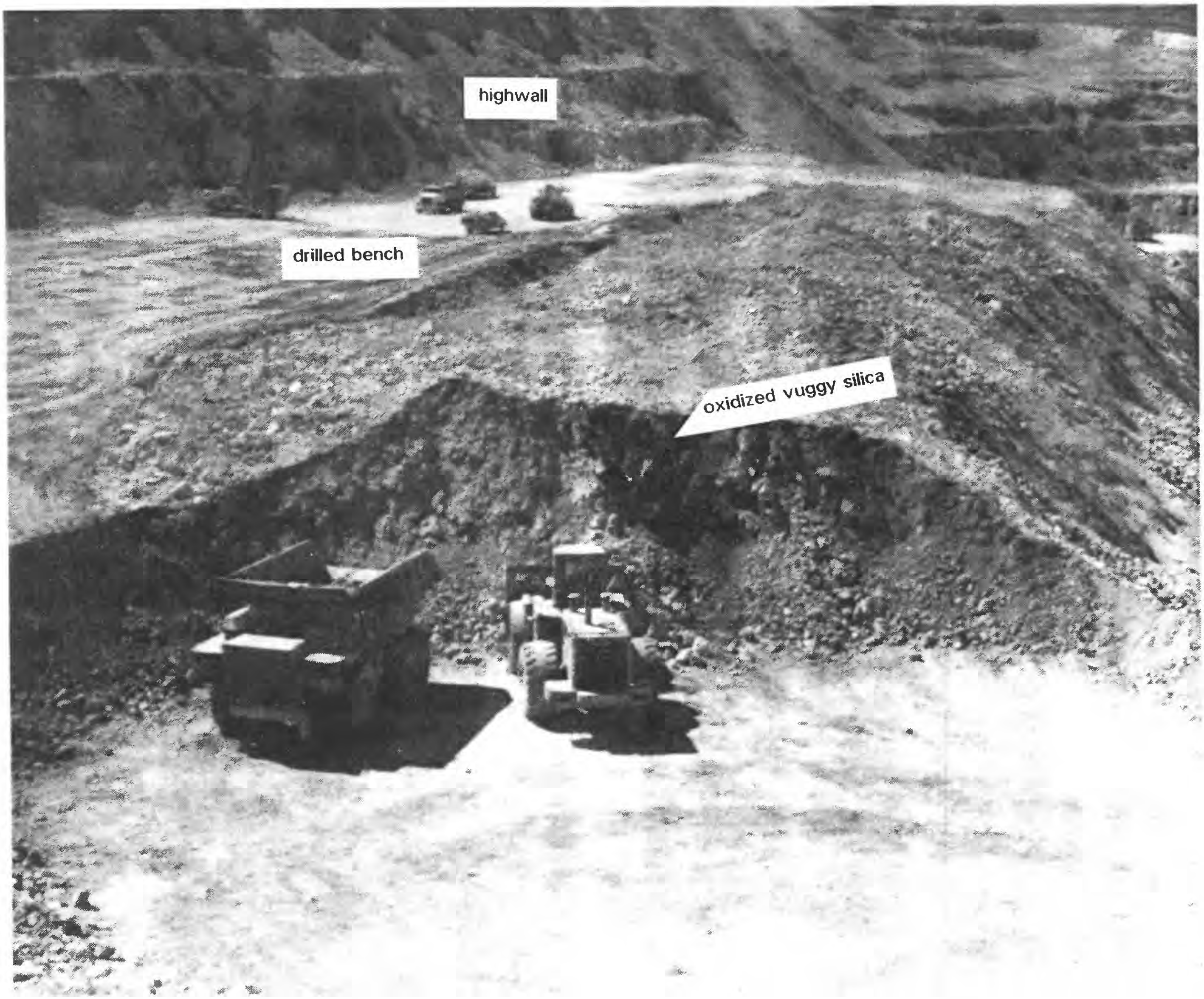

Figure 8. An oxidized gold-ore zone in the Summitville open-pit being removed during mining of a blasted bench in 1988.

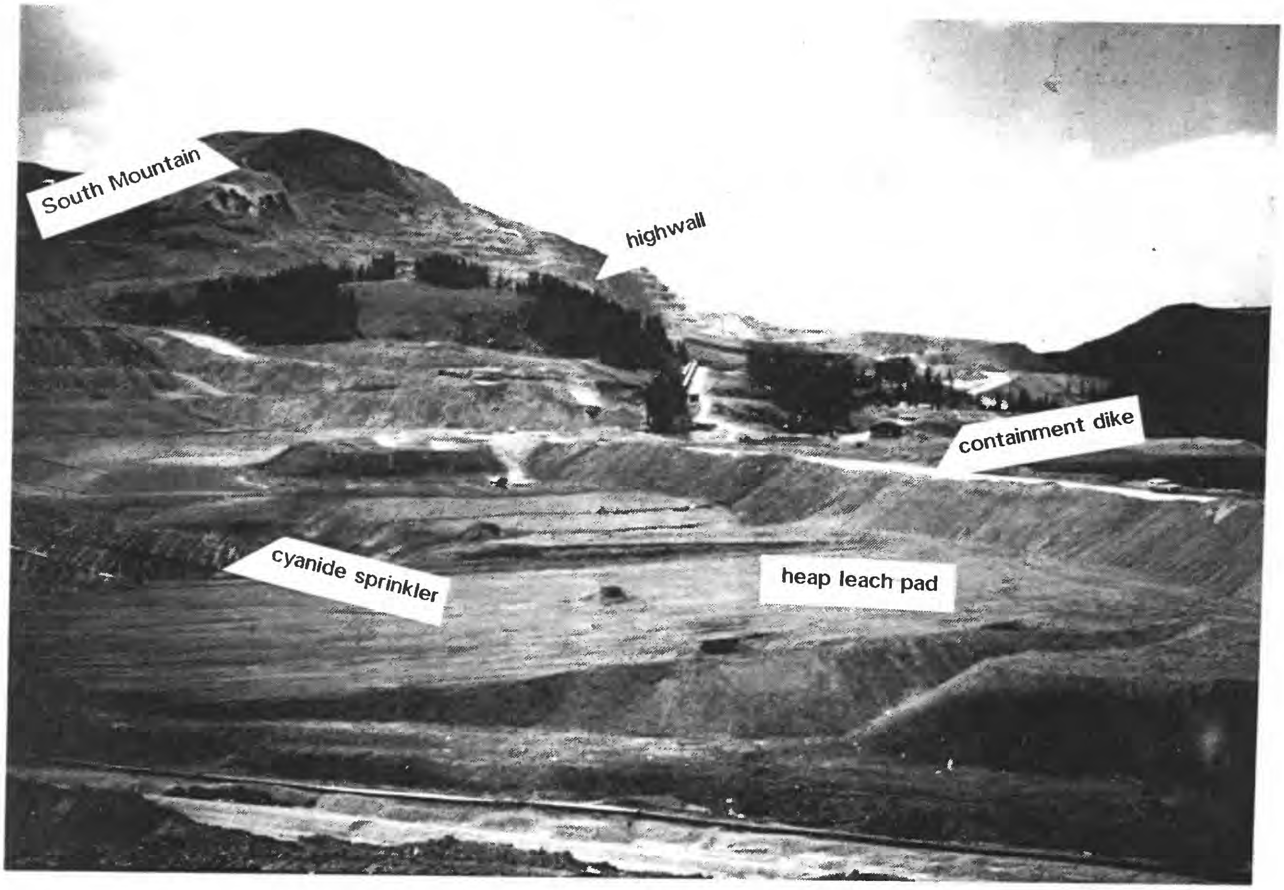

Figure 9. View of the heap leach pad in 1989 showing containment dike and cyanide sprinklers.

Figure 10. Aerial view of Summitville mine looking south showing location of open-pit, waste dumps, and heap leach pad (photo from IntraSearch, Inc., 1991).