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Natural acid drainage from altered areas within and adjacent to the Upper Alamosa River Basin, Colorado

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ABSTRACT

Remediation of environmental problems associated with the Summitville mining site and other sites with acid mine drainage, has raised questions as to what are natural geochemical background levels in natural media from altered and mineralized areas prior to mining activities.

Water quality of streams draining five altered but undeveloped areas were investigated within and adjacent to the upper Alamosa River Basin. The study focused on establishing geochemical baselines for stream waters from the altered areas, for a particular time (July, 1993) and investigated geochemical processes controlling the water chemistry and the generation of natural acid drainage.

The five altered areas are examples of mineralized areas that have not been significantly impacted by mining. The range in metal contents of the waters from these areas establishes a geochemical baseline for a period of time of approximately mean flow. Two types of water are generated from these areas. The waters from Cat Creek, Jasper, and Crater Creek altered areas are mainly calcium-bicarbonate type waters which appear to be buffered by carbonate minerals, particularly calcite, raising the pH, and limiting the metal content. The carbonate minerals may be accessory minerals associated with the alteration. The waters from the Stunner and Summitville areas (upper Cropsy Creek, above the Summitville mine site) are acid-sulfate waters with similar characteristics to acid mine drainage waters.

Numerous iron oxides deposits have and are forming in the Stunner and upper Cropsy Creek altered areas continuously since about 10,000 years ago. The presence of iron oxide deposits demonstrate that NAD waters have been present prior to mining.

Chemical modeling of the acid-sulfate waters using PHREEQE indicate that iron concentrations are controlled by ferrihydrite, aluminum by jurbanite, calcium and sulfate by gypsum (or anhydrite), and silica by amorphous silica or chalcedony. The observed concentrations of Zn, Cu, and Ni in acid-sulfate type waters are lower than that calculated by the chemical modeling and are probably controlled by adsorption onto precipitating hydrous metal oxides.

The geochemical background of stream waters draining the mine site prior to mining (Cropsy Creek above the junction with Wightman Fork) would probably fall between the geochemistry of stream waters presently draining upper Cropsy Creek above the mine site (a minimum) and Alum and Bitter Creeks at their confluence with the Alamosa River (a maximum).

Without the impact of mining, it is reasonable to assume that the pH values for the Wightman Fork above the junction with the Alamosa River would be in the range of 6-7 and metal values < 1 mg/l. In contrast, the Alamosa River above the Wightman Fork receives significant drainage from altered areas undergoing pyrite oxidation. Values for pH of waters from the Alamosa River above Wightman Fork have probably been in the range of 4-5 with metal values such as Fe, Al, and Zn in excess of 1 mg/l for the last 10,000 years.

INTRODUCTION

Remediation of environmental problems associated with the Summitville mining site and other sites with acid mine drainage (AMD) has raised questions as to what are natural geochemical background levels in natural media from altered and mineralized areas prior to mining activities. This information is important in order to establish geochemical baselines for natural material such as stream water for remediation purposes.

At Summitville, mining has exposed altered rocks, containing pyrite, to atmospheric oxygen, causing oxidation of the pyrite and the generation of AMD. Prior to 1875, when significant lode mining began, natural acid drainage (NAD) was most likely being generated at the present mine site. Several areas in the vicinity of the mine site, particularly in the upper Alamosa River basin, contain significant altered and mineralized rocks with abundant pyrite. These areas have not been significantly impacted by mining. But streams draining several of these altered areas contain NAD, similar to the more familiar AMD. The mineralized areas investigated include: 1) the Cat Creek area, north of the Alamosa River basin; 2) the Crater Creek area, west of the upper Alamosa River basin; 3) the Jasper area, within the Alamosa River basin; 4) the Stunner area, within the Alamosa River basin; and 5) the Summitville area (particularly the upper Cropsy Creek area above the Summitville mine site), within the Alamosa River basin. This study focuses on establishing geochemical baselines for stream waters draining these altered, but mainly undeveloped areas, for a particular time (July, 1993) and investigates the geochemical processes controlling the water chemistry and the generation of NAD. For comparative purposes, samples were also collected from unmineralized areas.

STUDY AREA

Elevations in the study area (fig. 1) range from nearly 13,000 feet at some of the higher peaks to 8400 feet at the mouth of the Alamosa River Canyon. Precipitation ranges from a high of around 40 inches, at the Summitville mine site, to 12 inches in the eastern portion of the study area (U.S. Dept. of Commerce, 1974). The study area lies within the San Juan volcanic field. This volcanic sequence consists of Oligocene and younger age volcanics beginning with an initial eruption of intermediate composition lavas and breccia, followed by more silicic ash-flow tuffs, and ending with bimodal association of basalt and rhyolite (Lipman and others, 1970). Alteration in the Cat Creek area, Jasper area, Stunner area, Summitville area, and the Crater Creek area (fig. 1) is associated with emplacement of monzonitic stocks. These areas occur along the ring structures and the margin of the Platoro caldera complex (Lipman, 1975). Two main events of alteration and mineralization occurred in association with the Plataro complex. The first event occurred during late-stage emplacement of monzonitic stocks around 29.1 to 27 m.y. ago (Lipman, 1975). The Stunner, Jasper, and Cat Creek areas were altered during this event. The Crater Lake area was probably

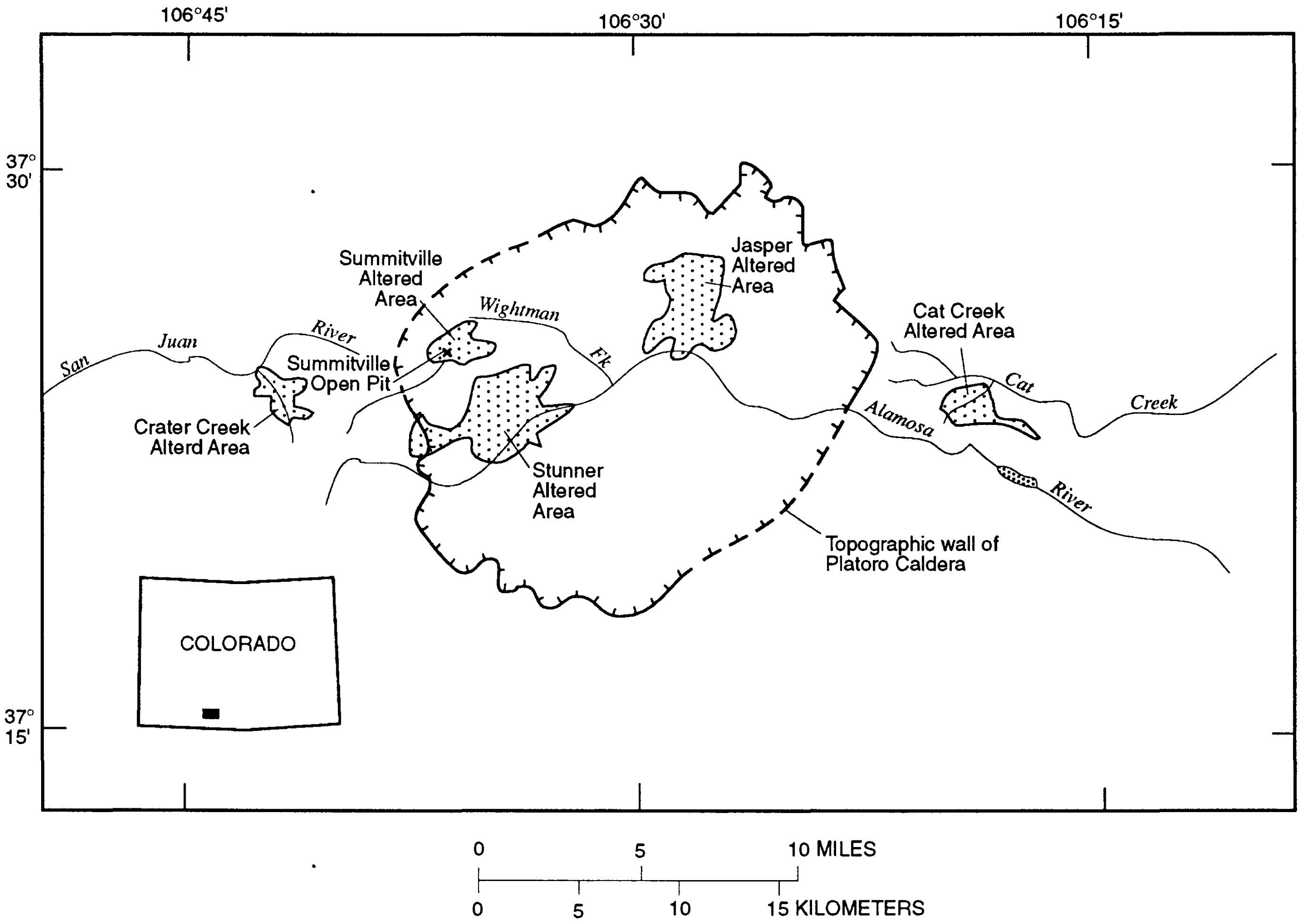

Figure 1.--Map showing location of the altered areas in and adjacent to the upper Alamosa River basin.

altered during this event, but age is uncertain. The second event was the emplacement of an underlying monzonitic stock at Summitville at 22.5 my ago (Mehnert and others, 1973) which deposited Au-Ag-Cu ore in a shallow volcanic environment.

Alteration in the study area consists, generally, of argillic to advanced argillic alteration as well as propylitic alteration. Pyrite is ubiquitous in the altered areas, occurring as disseminations, but also along fractures. At Summitville, alteration consists of zones emanating outward from a center of highly leached rocks in which only vuggy quartz and ore minerals remain, to an alunite and clay zone, and finally to propylitized rock (Steven and Ratte, 1960).

Much of the present topography in the study area has been influenced by Pinedale glaciation (late Pleistocene age), which was at its maximum approximately 18,000 years ago (Richmond, 1965). The glaciers were in retreat approximately 12,000 years ago, and only minor modification of the topography has taken place since then. Natural acid drainage and the formation of secondary iron oxide deposits began during melting of the glaciers and has continued since then. Iron oxide deposits, both fossil and actively precipitating deposits, consisting mainly of masses of geothite and limonite and iron oxide-cemented gravel, conglomerates, and talus, are present below pyritically altered rocks. Many of these deposits are associated with seeps that occur at changes in slope and along the valley floor. In addition, hydrous iron oxide deposits are precipitating within the stream bed of the Alamosa River and its tributaries downstream from pyritically altered areas. Pyrite is being oxidized, the products removed, and the steep to moderate relief ensures that fresh rocks containing pyrite continue to be exposed to oxidation.

METHODS

Samples of rocks, soils, and waters from streams and seeps were collected during July 16-20, 1993 (fig. 2). Chemical analyses of these samples are shown in Appendix table 1. Water samples were collected in polyethylene bottles that had been rinsed with 10 percent HNO_3. At each site, a 60-mL sample was collected and filtered through a 0.45-μm filter, and acidified to pH<2. An additional untreated 500-mL sample also was collected. Temperature and pH were measured at each site (Appendix table 1). At many sites, ferrous and ferric iron and oxygen were determined colorimetically with a Hach DR/2000 spectrophotometer. Alkalinity, specific conductance, SO_4^{2-}, Cl^-, and F^- were determined on the untreated samples within 14 days of collection. The remaining species were determined using the filtered and acidified sample. Major and minor elements were determined according to standard methods of the USGS (table 1). Trace metals were determined by graphite furnace atomic absorption spectrometry. Anions were measured with the ion chromatograph, except for alkalinity (HCO_3^-), which was determined by titration with sulfuric acid.

The stream waters are all oxidizing. Measurements of

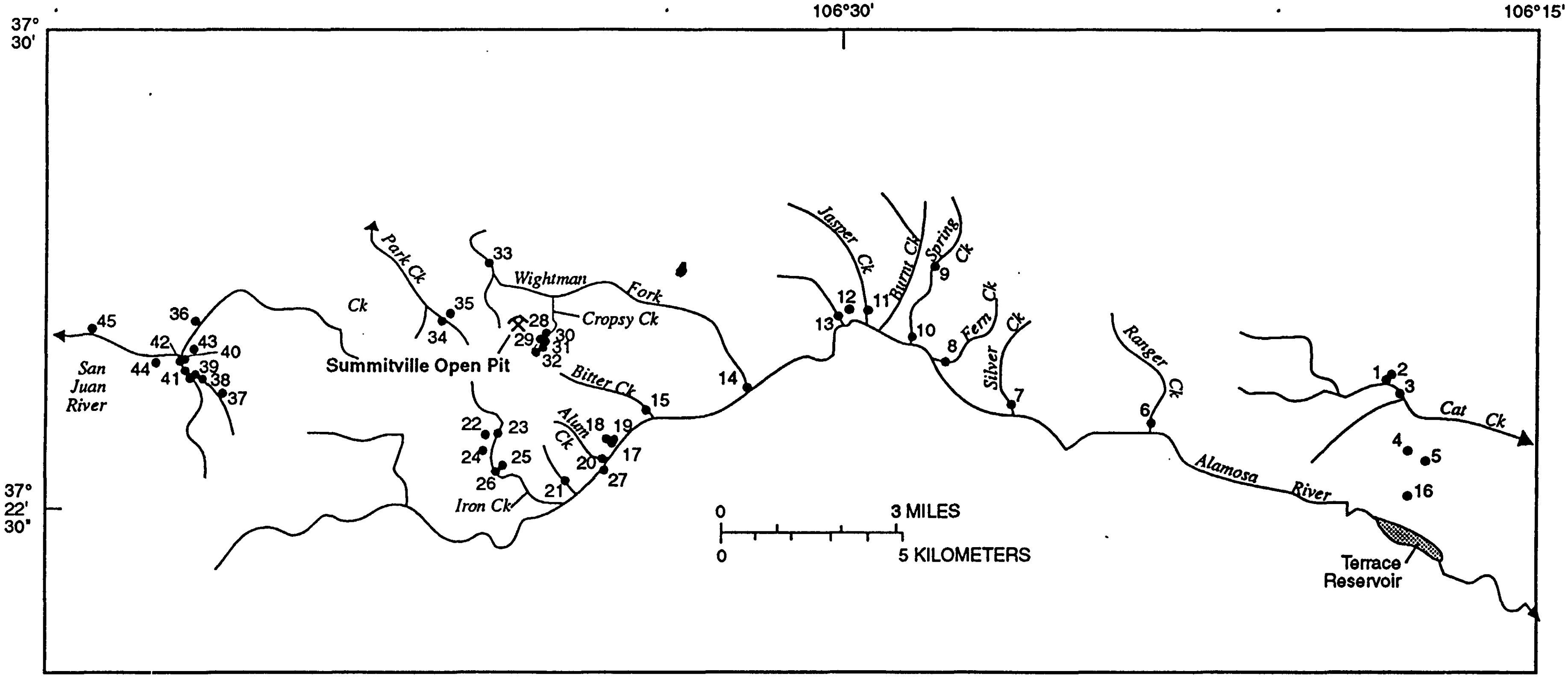

Figure 2.--Map showing site location for water samples in and adjacent to the upper Alamosa River basin.

Table 1. Analytical methods used for water analyses

Constituents	Method	Reference
Alkalinity	Gran's plot potentiometric titration	Orion Research, Inc. (1978)
Specific conductance	Conductivity bridge	Skougstad, et al. (1979)
Sulfate, fluoride, chloride, and nitrate.	Ion chromatography	Fishman and Pyen (1979)
Calcium, magnesium, sodium, potassium, silica, iron, manganese, aluminum, and zinc.	Flame atomic absorption spectrophotometry.	Perkin-Elmer, Corp. (1976)
Arsenic, silver, copper, cadmium, cobalt, lead, nickel, and chromium.	Flameless atomic absorption spectrophotometry.	Perkin-Elmer, Corp. (1977)

dissolved oxygen in the stream waters ranged from 7 to 12 mg/L, which is near saturated for the observed temperature and elevation. Redox potential was determined by using the ferrous/ferric couple and on the assumption that the water is in equilibrium with ferrihydrite.

Rocks and soils were analyzed for chemical composition by inductively coupled plasma atomic emission spectroscopy analysis after acid digestion (Lichte and others, 1987). The results are shown in the Appendix tables 2-3.

The water analyses were used as input for chemical modeling using PHREEQE (Parkhurst and others, 1980). This was done to gain an understanding of chemical speciation, redox conditions, and saturation states of minerals that may control concentrations of elements in the stream waters. Information on modeling programs can be found in Bassett and Melchior, 1990. The modeling calculations do not account for kinetic effects that may inhibit precipitation, particularly at low temperatures.

SEASONAL VARIATION

Water samples were collected July 16-20, 1993. Therefore seasonal variation was not determined. Long term stream-flow records of a gauging station on the East San Juan River above Sand Creek, an adjacent basin west of the Alamosa River basin, are available. The spring runoff period occurs in late May to mid June (USGS, 1993). The most stable flows usually occur from October to March. The variation in mean monthly discharge for the water years 1957 to 1992 is shown in fig. 3. Studies by past workers such as Miller and Drever (1977), Baldwin et al. (1978), and a summary by Jeffries (1991), indicate that stream-water chemistry in the Rocky Mountains follows a general pattern with increase in dissolved constituents at the beginning of the spring runoff due to two processes: 1) flushing of salts from the soil zone, which have built up by capillary action and evaporation during the more stable winter flow; and 2) the tendency of the first snow melt to be enriched in dissolved solids. This is followed by dilution during the spring runoff when the concentrations of dissolved species reach a minimum, a gradual increase in dissolved solids during the summer, and a stable flow in late autumn and winter. Precipitation from occasional thunderstorms in the summer and unusually warm weather in the winter with associated melting of snow cause fluctuations from the normal pattern.

The mean annual stream flow in July, using the San Juan River gauging station, is 115 cfs, and the average annual mean is 89.3 cfs. The flow in July is only slightly less than the mean annual flow. Therefore the geochemistry of the water samples, which were collected in July, approximate the annual mean geochemistry.

RESULTS

Cat Creek Area

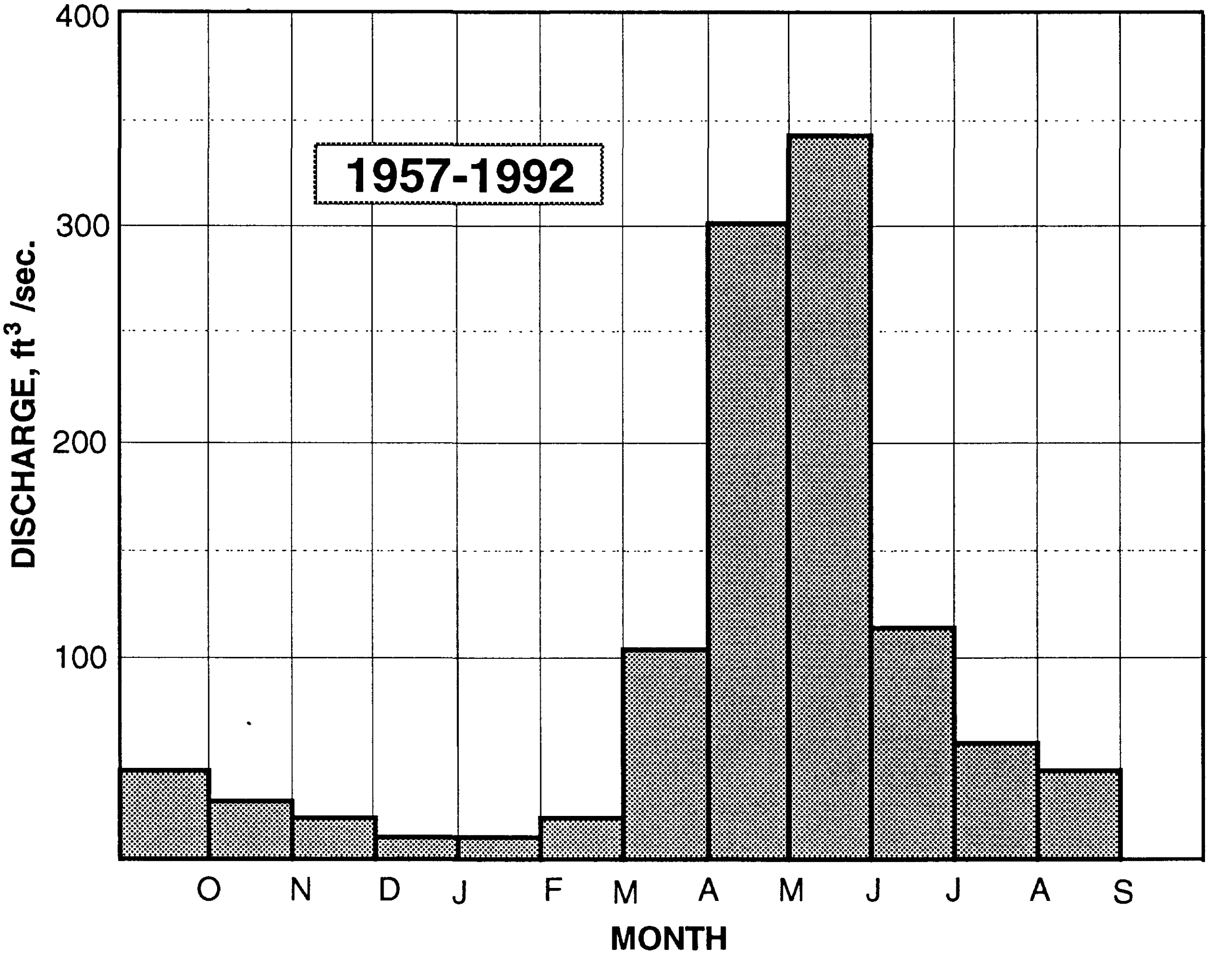

Figure 3.--Variation in mean monthly discharge for the San Juan River above Sand Creek (USGS, 1993)

Alteration occurs along the upper Cat Creek drainage which exits the mountain front and flows into the San Luis valley north of the Alamosa River (fig. 1). The observed alteration is associated with the 27 to 27.5 m.y. Cat Creek monzonitic stock, that is probably the core of a volcano. The stock consists of fine-grain monzonite flanked by satellitic laccolithic bodies of porphyry (Lipman, 1975). Pyritization occurs along a southeast-trending fracture system adjacent to the stock. Alteration consists of iron-stained fractures and local silicified areas with massive pyrite. Galena was observed at one location. Samples of altered rocks and soils are anomalous in Ag, As, Ba, Bi, Cu, Pb, and Zn (Appendix tables 2-3). Prospect pits and small adits are present, but no drainage was observed from these workings. No mineral production is recorded from this area.

Water samples were collected from two streams, two seeps, and a spring. The waters are calcium-bicarbonate type waters with alkaline pH values (Appendix table 1). Trace metal contents are low, probably because of the alkaline pH values. The maximum conductivity value is 710 μS/cm, which indicates significant reaction of the waters with minerals in the subsurface. The range in chemical composition of the waters is summarized in table 2. This area receives the least precipitation in the study area (approximately 12 inches). Cl^- concentration, is greater in the Cat Creek area than the other altered areas in this study, which suggests that the waters in this area have undergone greater evaporation. The maximum sulfate content is 120 mg/L, which indicates that the waters are reacting with pyrite, but minerals are buffering and mitigating the acidity generated by oxidation of pyrite.

Chemical modeling using PHREEQE indicates that the waters are saturated or are near saturation with respect to calcite. In addition, several of the water samples are saturated with respect to dolomite, fluorite, and rhodochosite, suggesting these minerals are present, possibly as alteration minerals. Another possibility is that the waters are in contact with underlying carbonate rock. The waters from the Cat Creek area present no environmental problem.

Jasper Area

The Jasper altered area is located on the north side of the Alamosa River on the east margin of the Summitville caldera. Argillic to advanced argillic alteration occurs within the roof zone of the > 28 m.y. old Jasper stock (Lipman, 1975). Mineralization, which occurs along the southern margin of the stock, consists of quartz veins with pyrite containing gold and silver values (Patton, 1917). On the north side of the Alamosa River, a few prospect pits are present, but no associated discharge occurs from the workings.

Water samples were collected from four streams draining the altered area. Burnt Creek, which drains the most intensely altered area, was dry. Considerable altered rock with pyrite occur as float in the stream bed. Burnt Creek is probably the most chemically degraded of the streams draining the altered

Table 2. Range of chemistry of waters from the Cat Creek altered area. Samples were collected July 16 and July 17, 1993.

Dominant water type: alkaline calcium bicarbonate

Conductivity	270-710 µS/cm
pH	7.5-8.1
Eh	.02-.16 v
$SO_4^{=}$	8-120 mg/l
Fe	.01-.09 mg/l
Al	<.1 mg/l
Cu	<1 µg/l
Zn	6-10 µg/l

area. The four streams contain calcium-bicarbonate type waters with alkaline pH values (Appendix table 1). The maximum conductivity value is 290 µS/cm. Trace metal content is low, probably because of the alkaline pH values. The chemical composition of the waters is summarized in table 3. The maximum sulfate content is 90 mg/L, which probably indicates pyrite oxidation. Samples of three rocks and two soils contain slightly anomalous concentrations of As and Ba (Appendix tables 2-3).

Chemical modeling of the waters indicate that one stream water sample is saturated with respect to calcite. This suggests that calcite may be present as an alteration mineral and therefore may be buffering any acidity derived from oxidizing pyrite in that stream drainage. During the first flush of Spring runoff, and after significant thunderstorms, Burnt Creek, may carry significant trace metal loadings and acidity. The waters of the Jasper area are alkaline with low trace metal concentrations, and present no environmental problems at this time. During spring runoff and after thunderstorms, the flushing of soluble salts in the Burnt Creek drainage may cause environmental problems due to acidity and high trace metal loadings.

Stunner Area

The Stunner altered area is associated with the Alamosa River monzonitic stock. Advanced argillic alteration, occurs on the northern part of stock and the adjacent wall rock. Mineralization, which occurs along the south bank of the Alamosa River, consists of quartz veins with pyrite containing gold and silver tellurides (Patton, 1917). Some of the most intensely altered rocks occur north of the river within the Alum and Bitter Creek drainages (fig. 2). Calkins (1971) and Sharp and Gualtiere (1968) conducted studies in this area and described the rocks as a porphyritic phase with locally anomalous metals and abundant quartz veinlets containing pyrite. Most of the mine workings in the Stunner altered area are along the south side of the Alamosa River. Only one mine on the north side of the river, the Pass-Me-By mine which occurs along Iron Creek, contributes AMD to the Alamosa River. One soil and 11 rock samples were collected from the Stunner area. The samples are weakly or moderately anomalous in As, Ba, Cu, Pb, and Zn (Appendix tables 2-3).

Samples of water collected from eight streams and three seeps are acid-sulfate type waters with pH values down to 2.52 and conductivity values up to 2400 µS/cm (Appendix table 1). Sulfate and metal concentrations are also high. Chemical compositions of the waters are shown in table 4. Many of the waters from the Stunner area have similar geochemical characteristics to AMD waters. Except for the Pass-Me-By mine, which contributes only a small volume of flow to the upper Alamosa River drainage (probably less than 1 %), no other mine workings contribute AMD. The most chemically degraded stream is Alum Creek, which drains an intensely altered area with no mine workings.

Numerous deposits of iron oxides and to a lesser extent

Table 3. Range of chemistry of waters from the Jasper altered area. Samples were collected July 17, 1993.

Dominant water type: alkaline calcium sulfate, bicarbonate

Conductivity	150-290 µS/cm
pH	7.5-8.1
Eh	.05-.15 v
$SO_4^{=}$	13-90 mg/l
Fe	.01-.15 mg/l
Al	<.1-.2 mg/l
Cu	<1-1 µg/l
Zn	5-7 µg/l

Table 4. Range of chemistry of waters from the Stunner altered area. Samples were collected July 17 and 18, 1993.

Dominant water type: acid calcium sulfate

Conductivity	80-2400 µS/cm
pH	2.5-7.3
Eh	.12-.74 v
$SO_4^{=}$	10-1250 mg/l
Fe	.12-141 mg/l
Al	<.1-55 mg/l
Cu	<1-370 µg/l
Zn	8-1000 µg/l

manganese oxides are present in the Stunner area. The oxide deposits occur as masses or as material cementing clastic debris, usually at changes in slope and along faults and fractures below oxidizing pyrite. Also hydrous iron oxide precipitates are presently forming along stream beds. The iron oxides have formed continuously since about 10,000 years ago, when the melting of the last glaciers of Pinedale age occurred. The presence of iron oxide deposits in the Stunner area demonstrate that NAD waters have been present prior to mining.

Chemical modeling of the acid-sulfate waters from the Stunner area indicate that iron concentrations are controlled by ferrihydrite (poorly crystalline hydrous iron oxides), aluminum by jurbanite, calcium and sulfate by gypsum (or anhydrite), and silica by amorphous silica or chalcedony. The concentration of Cu and Zn are probably controlled by adsorption onto hydrous iron oxide and Ni by adsorption onto manganese oxides, similar to that found by Miller and others (in press) in a study in the Front Range, Colorado. The Stunner area contains stream waters that are an environmental concern with respect to pH and Zn concentrations.

Summitville area

The alteration and mineralization in the Summitville area is associated with a late-stage volatile-rich phase of an underlying monzonitic stock. Intensely altered rocks ranging from vuggy silica in which all the original minerals are leached to advanced argillic, argillic, and propylitic alteration are present (Steven and Ratte, 1960). Sampling was designed to avoid the mine site and any influence from prior mining. The area that is most similar to the mine site and is not disturbed by mining is upper Cropsy Creek drainage above the mine site. The area is intensely altered, similar to the mine site (but obviously not containing high enough ore-grade values and/or volume to make an economic deposit). Most of the alteration appears to be argillic to advanced argillic, which probably resulted from solfataric activity. Samples of one rock and one manganese-oxide cemented stream sediment were collected. The rock sample is anomalous in Ba and weakly anomalous in As. The manganese-oxide cemented sediment is anomalous in Mn, Ba, As, Cd, Cu, and Zn.

Samples of water from four small streams and one seep were sampled in the upper Cropsy Creek drainage. The waters are acid-sulfate type waters, resulting from the oxidation of pyrite. Values of pH are as low as 4.4 and conductivity as high as 460 μS/cm (Appendix table 1). Concentrations of sulfate and trace metals except for zinc are moderate. Zinc concentrations reach 1800 μg/L. The chemical composition of the waters is summarized in table 5. Iron oxide deposits are present in the altered area, particularly at changes in slope, but are not as numerous as those seen in the Stunner altered area. Manganese-oxide cemented sediments are present in the stream bed of one of the tributaries.

Chemical modeling of the water chemistry indicates that iron concentrations are controlled by ferrihydrite, aluminum by

Table 5. Range of chemistry of waters from the Summitville altered area (excludes drainage from mine sites). Samples were collected July 19, 1993.

Dominant water type: acid calcium sulfate

Conductivity	50-460 µS/cm
pH	4.4-7.3
Eh	.16-.73 v
$SO_4^{=}$	2-220 mg/l
Fe	.02-.22 mg/l
Al	<.1-17 mg/l
Cu	<1-46 µg/l
Zn	27-1800 µg/l

jurbanite or aluminum hydroxide, and silica by amorphous silica or chalcedony. Cu and Zn are probably controlled by adsorption onto hydrous iron or manganese oxides. The waters from the upper Cropsy Creek area are similar to those from the Stunner area with low pH values and high trace metals. These waters are an environmental concern with respect to pH and Zn concentrations.

Crater Creek Area

Crater Creek altered area is located along Crater Creek and occurs within the Bear Creek stock and along faults adjacent to the stock. Rocks are pervasively argillized. Three adits and numerous prospect pits are present. Samples of the altered stock containing disseminated pyrite and chalcopyrite were collected from outcrops. In addition, quartz veins containing galena and sphalerite were collected from the dumps of two adits. No recorded production is known. The three mine dump samples are highly anomalous in Ag, Pb, and Zn. The four samples of altered rocks are weakly anomalous in Ba, Cu, and Zn (Appendix table 2).

Water samples were collected from 7 streams and 2 mine adits. The drainage from the two mine adits have pH values of 7.42 and 4.19, conductivities of 540 and 560 μS/cm, and high concentrations of sulfate and Zn (Appendix table 1). The drainage from one of the two mine adits would be classified as AMD. The 7 steams that were sampled are draining altered but undeveloped areas. The stream waters are all calcium-bicarbonate type waters with alkaline pH values and conductivities up to 250 μS/cm. Concentrations of sulfate are moderately anomalous, but trace metal contents are low (Appendix table 1). The chemical composition of the waters is summarized in table 6. Chemical modeling indicates that most of the stream waters are saturated or near saturation with respect to calcite and chalcedony. One stream is near saturation with respect to dolomite. The moderate contents of sulfate and saturation with respect to calcite suggest that the waters are in contact with oxidizing pyrite, but that calcite, probably as an accessory mineral in the altered rock, buffers the pH to above neutral, limiting the trace metal contents. Stream waters from the Crater Creek area represent no environmental concerns. The one mine adit with AMD is an environmental concern with respect to pH and Zn. Because of its low flow and immediate dilution by Crater Creek, the water from the mine adit represents little overall environmental concern.

Background Areas and Wightman Fork

Waters from several streams draining unaltered, but similar to the rocks in the altered areas, were also sampled. The purpose was to establish baseline geochemistry for stream waters draining unaltered and unmineralized rocks in the study area. Water from Wightman Fork, which drains the Summitville mine site, was also sampled for comparative purposes.

Two tributaries to the Alamosa River and a tributary to Wightman Fork, north of Summitville were sampled. The waters from the two tributaries are dilute, calcium-bicarbonate type

Table 6. Range of chemistry of waters from the Crater Creek altered area (excludes drainage from mine adits). Samples were collected July 20, 1993.

Dominant water type: alkaline calcium bicarbonate

Conductivity	90-250 µS/cm
pH	7.5-8.5
Eh	-.03-.52 v
$SO_4^=$	6-53 mg/l
Fe	.01-.05 mg/l
Al	<.1 mg/l
Cu	<1 µg/l
Zn	6-8 µg/l

water with conductivities of 120 and 150 µS/cm and pH of 8.11 and 8.13. Fe, Mn, and Al contents are less than 0.1 mg/L and Cu, As, Co, Cd, Ag, Ni, and Pb are less than 1 µg/L. Zn contents for both streams are 4 µg/L (Appendix table 1).

The water from the tributary north of the Summitville mine site (fig. 2) is very dilute water, with a conductivity of 40 µS/cm, pH of 7.25, and very low metal contents (Appendix table 1). These background samples indicate a range in chemical composition of surface waters draining unmineralized and unaltered areas (table 7).

The water sample collected from the Wightman Fork has a conductivity of 1210 µS/cm and pH of 4.64 (table 8). Metal contents are high, particularly for Cu at 7800 µg/L (table 8). Except for the Cu content, the chemistry of the Wightman Fork is similar to Alum Creek. But because the volume of flow of the Wightman Fork is greater than the other tributaries draining the altered areas on the north, the input of loadings of metals and acidity to the Alamosa River are probably greater than that contributed from the other altered areas.

DISCUSSION AND SUMMARY

Pyrite is present in each of the five altered areas. Oxygenated waters from rain and snow oxidize and dissolve pyrite, releasing Fe^{2+}, SO_4^{2-}, H^+, and metals originally contained within the pyrite. Many workers have studied the oxidation of pyrite (summarized in Nordstrom, 1982). Overall, pyrite oxidation is described by the following reaction:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+ \quad (1)$$

For every mole of pyrite that is oxidized, four moles of H^+ are released to the water. Few reactions in nature produce this amount of acidity. The steps in the oxidation of pyrite are not fully understood, but initially pyrite, in the presence of moisture and oxygen, is oxidized releasing S° (Sato, 1960), which is then oxidized. These reactions can be summarized by:

$$FeS_2(s) + 7/2\ O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (2)$$

The ferrous iron in reaction (2) is then oxidized to ferric iron by:

$$Fe^{2+} + 1/4\ O_2 + H^+ \rightarrow Fe^{3+} + 1/2\ H_2O \quad (3)$$

Ferric iron in the presence of pyrite is an effective oxidant of pyrite (Garrels and Thompson, 1960, Smith and Shumate, 1970) as shown by :

$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+ \quad (4)$$

Reaction (3) is considered to be the rate determining step. The rate of this step decreases as a function of hydrogen ion concentration down to pH 3.5. At around pH 3.5 or less, the

Table 7. Range of chemistry of waters from unmineralized areas. Samples were collected July 17 and 19, 1993.

Dominant water type: alkaline calcium bicarbonate

Conductivity	40-150 µS/cm
pH	7.3-8.1
Eh	.02-.10 v
$SO_4^{=}$	0.8-7 mg/l
Fe	.01-.04 mg/l
Al	<.1-.1 mg/l
Cu	<1-1 µg/l
Zn	4 µg/l

Table 8. Chemical analysis of stream water from the Wightman Fork. Samples were collected July 17, 1993.

Water type: acid sodium, calcium sulfate

Conductivity	1200 µS/cm
pH	4.6
Eh	.47 v
$SO_4^{=}$	630 mg/l
Fe	14 mg/l
Al	13 mg/l
Cu	7800 µg/l
Zn	1700 µg/l

bacteria *Thiobacillus* and *Ferrobacillus ferrooxidans* may act as catalysts and accelerate the rate up to six orders of magnitude (Singer and Stumm, 1970 and Lacey and Lawson, 1970). Once pyrite has been oxidized by oxygen, (reaction (2)), reaction (4) can continue as long as pyrite and enough oxygen necessary to sustain microbial respiration are present (Nordstrom et al., 1979).

When the ferric iron is out of contact with pyrite or the pyrite has been completely used up, the ferric iron is rapidly hydrolyzed producing ferrihydrite:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \quad (5)$$

The oxidation of pyrite not only causes a large increase in acidity, but also can increase the oxidation of other metal sulfides that normally would be slow, such as the oxidation of chalcopyrite (Baldwin, et al., 1978):

$$CuFeS_2 + 2\ Fe_2(SO_4)_3 + 2\ H_2O + 3\ O_2 \rightarrow CuSO_4 + 5\ FeSO_4 + 2\ H_2SO_4$$

Based on the chemical modeling using PHREEQE, the dominant metal species in the acid-sulfate type waters in the study area are Fe^{2+}, Al^{3+}, Mn^{2+}, Zn^{2+}, Cu^{2+}, and Ni^{2+}, all simple cations. Other species become dominant at a few sites, particularly at higher pH values. PHREEQE was also used to determine dominant species for Zn, Cu, and Ni in a solution with changing pH and in equilibrium with atmospheric CO_2. Zn^{2+} is the dominant Zn specie for pH values up to about 8.4 where $ZnCO_3^0$ becomes dominant (fig. 4). Cu^{2+} is dominant Cu specie for pH values up to about 6.9 where $Cu(OH)_2^0$ becomes dominant (fig. 4). Ni^{2+} is dominant Ni specie for pH values up to about 7.4 where $NiHCO_3^+$ becomes dominant (fig. 4). The order in terms of mobility is Zn > Ni > Cu.

The observed concentrations of Zn, Cu, and Ni in acid-sulfate type waters are lower than that calculated by the chemical modeling and are probably controlled by adsorption onto precipitating hydrous metal oxides. Dzombak and Morel (1987) have comprehensively reviewed adsorption processes in aquatic systems. The most ubiquitous precipitate throughout the area is ferrihydrite, which probably plays a major role in limiting the concentration of these trace metals. The ferrihydrite precipitates are very fine grained with high surface areas and high adsorption capacities for trace metals (Drever, 1982, p 313). Flocculated material identified mainly as ferrihydrite also occurs suspended in the stream waters. Metal adsorption by ferrihydrite is pH dependent, increasing significantly with increasing pH (James and Healy, 1972). Other factors influencing adsorption processes are specific metal species and presence of other ligands such as dissolved organic carbon that may interfere with metal adsorption. Not enough information is available from the study area to quantify the influence of these precipitates on the concentrations of As, Cr, Cu, and Zn in the waters. The controls on the concentrations of Ni and to some extent Zn and Cu are probably adsorption processes associated with manganese oxides.

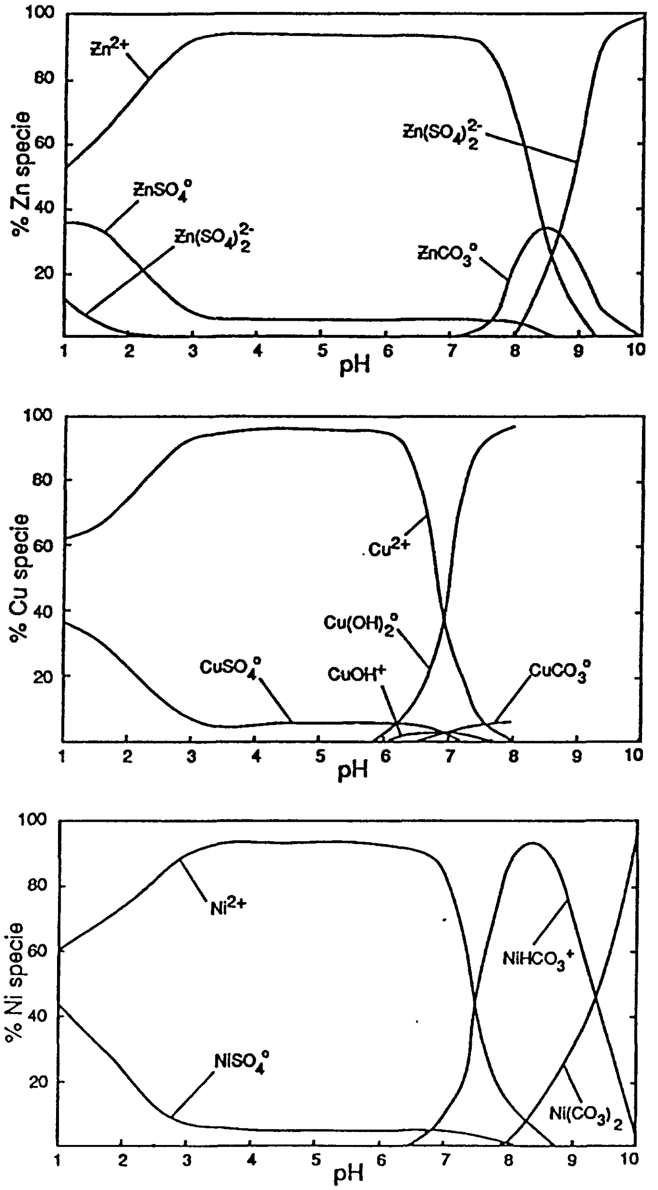

Figure 4.--Speciation of dissolved Zn, Cu, and Ni as a function of pH assuming equilibrium with atmospheric CO_2.

The five altered areas are examples of mineralized areas that have not been significantly impacted by mining. The range in metal contents of the waters from these areas establishes a geochemical baseline for a period of approximately mean flow in July 1993. Two types of water are generated from these areas. The waters from Cat Creek, Jasper, and Crater Creek areas are mainly calcium-bicarbonate type waters which appear to be buffered by carbonate minerals, particularly calcite, raising the pH, and limiting the metal content. The carbonate minerals are probable accessory minerals associated with the alteration. The waters from the Stunner and Summitville areas (upper Cropsy Creek, above the mine site) are acid-sulfate waters or NAD, similar to AMD waters. Factors which control the generation of NAD are shown in table 9. These two areas were extensively leached during alteration, and reactive minerals such as calcite and plagioclase, that may have been originally present, were destroyed. Therefore these two areas have no minerals with significant buffering capacity to neutralize the acidity of the waters.

Geochemical background of waters at the Summitville mine site prior to mining

Prior to mining, the area of the Summitville mine site probably generated NAD greater than NAD presently being generated in upper Cropsy Creek basin above the mine site. Probably more pyrite and sulfide minerals were originally present at the mine site than are present in upper Cropsy Creek basin above the mine site. In addition, the host rocks at the mine site have little buffering capacity to neutralize the acidity of the waters in contact with the oxidizing pyrite. The rocks in upper Cropsy Creek above the mine site are agillically altered, and some of the reactive buffering minerals such as plagioclase have been altered to clay. But more reactive buffering minerals are present in upper Cropsy Creek than at the mine site. For these reasons, the acidity generated originally at the mine site was probably higher than what is presently observed occurring in upper Cropsy Creek basin above the mine site.

In contrast, the original terrain at the mine site was less sever than upper Cropsy, Alum Creek or Bitter Creek drainages, which produce large amounts of NAD. Steep relief allows mechanical erosion to keep ahead of chemical weathering, continuing to expose pyrite to the atmosphere and subsequent oxidation. In alpine areas with less relief, bogs and wetlands often form, which tend to reduce the exposure of oxygen to sulfides, decreasing oxidation and the generation of NAD.

In order to establish reasonable geochemical baselines for streams draining the Summitville mine site, all these factors must be taken into account. Table 10 lists steps to calculate resonable geochemical baseline. Within undeveloped altered areas containing pyrite, springs and seeps often exceed water quality standards. It is not resonable to apply standards indiscriminately to any site, without taking into account volume of water flow. In some cases, water standards should be based on

Table 9. Factors controlling the generation of natural acid drainage (NAD) and metal loadings

Factors	Comments
1. Presence, amount, and character of iron sulfides	Influenced by type of mineralization and alteration; fine-grained disseminated iron sulfide has greater capacity for generating NAD than coarse-grained iron sulfides.
2. Accessibility of iron sulfides to O_2	Depends on rates of mechanical erosion, chemical reactivity of the host rocks, hydrologic system, fractures, porosity.
3. Chemistry of gangue and host rocks	Potential acid buffering capacity depends on rock and gangue minerals; acid buffering capacity: carbonates > mafic minerals > felsic minerals; also fine-grained minerals > coarse-grained minerals.
4. Presence of other sulfide minerals and trace-metal contents of iron sulfides.	Contributes to the addition of metal loadings.
5. Climate	Influences amounts of moisture in contact with iron sulfides, capacity to carry away oxidation products and exposing fresh sulfide minerals; for chemical weathering: humid > arid and warm > cool.
6. Physical setting	If mechanical erosion > chemical erosion, fresh sulfides will be continuously exposed; otherwise oxidized products will limit accessibility of O_2 and the generation of NAD; for NAD generation: steep topography > moderate > flat.

Table 10. Calculation of geochemical baselines for acid mine drainage sites (AMD)

- Select undeveloped site with equivalent basin size, geology, mineralization, and physical setting.
- Select background site with equivalent basin size, geology, and physical setting without mineralization.
- Determine geochemical baselines for these areas during high and low flow.
- Determine size of drainage basin and estimate the amount of mineralized verses unmineralized area of the basin above the AMD site.
- For natural geochemical baseline for AMD site, make mass balance calculation using geochemical baseline of control areas to represent the mineralized and unmineralized portions of the AMD basin.
- Extrapolate and adjust calculations for less than perfect fit between control areas and AMD basin.

loadings of acidity and metals instead of water quality.

We believe that the geochemical background of stream waters draining the mine site prior to mining (Cropsy Creek above the junction with Wightman Fork) would fit between the geochemistry of stream waters presently draining upper Cropsy Creek above the mine site (a minimum) and Alum and Bitter Creeks at their confluence with the Alamosa River (a maximum).

Wightman Fork above the junction with the Alamosa River, receives significant water flow from tributaries draining unmineralized rocks, which dilutes concentrations of metals and raises pH. Without the impact of mining, it is reasonable to assume that the pH values for the Wightman Fork above the junction with the Alamosa River be in the range of 6-7 and metal values < 1 mg/l. In contrast, the Alamosa River above the Wightman Fork receives significant drainage from altered areas undergoing pyrite oxidation. Values for pH of waters from the Alamosa River above Wightman Fork have probably been in the range of 4-5 with metal values such as Fe, Al, and Zn in excess of 1 mg/l for the last 10,000 years. Calculations would need to be made using the percent of mineralized rock verses the percent of unmineralized rock within the drainage basin in order to make mass balance calculations that would be reasonable estimates of a baseline at any particular site.

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APPENDIX

Table 1. Chemical Data for Stream Waters

Sample	Latitude	Longitude	Ca(mg/l)	Mg(mg/l)	Na(mg/l)	K(mg/l)	SiO_2(mg/l)	Fe(mg/l)	Fe^{2+}(mg/l)
Cat Creek Area									
3SW02	37 24 34	106 18 7	47	9.1	12	1.8	30	.02	--
3SW03	37 24 11	106 17 58	30	5.7	7.9	2.1	26	.09	--
3SW04	37 23 17	106 17 53	47	11	15	.9	26	.03	--
3SW05	37 23 11	106 17 30	82	15	39	2.8	26	.03	--
3SW16	37 22 32	106 17 49	65	11	12	1.2	18	.01	.01
Jasper Area									
3SW08	37 24 46	106 27 23	19	3.2	3.4	1	17	.02	--
3SW10	37 25 8	106 27 56	17	3.2	3.9	.9	15	.01	--
3SW11	37 25 22	106 28 46	18	2.4	2	.4	11	.15	<.01
3SW13	37 25 19	106 29 19	38	3.3	4.3	1.1	17	.02	--
Stunner Area									
3SW15	37 23 42	106 33 7	18	5.7	2.4	1.1	27	5.1	2.71
3SW17	37 23 16	106 33 48	46	18	3.2	2.2	40	3.1	.8
3SW18	37 23 19	106 33 48	150	122	1.1	<.1	45	103	6
3SW19	37 23 17	106 33 48	170	119	1.2	<.1	52	92	3.7
3SW20	37 23 5	106 33 59	33	17	2	1.9	62	141	76
3SW21	37 22 38	106 34 56	12	6.2	1.8	1.6	35	1.7	1
3SW22	37 23 25	106 36 29	11	3.1	1.4	.4	8	.29	.03
3SW23	37 23 25	106 36 24	8.1	1.8	2.2	.9	20	1.1	1
3SW24	37 23 6	106 36 27	12	4.8	1.7	.7	21	3.3	2.05
3SW26	37 22 53	106 36 9	10	2.5	2.1	1	20	1.6	1.56
3SW27	37 22 54	106 34 3	7.7	1.5	1.3	.5	10	.12	.07
Summitville Area									
3SW28	37 24 56	106 35 41	10	1.6	1	.8	10	.07	.03
3SW29	37 24 55	106 35 41	4.6	.8	1.2	.2	7	.3	.03
3SW30	37 24 55	106 35 39	21	2.6	2.4	1.3	19	.03	<.01
3SW31	37 24 52	106 35 39	33	6.4	6.4	2.8	28	.22	.23
3Sw32	37 24 49	106 35 43	10	1.5	1.8	.9	19	.01	.03
3SW34	37 25 23	106 37 16	6.3	1.1	3.4	1.1	19	.09	<.01
3SW35	37 25 27	106 37 13	6.8	1.2	2.7	.8	15	.02	--
Crater Creek Area									
3SW36	37 25 16	106 42 22	20	4.3	2.1	.4	8	.01	--
3SW37	37 24 15	106 42 13	34	10	1.6	.8	4	.01	<.01
3SW39*	37 24 29	106 42 33	105	10	3.7	.9	13	.05	.04
3SW40*	37 24 39	106 42 39	62	14	3.5	1	30	33	30
3SW41	37 24 30	106 42 39	12	1.9	1.2	.3	5	.01	--
3SW42	37 24 31	106 42 38	16	2.9	1.3	.4	5	.01	--
3SW43	37 24 45	106 42 35	23	4.5	1.5	.6	7	.01	--
3SW44	37 24 36	106 43 20	12	1.9	1.2	.3	5	.01	--
3SW45	37 24 55	106 44 13	34	6.1	2.9	.7	8	.01	--
Background of Unmineralized Areas									
3SW06	37 23 33	106 23 4	10	2.3	3.7	2	38	.03	--
3SW07	37 23 50	106 25 46	17	2.9	3.7	1.4	21	.01	--
3SW33	37 26 6	106 36 31	2.8	.7	1.2	1.4	24	.04	<.01
Wightman Fork									
3SW14	37 24 15	106 31 19	90	8.5	130	3.5	18	14	2.29

* AMD from mine adit

Table 1. Chemical Data for Stream Waters--Continued

Sample	Mn(mg/l)	Al(mg/l)	Alk(mg/l)	SO_4(mg/l)	Cl(mg/l)	F(mg/l)	NO_3(mg/l)	As(μg/l)	Co(μg/l)	Cd(μg/l)
Cat Creek Area										
3SW02	.05	<.1	180	23	1.7	.4	<.1	<1	<1	<1
3SW03	.06	<.1	120	7.7	1	.4	<.1	<1	<1	<1
3SW04	.2	<.1	180	34	4.1	.5	<.1	<1	1	<1
3SW05	.45	<.1	230	120	3.9	.8	<.1	<1	<1	<1
3SW16	.01	<.1	250	21	2.5	.5	<.1	<1	1	<1
Jasper Area										
3SW08	.01	<.1	23	39	.7	.3	<.1	<1	<1	<1
3SW10	<.01	<.1	41	13	.5	.3	<.1	<1	<1	<1
3SW11	.03	.1	<1	46	<.1	.3	<.1	<1	1	<1
3SW13	.07	.2	12	90	<.1	.5	<.1	1	2	<1
Stunner Area										
3SW15	.58	3.7	<1	95	.6	.3	<.1	1	15	1
3SW17	3.1	14	<1	320	.8	.6	<.1	5	50	1
3SW18	14	35	<1	1,250	1.2	1.5	<.1	13	250	9
3SW19	15	42	<1	1,250	1.3	1.4	<.1	17	280	9
3SW20	2.7	55	<1	800	1	.5	<.1	30	170	10
3SW21	.44	6	<1	100	.6	<.1	<.1	1	17	1
3SW22	.38	<.1	<1	32	.6	.3	<.1	<1	2	<1
3SW23	.11	1.8	<1	41	<.1	<.1	<.1	<1	5	<1
3SW24	.75	2.6	<1	74	.7	<.1	<.1	<1	11	1
3SW26	.22	3	<1	56	.5	<.1	<.1	<1	8	<1
3SW27	.05	.1	<1	10	<.1	<.1	<.1	<1	2	<1
Summitville Area										
3SW28	1.7	2.9	<1	49	<.1	.3	<.1	<1	4	10
3SW29	.21	<.1	<1	2	<.1	<.1	<.1	<1	1	<1
3SW30	.82	1.7	<1	70	<.1	.4	<.1	<1	7	1
3SW31	5.9	17	<1	220	.6	.6	.8	9	82	7
3SW32	.48	2.1	<1	39	<.1	.3	<.1	<1	5	<1
3SW34	.01	.1	<1	15	<.1	<.1	<.1	<1	1	<1
3SW35	.01	<.1	1	7.2	<.1	<.1	<.1	<1	1	<1
Crater Creek Area										
3SW36	.01	<.1	63	5.8	<.1	<.1	<.1	<1	1	<1
3SW37	.04	<.1	75	53	<.1	<.1	<.1	<1	1	<1
3SW39*	.26	<.1	82	220	.7	<.1	<.1	1	5	7
3SW40*	1.3	6.5	<1	300	.8	.6	<.1	2	38	4
3SW41	.01	<.1	19	6.6	.5	<.1	<.1	<1	<1	<1
3SW42	.01	<.1	29	15	<.1	<.1	<.1	<1	<1	<1
3SW43	<.01	<.1	47	24	.6	<.1	<.1	<1	<1	<1
3SW44	<.01	<.1	19	6.2	<.1	<.1	<.1	<1	<1	<1
3SW45	<.01	<.1	120	9.2	<.1	<.1	<.1	<1	1	<1
Background of Unmineralized Areas										
3SW06	<.01	.1	38	1.5	.5	<.1	<.1	<1	<1	<1
3SW07	<.01	<.1	50	7.2	.6	.3	<.1	<1	<1	<1
3SW33	<.01	<.1	<1	.8	<.1	<.1	<.1	<1	1	<1
Wightman Fork										
3SW14	2.9	13	<1	630	11	.4	1.3	3	120	18

* AMD from mine adit

Table 1. Chemical Data for Stream Waters--Continued

Sample	Cr(μg/l)	Cu(μg/l)	Ag(μg/l)	Ni(μg/l)	Pb(μg/l)	Zn(μg/l)	Sp.Cond.(μS)	pH	O_2(mg/l)	Temp.(C°)
Cat Creek Area										
3SW02	<1	<1	<.05	3	<1	7	390	7.68	--	17
3SW03	<1	<1	<.05	3	<1	6	270	8.08	--	14
3SW04	<1	<1	<.05	<1	<1	6	420	7.5	--	14
3SW05	<1	<1	<.05	2	<1	10	710	8.1	--	11
3SW16	<1	<1	<.05	1	<1	7	440	7.45	5.5	9
Jasper Area										
3SW08	<1	<1	<.05	<1	<1	5	180	7.96	--	11
3SW10	<1	<1	<.05	1	<1	6	150	8.09	--	15
3SW11	<1	1	<.05	1	<1	7	160	7.51	--	12
3SW13	<1	<1	<.05	2	1	7	290	7.73	--	12
Stunner Area										
3SW15	<1	7	<.05	10	<1	68	340	3.44	8.3	13
3SW17	<1	5	<.05	35	<1	340	870	3.11	8.3	10
3SW18	7	320	.12	230	<1	1,000	2,200	2.59	--	12
3SW19	10	370	.1	230	<1	1,000	2,400	2.52	12.3	12
3SW20	13	250	<.05	170	4	710	1,350	2.64	--	14
3SW21	<1	24	<.05	15	<1	60	390	3.3	--	13
3SW22	<1	<1	<.05	2	<1	25	120	6.58	--	10
3SW23	<1	11	<.05	7	<1	28	140	4.35	--	10
3SW24	<1	14	<.05	10	1	55	280	3.56	--	14
3SW26	<1	12	<.05	6	1	35	190	3.91	--	16
3SW27	<1	<1	<.05	1	<1	8	80	7.27	--	15
Summitville Area										
3SW28	<1	10	<.05	13	<1	1,800	150	4.4	--	7
3SW29	<1	<1	<.05	1	<1	27	50	6.66	--	15
3SW30	<1	10	<.05	12	<1	130	230	4.76	--	9
3SW31	1	46	<.05	90	<1	1,200	460	6.7	--	4
3Sw32	<1	6	<.05	13	<1	86	140	4.69	--	9
3SW34	<1	<1	<.05	2	<1	34	80	7.12	--	11
3SW35	<1	<1	<.05	1	<1	34	70	7.33	--	11
Crater Creek Area										
3SW36	<1	<1	<.05	<1	<1	6	150	8.02	--	10
3SW37	<1	<1	<.05	<1	1	6	250	8.4	--	8
3SW39*	<1	<1	<.05	5	<1	860	540	7.42	7.4	8
3SW40*	<1	15	<.05	30	<1	510	560	4.19	--	7
3SW41	<1	<1	<.05	<1	<1	6	90	7.69	--	10
3SW42	<1	<1	<.05	3	<1	6	120	8.06	--	13
3SW43	<1	<1	<.05	1	1	8	160	8.16	--	11
3SW44	<1	<1	<.05	<1	<1	7	90	8	--	12
3SW45	<1	<1	<.05	1	<1	6	220	8.54	--	13
Backgound of Unmineralized Areas										
3SW06	<1	<1	<.05	1	<1	4	130	8.11	--	11
3SW07	<1	<1	<.05	<1	<1	4	150	8.13	--	12
3SW33	<1	1	<.05	2	<1	4	40	7.25	--	12
Wightman Fork										
3SW14	2	7,800	.1	120	5	1,700	1,210	4.64	7	12

* AMd from mine adit

Table 2. Chemical analyses of rocks

[N, not detected; <, detected but below the limit of determination shown]

Sample	Latitude	Longitude	Al %	Ca %	Fe %	K %	Mg %	Na %	P %	Ti %
Cat Creek Area										
3SR01	37 24 33	106 18 10	8.1	.11	3.4	.11	.86	.07	.13	.19
3SR05A	37 23 11	106 17 30	.27	.05	9.6	.01	<.005	.007	.02	.008
3SR05B	37 23 8	106 17 31	4.7	.1	11	.47	.03	.02	.1	.14
3SR05C	37 23 8	106 17 31	7.8	.07	2.3	.07	.02	.01	.09	.24
Jasper Area										
3SR09	37 26 9	106 27 27	8.1	1.4	4.5	2.2	1.2	2.9	.13	.51
3SR12A	37 25 26	106 29 17	2.1	.05	1.8	.08	.008	.009	.06	.17
3SR12B	37 25 26	106 29 17	7.3	.04	1.8	2.7	.51	.62	.05	.28
Stunner Area										
3SR17A	37 23 16	106 33 48	1.6	.01	37	1.3	.07	.05	.11	.06
3SR17B	37 23 16	106 33 48	7.6	.1	1.2	3	.31	.05	.02	.11
3SR17C	37 23 16	106 33 48	8.5	2.4	4.6	3.2	1.4	2.7	.14	.45
3SR19	37 23 17	106 33 48	6.8	.05	8.4	2.3	.21	.05	.14	.08
3SR20A	37 23 5	106 33 59	5.7	.76	13	2.7	.38	1.9	.11	.21
3SR20B	37 23 5	106 33 59	5	.04	19	1.9	.33	.18	.13	.11
3SR23	37 23 25	106 36 24	7.6	.02	3.2	.03	.006	.009	.04	.16
3SR25A	37 22 57	106 36 7L	.08	<.005	43	2	<.005	.04	.16	<.005
3SR25B	37 22 57	106 36 7L	.04	<.005	37	4.1	<.005	.07	.39	<.005
Upper Cropsy Creek Area										
3SR28	37 24 56	106 35 41	7.4	.45	2.4	2.8	.33	1.6	.1	.29
3SR31	37 24 52	106 35 39	7.7	.43	2.5	3.7	.31	1.9	.19	.3
Crater Creek Area										
3SR36A	37 25 16	106 42 22	7.8	1.1	5.7	2.3	.98	.81	.13	.32
3SR36B	37 25 16	106 42 22	7.1	3.7	4.4	2.1	1.4	.28	.1	.33
3SR36C	37 25 16	106 42 22	8.1	3.8	5.4	2.1	1.9	.72	.14	.35
3SR38A	37 24 26	106 42 31	3	.06	2.2	.03	.009	.02	.07	.12
3SR38B	37 24 26	106 42 31	5	.01	5	<.01	<.005	.007	.03	.03
3SR39	37 24 29	106 42 33	5.6	.02	2.1	<.01	<.005	.01	.03	.03
3SR43	37 24 45	106 42 35	8.4	.19	4.1	2.3	.99	1.9	.11	.26

Table 2. Chemical analyses of rocks--Continued

Sample	Mn ppm	Ag ppm	As ppm	Au ppm	B ppm	Ba ppm	Be ppm	Bi ppm	Cd ppm
Cat Creek Area									
3SR01	390	<2	53	<8	--	450	<1	<10	<2
3SR05A	17	190	27	<8	--	210	<1	18	82
3SR05B	460	110	760	<8	--	1,200	<1	32	<2
3SR05C	150	5	110	<8	--	1,100	<1	<10	<2
Jasper Area									
3SR09	570	<2	<10	<8	--	810	1	<10	<2
3SR12A	29	<2	13	<8	--	780	<1	<10	<2
3SR12B	140	<2	<10	<8	--	470	1	<10	<2
Stunner Area									
3SR17A	46	<2	<10	<8	--	160	<1	<10	<2
3SR17B	44	<2	<10	<8	--	330	1	<10	<2
3SR17C	880	<2	<10	<8	--	710	2	<10	<2
3SR19	34	<2	19	<8	--	560	<1	<10	<2
3SR20A	220	<2	<10	<8	--	480	1	<10	<2
3SR20B	67	<2	<10	<8	--	510	1	<10	<2
3SR23	7	<2	15	<8	--	110	<1	<10	<2
3SR25A	15	<2	53	<8	--	66	<1	<10	<2
3SR25B	8	<2	140	<8	--	23	<1	<10	<2
Summitville Area									
3SR28	34,000	<2	12	<8	--	1,200	3	<10	10
3SR31	120	<2	<10	<8	--	3,800	2	<10	<2
Crater Creek Area									
3SR36A	540	<2	15	<8	--	2,300	1	<10	<2
3SR36B	950	<2	<10	<8	--	870	1	<10	<2
3SR36C	990	<2	<10	<8	--	860	1	<10	<2
3SR38A	17	57	15	<8	--	160	<1	<10	280
3SR38B	14	100	17	<8	--	89	<1	<10	300
3SR39	15	140	61	<8	--	780	<1	290	510
3SR43	370	<2	<10	<8	--	490	1	<10	<2

Table 2. Chemical analyses of rocks--Continued

Sample	Ce ppm	Co ppm	Cr ppm	Cu ppm	Eu ppm	Ga ppm	Ge ppm	Ho ppm	La ppm	Li ppm
					Cat Creek Area					
3SR01	46	5	73	32	<2	17	--	<4	26	190
3SR05A	6	17	<1	890	<2	<4	--	<4	5	11
3SR05B	18	6	2	740	<2	26	--	<4	11	67
3SR05C	31	2	4	240	<2	18	--	<4	18	110
					Jasper Area					
3SR09	47	6	10	19	<2	18	--	<4	26	9
3SR12A	32	<1	7	27	<2	<4	--	<4	17	2
3SR12B	44	4	10	18	<2	16	--	<4	24	6
					Stunner Area					
3SR17A	11	6	4	13	<2	9	--	<4	6	<2
3SR17B	48	2	5	5	<2	17	--	<4	27	<2
3SR17C	88	16	12	56	<2	20	--	<4	48	13
3SR19	26	1	10	21	<2	11	--	<4	15	3
3SR20A	37	6	8	35	<2	12	--	<4	23	18
3SR20B	36	3	8	55	<2	8	--	<4	21	3
3SR23	15	11	17	11	<2	23	--	<4	8	43
3SR25A	<4	6	5	31	<2	16	--	<4	2	<2
3SR25B	6	5	5	13	<2	13	--	<4	5	<2
					Summitville Area					
3SR28	160	290	14	48	<2	67	--	<4	48	14
3SR31	82	4	12	5	<2	19	--	<4	52	8
					Crater Creek Area					
3SR36A	44	13	39	44	<2	16	--	<4	26	10
3SR36B	48	18	37	30	<2	16	--	<4	26	14
3SR36C	62	24	33	51	<2	19	--	<4	33	15
3SR38A	24	6	<1	180	<2	50	--	<4	12	13
3SR38B	15	16	3	280	<2	65	--	<4	8	35
3SR39	10	5	1	490	<2	180	--	<4	5	29
3SR43	54	7	16	10	<2	19	--	<4	30	10

Table 2. Chemical analyses of rocks--Continued

Sample	Mo ppm	Nb ppm	Nd ppm	Ni ppm	Pb ppm	Sc ppm	Sn ppm	Sr ppm	Ta ppm
Cat Creek Area									
3SR01	<2	5	31	11	130	6	<5	1,900	<40
3SR05A	5	<4	<4	25	11,000	<2	<5	310	<40
3SR05B	15	5	7	<2	120	3	100	1,200	<40
3SR05C	4	9	12	<2	660	4	<5	1,100	<40
Jasper Area									
3SR09	<2	11	20	7	16	11	<5	490	<40
3SR12A	7	<4	14	<2	14	2	<5	360	<40
3SR12B	<2	9	20	3	20	7	<5	100	<40
Stunner Area									
3SR17A	<2	<4	4	<2	<4	4	<5	37	<40
3SR17B	<2	7	21	<2	13	6	<5	120	<40
3SR17C	<2	12	42	12	11	13	<5	580	<40
3SR19	<2	<4	11	<2	65	8	<5	230	<40
3SR20A	<2	8	14	4	14	4	<5	380	<40
3SR20B	5	<4	16	<2	30	7	<5	110	<40
3SR23	<2	5	7	8	25	6	<5	550	<40
3SR25A	<2	<4	<4	<2	<4	2	<5	170	39
3SR25B	<2	<4	<4	<2	<4	2	<5	710	<40
Summitville Area									
3SR28	7	13	33	47	91	6	<5	450	<40
3SR31	<2	14	33	5	19	4	<5	440	<40
Crater Lake Area									
3SR36A	<2	8	24	14	60	13	<5	280	<40
3SR36B	<2	7	21	15	<4	14	<5	140	<40
3SR36C	<2	8	31	19	<4	14	<5	230	<40
3SR38A	4	4	11	<2	24,000	<2	<5	610	<40
3SR38B	3	<4	5	4	43,000	<2	<5	300	<40
3SR39	6	<4	5	<2	340	<2	6	230	<40
3SR43	<2	6	26	3	27	10	<5	290	<40

Table 2. Chemical analyses of rocks--Continued

Sample	Th ppm	U ppm	V ppm	W ppm	Y ppm	Yb ppm	Zn ppm	Zr ppm	Ag ppm	As ppm
Cat Creek Area										
3SR01	4	<100	130	--	9	1	65	--	.24	60
3SR05A	<4	<100	<2	--	<2	<1	11,000	--	320	15
3SR05B	4	<100	36	--	4	<1	1,000	--	130	930
3SR05C	5	<100	49	--	9	<1	150	--	5.8	130
Jasper Area										
3SR09	7	<100	110	--	12	1	64	--	N	2
3SR12A	<4	<100	46	--	3	<1	10	--	.094	11
3SR12B	8	<100	80	--	9	1	29	--	N	4.2
Stunner Area										
3SR17A	7	<100	130	--	<2	1	30	--	N	6.2
3SR17B	21	<100	50	--	7	1	8	--	N	3
3SR17C	15	<100	110	--	26	2	70	--	N	2
3SR19	9	<100	88	--	5	<1	6	--	.085	18
3SR20A	9	<100	42	--	3	<1	46	--	N	4.6
3SR20B	10	<100	72	--	4	<1	14	--	N	6.8
3SR23	<4	<100	160	--	3	<1	14	--	.081	3.4
3SR25A	7	<100	410	--	<2	<1	24	--	N	4.2
3SR25B	6	<100	230	--	<2	<1	<2	--	N	120
Summitville Area										
3SR28	9	<100	49	--	12	<1	890	--	N	9.9
3SR31	14	<100	51	--	7	<1	44	--	N	3
Crater Creek Area										
3SR36A	6	<100	110	--	15	1	120	--	.12	15
3SR36B	4	<100	110	--	17	2	47	--	N	N
3SR36C	6	<100	130	--	21	2	59	--	N	.77
3SR38A	<4	<100	17	--	2	<1	41,000	--	56	N
3SR38B	<4	<100	25	--	<2	<1	42,000	--	79	N
3SR39	<4	<100	30	--	<2	<1	72,000	--	140	48
3SR43	<4	<100	110	--	9	<1	66	--	.16	N

Table 2. Chemical analyses of rocks--Continued

Sample	Au ppm	Bi ppm	Cd ppm	Cu ppm	Mo ppm	Pb ppm	Sb ppm	Zn ppm	Au ppm
Cat Creek Area									
3SR01	N	N	N	32	5	110	1.4	61	.006
3SR05A	N	7.9	79	210	3.6	12,000	42	>840	.045
3SR05B	.32	31	1.7	680	18	140	500	770	.16
3SR05C	N	.95	.53	240	6.6	690	34	130	.002
Jasper Area									
3SR09	N	N	N	20	.45	19	N	64	<.001
3SR12A	N	1.2	N	12	7.4	3	N	6.7	<.001
3SR12B	N	N	N	12	3.9	11	N	8.6	.001
Stunner Area									
3SR17A	N	N	N	8.9	.29	1.1	1.2	N	.001
3SR17B	N	1.3	N	2.6	.61	5.7	N	6.5	<.001
3SR17C	N	N	.052	51	.76	5.1	N	51	<.001
3SR19	N	1.6	N	17	5.4	72	1.1	4.5	.004
3SR20A	N	N	N	33	3	9.8	N	34	.001
3SR20B	N	.67	N	56	10	30	N	5.7	.006
3SR23	N	.72	N	3.4	.2	5.2	N	2.9	<.001
3SR25A	N	N	N	3.2	.21	N	N	N	<.001
3SR25B	N	N	N	11	4.1	N	.69	N	<.001
Summitville Area									
3SR28	N	N	12	50	8.8	33	N	760	.001
3SR31	N	N	N	3.9	1.1	4.4	N	22	<.001
Crater Creek Area									
3SR36A	N	N	.092	42	.98	68	N	110	.001
3SR36B	N	N	N	27	.37	3.5	N	49	.001
3SR36C	N	N	N	52	.18	3	N	59	.001
3SR38A	N	N	240	140	1.7	25.000	55	>4.200	.004
3SR38B	N	N	220	120	.67	41.000	83	3.100	.013
3SR39	N	270	370	330	2.1	410	24	>840	<.001
3SR43	N	N	.18	6.9	.51	25	N	46	<.001

Table 3. Chemical Analyses of Soils
[N, not detected; <, detected but below the limit of determination shown]

Sample	Latitude	Longitude	Al %	Ca %	Fe %	K %	Mg %	Na %	P %
Cat Creek Area									
3SD05	37 23 8	106 17 31	7.3	.48	4.1	2.5	.36	.35	.12
Jasper Area									
3SD09	37 26 9	106 27 27	6.2	.42	4	1.7	.72	1.4	.09
3SD12	37 25 26	106 29 17	6.8	.47	2.7	1.9	.39	.92	.12
Stunner Area									
3SD18	37 23 19	106 33 48	6.8	.64	4.1	2.2	.62	.92	.09

Table 3. Chemical Analyses of Soils--Continued

Sample	Ti %	Mn ppm	Ag ppm	As ppm	Au ppm	B ppm	Ba ppm	Be ppm	Bi ppm	Cd ppm
Cat Creek Area										
3SD05	.26	2,400	3	160	<8	--	1,500	2	<10	<2
Jasper Area										
3SD09	.71	400	<2	<10	<8	--	530	2	<10	<2
3SD12	.58	200	<2	10	<8	--	780	1	<10	<2
Stunner Area										
3SD18	.36	690	<2	14	<8	--	620	2	<10	<2

Table 3. Chemical Analyses of Soils--Continued

Sample	Ce ppm	Co ppm	Cr ppm	Cu ppm	Eu ppm	Ga ppm	Ge ppm	Ho ppm	La ppm
				Cat Creek Area					
3SD05	46	13	8	250	<2	19	--	<4	26
				Jasper Area					
3SD09	63	6	21	21	<2	14	--	<4	33
3SD12	68	4	28	17	<2	15	--	<4	35
				Stunner Area					
3SD18	69	13	22	37	<2	15	--	<4	34

Table 3. Chemical Analyses of Soils--Continued

Sample	Li ppm	Mo ppm	Nb ppm	Nd ppm	Ni ppm	Pb ppm	Sc ppm	Sn ppm	Sr ppm	Ta ppm
Cat Creek Area										
3SD05	20	4	8	20	5	320	7	<5	200	<40
Jasper Area										
3SD09	13	<2	12	30	8	15	9	<5	300	<40
3SD12	9	<2	12	29	5	22	8	<5	670	<40
Stunner Area										
3SD18	16	<2	10	28	10	23	10	<5	190	<40

Table 3. Chemical Analyses of Soils--Continued

Sample	As ppm	Au ppm	Bi ppm	Cd ppm	Cu ppm	Mo ppm	Pb ppm	Sb ppm	Zn ppm	Au ppm
Cat Creek Area										
3SD05	200	N	8.4	.89	260	7.2	320	40	330	.025
Jasper Area										
3SD09	.86	N	N	N	15	1.2	8.2	N	45	.003
3SD12	2	N	N	N	13	2.7	10	N	21	<.001
Stunner Area										
3SD18	9.5	N	N	.1	34	2.8	17	5.3	63	.001

Table 3. Chemical Analyses of Soils--Continued

Sample	Th ppm	U ppm	V ppm	W ppm	Y ppm	Yb ppm	Zn ppm	Zr ppm	Ag ppm
				Cat Creek Area					
3SD05	5	<100	60	--	13	2	370	--	4.7
				Jasper Area					
3SD09	7	<100	120	--	15	1	63	--	N
3SD12	8	<100	110	--	10	<1	38	--	N
				Stunner Area					
3SD18	13	<100	97	--	17	1	76	--	N