Bulletin 54

Natural Acid Rock Drainage

Associated with Hydrothermally Altered Terrane in Colorado

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FOREWORD

This report, *Natural Acid Rock Drainage Associated with Hydrothermally Altered Terrane in Colorado*, examines the water quality and geology of several areas in Colorado exhibiting acid rock drainage (ARD) that is not caused by mining, but by nature. These areas are characterized by hydrothermally altered host rocks, with mineralogy that naturally “degrades” the water. Often, areas with natural ARD overlap mining districts, where mining-related ARD (also known as acid mine drainage) also occurs.

The information contained in this report will be of interest to professionals in several disciplines. Environmental professionals will be interested in the abundant water quality data available and the downstream effects of the identified natural ARD areas. Economic geologists will be interested in the geologic and hydrothermal alteration mapping of the natural ARD areas, but will also gain general knowledge of the attendant background, or baseline, water quality conditions. Aquatic biologists will find this information useful as it relates to natural limitations on aquatic habitat.

Because of the interdisciplinary nature of this study, some readers may be unfamiliar with certain technical aspects of the report, especially related to geologic and hydrothermal alteration mapping. A short glossary is provided to aid the reader’s understanding.

State and Federal agencies and private land owners will find these data helpful for developing realistic reclamation plans for active and abandoned mines in areas where natural ARD is a contributor to poor water quality.

Funding for this project was provided by the Colorado Geological Survey from the Colorado Department of Natural Resources Severance Tax Operational Fund. Severance taxes are derived from the production of gas, oil, coal, and minerals

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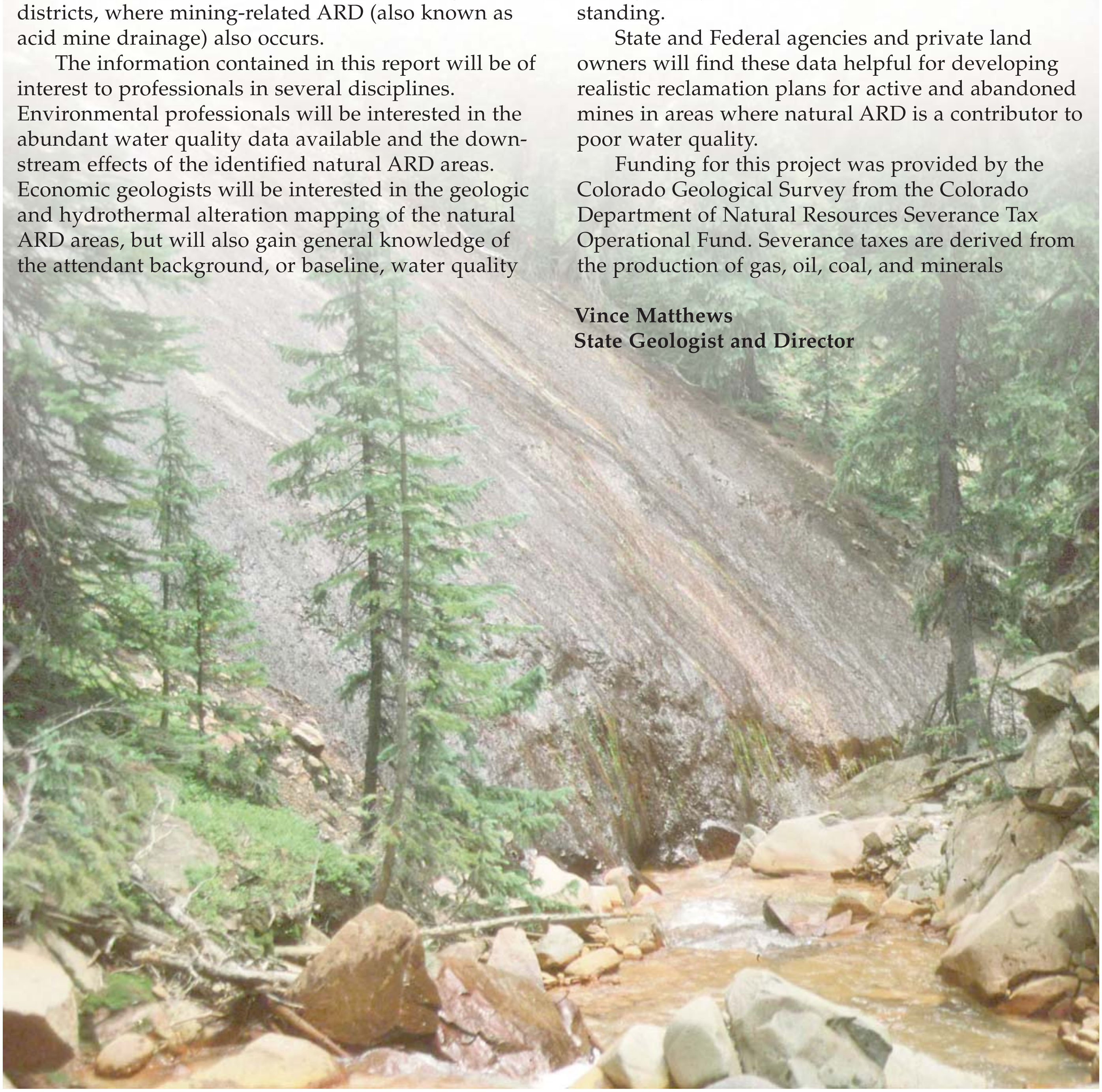

Lower Iron Creek, Alamosa County. Ferrosinter deposits cover the hillside as natural ARD flows into the creek.

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GLOSSARY

Acid-sulfate alteration: Low pH hydrothermal process associated with sulfate-rich fluids that produces a mineral assemblage characterized by alunite, kaolinite, dickite, quartz, and pyrite, and commonly includes pyrophyllite, topaz and diaspore. The associated ore assemblage invariably includes enargite and covellite. Acid-sulfate alteration is essentially equivalent to advanced argillic alteration.[1]

Alaskite: A granitic rock containing only a few percent dark minerals.[2]

Alunite: A hydrous potassium sulfate mineral, generally occurs as a hydrothermal alteration product in feldspathic igneous rocks; $KAl_3(SO_4)_2(OH)_6$.[2]

Amorphous ferric hydroxide: An oxide mineral of iron, oftentimes a product of pyrite oxidation; $Fe(OH)_3$.

Argillic alteration: Alteration in which certain minerals of a rock are converted to clay minerals.[8]

Barite: A white, yellow, or colorless mineral that is the principle ore of barium; $BaSO_4$.[2]

Basaluminite: A hydrous aluminum sulfate; $Al_4(OH)_{10}SO_4$.[5]

Blackjack sphalerite: A black, iron-rich form of the zinc ore mineral, sphalerite, ZnS.

Boehmite: A polymorph of aluminum hydroxide; AlOOH.[4]

Bog iron: Loose, porous form of limonite occurring in wet ground, often mixed with vegetable matter $Fe_2O_3{\leq}nH_2O$; a deposit of hydrated iron oxides found in swamps and peat mosses.[3]

Calcite: The most common carbonate mineral; $CaCO_3$.[4]

Caldera: A large, basin-shaped volcanic depression, more or less circular in form, the diameter of which is many times greater than that of the included vent or vents. It is formed by collapse during an eruption.[2]

Chalcedony: A microcrystalline, fibrous variety of quartz; SiO_2.[4]

Chalcopyrite: An ore mineral of copper; $CuFeS_2$.[4]

Chlorite: A group of platy, usually greenish aluminosilicate micaceous minerals of the general formula $(Mg,Fe2+,Fe3+)_6AlSi_3O_{10}(OH)_8$.[2] Commonly formed by alteration or metamorphism of iron and magnesium rich igneous minerals or from clays in shales.

Copiapite: An oxidation product of pyrite and other sulfides; $(Fe,Mg)Fe3+_4(SO_4)_6(OH)_2{\leq}20H_2O$.[5]

Diaspore: A variously colored mineral of aluminum hydroxide, dimorphous with boehmite; $AlO{\leq}OH$.[2]

Dickite: A well-crystallized, white to variously colored, clay mineral of the kaolin group; $Al_2Si_2O_5(OH)_4$.[2] Commonly found in the acid-sulfate alteration assemblage.

Enargite: A grayish black arsenic-rich ore mineral of copper; Cu_3AsS_4. It often contains antimony (up to 6%).[2]

Epidote: An aluminosilicate mineral; $Ca_2(Fe3+,Al)_3(SiO_4)_3(OH)$.[2] Common in propylitically altered rocks and contact metamorphosed carbonate rocks.

Epithermal: Said of a hydrothermal mineral deposit formed within 3,000 ft of the Earth's surface and in the temperature range of 50° – 200° C.[2]

Felsic: A mnemonic adjective derived from *f*eldspar + *l*enad (feldspathoid) + silica + *c*, and applied to an igneous rock having light-colored minerals in its mode; the opposite of mafic.[2]

Fen: A waterlogged, spongy groundmass containing alkaline, decaying vegetation characterized by reeds and which may develop into peat.[2]

Ferricrete: Ferruginous concreted gravel, or a variety of calcrete with ferruginous cement.[3]

Ferrihydrite: An amorphous polymorph of ferric hydroxide; $Fe[OH]_3$.[7]

Ferrosinter: An iron-rich chemical sediment deposited by a mineral spring, either hot or cold.[3]

Galena: An ore mineral of lead; PbS.[4]

Gangue: The valueless rock or mineral aggregates in an ore.[2]

Gibbsite: A polymorph of aluminum hydroxide; $Al[OH]_3$.[4]

Gypsum: The most common sulfate mineral, a common mineral of evaporite deposits or a secondary alteration product of anhydrite. Also occurs as a precipitate in acid-rock drainage; $CaSO_4 \leq 2H_2O$.[4]

Hypogene: Said of a mineral deposit, formed by ascending solutions; also, said of the associated solutions and of that environment.[2]

Ilmenite: An oxide mineral of iron and titanium, a common accessory mineral in igneous rocks; $FeTiO_3$.[4]

Jarosite: An ocher-yellow or brown mineral of the alunite group; $KFe_3(SO_4)_2(OH)_6$.[2] Varieties include Na-Jarosite ($NaFe_3[SO_4]_2[OH]_6$), and ($[H_3O]Fe_3[SO_4]_2[OH]_6$).[7]

Jurbanite: A hydrous aluminum sulfate; $AlOHSO_4$.[5]

Kaolinite: A common, white, grayish, yellowish, etc., clay mineral of the kaolin group; $Al_2Si_2O_5(OH)_4$.[2] Considered, along with dickite, to be diagnostic of argillic alteration in hydrothermally altered terranes.

Leucoxene: A general term for fine-grained, opaque, whitish alteration products of ilmenite, commonly consisting mostly of rutile and partly of anatase or sphene, and occurring in some igneous rocks.[2]

Limonite: A general field term for a group of brown, amorphous, naturally occurring hydrous ferric oxides whose real identities are unknown in the absence of determinitive study, but considered to have a variable composition and to consist of any of several iron hydroxides, or of a mixture of several minerals (such as hematite, goethite, and lepidocrocite) with or without presumably adsorbed additional water.[2]

Mafic: Said of an igneous rock composed chiefly of one or more ferromagnesian, dark-colored minerals in its mode; also, said of those minerals.[2]

Major ion: Elements commonly present at dissolved concentrations of greater than 1 part per million (1 mg/L) in natural waters; typically calcium, magnesium, sodium, potassium, sulfate, chloride, carbonate, and bicarbonate.[6]

Malachite: A hydrous copper carbonate; $Cu_2CO_3(OH)_2$.[4]

Marcasite: A common metallic light-yellow or grayish mineral; a sulfide of iron; dimorphous with pyrite, but lower specific gravity, less chemical stability, and usually a paler color; FeS_2.[2]

Natroalunite: A colorless to variously colored mineral of the alunite group, $Na,KAl_3(SO_4)_2(OH)_6$.[2]

Phyllite: A metamorphic rock, intermediate in grade between slate and mica schist.[2]

Pyrite: A common pale-bronze or brass-yellow, cubic iron sulfide mineral; FeS_2.[4]

Pyrophyllite: An aluminosilicate mineral; $AlSi_2O_5(OH)_2$. It resembles talc and is frequently found in acid-sulfate altered felsic rocks.[2]

Pyrite: A common pale-bronze or brass-yellow, cubic iron sulfide mineral; FeS_2.[4]

QSP: Quartz-Sericite-Pyrite; a type of alteration mineral assemblage that generally contains the most pyrite of any alteration type.

Rhodochrosite: A carbonate of manganese, $MnCO_3$, sometimes found as gangue in ore veins.[4]

Rutile: An accessory mineral common in igneous intrusive rocks; TiO_2.[4]

Selenite: The clear, colorless variety of gypsum; $CaSO_4 \leq 2H_2O$.[2]

Sericite: A white, fine-grained potassium mica occurring in small scales and flakes as an alteration product of various aluminosilicate minerals1; $KAl_2(AlSi_3O_{10})(OH)_2$.[4]

Smectite: Group of clay minerals that includes montmorillonite, beidellite, nontronite and saponite.[6]

Specularite: A brilliant, black or gray variety of hematite with a splendent metallic luster; Fe_2O_3.[2]

Sphalerite: The most important ore mineral of zinc; ZnS.[4]

Stream Segment: Within each river basin, specific water segments are defined, for which use classifications and numeric water quality standards, if appropriate, are adopted. These segments may constitute a specified stretch of a river mainstem, a specific tributary, a specific lake or reservoir, or a generally defined grouping of waters within the basin; for example, a specific mainstem segment and all tributaries flowing into that mainstem segment. (from Code of Colorado Regulations 5 CCR 1002-8).

Supergene: Said of a mineral deposit or enrichment formed near the surface, commonly by descending solutions; also, said of the solutions and that environment.[2]

Tetrahedrite: An antimony-rich ore mineral of copper and the most common sulfosalt; $Cu_{12}Sb_4S_{13}$.[4]

Trace element: Elements commonly present at dissolved concentrations of less than 1 part per million (1 milligram per liter) in natural waters.[6]

Zunyite: A colorless, gray, or pink mineral common to acid-sulfate alteration; $Al_{13}Si_5O_{20}(OH,F)_{18}Cl$.[2]

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ABBREVIATIONS AND SYMBOLS

~	approximate value
ARD	acid rock drainage
BLM	United States Department of Interior — Bureau of Land Management
cc	cubic centimeters (synonymous with milliliters)
cm	centimeter(s)
CGS	Colorado Geological Survey
cps	counts per second
°	degree
DO	dissolved oxygen
EC	Electrical Conductivity
el	elevation
ft	foot (feet)
4WD	four-wheel drive
gpm	gallons per minute
GPS	Global Positioning System
>	greater than
<	less than
≤	less than or equal to
µg/L	micrograms per liter
µ	micron (10-6 meter)
µm	micrometer (synonymous with micron)
µS/cm	microsiemens per centimeter
Ma	million years old, million years ago
mg/L	milligrams per liter
mL	milliliter
mi	miles
NARD	natural acidic rock drainage
NOAMS	naturally occurring, acidic, metal-rich spring or seep
n/a	not applicable or not analyzed
no.	number
NRI	not reported due to interference
#	number
p.	page(s)
PHREEQC	geochemical computer modeling program (Parkhurst & Appelo, 1999)
ppm	parts per million
%	percent
quad	quadrangle (7.5-minute)
QA/QC	Quality Assurance/Quality Control
QNS	Quantity not sufficient
TDS	total dissolved solids
trec	total recoverable
U.S.	United States
USEPA	United States Environmental Protection Agency
USFS	United States Department of Agriculture — Forest Service
v.	Volume

EXECUTIVE SUMMARY

Colorado is an area of abundant historic mining activity, and thus has numerous environmental issues related to mining impacts. It is a well-known fact that the physical disturbances caused by mining (i.e., excavation of rock, stockpiling of ore, and disposal of waste or tailings) can adversely affect the local water quality if interaction with surface water and precipitation are not carefully controlled. This is primarily caused by the abundance of sulfide minerals in many types of mined ore rock. The sulfide minerals react with water and atmospheric oxygen to begin a chemical reaction process called "acid rock drainage" or ARD (**Figure ES-1**). When associated with mining this process is often called "acid mine drainage."

Reaction 1:

$FeS_{2(s)} + H_2O + 7/2O_2 \rightarrow Fe^{2+} + 2SO_4 + \mathbf{2H^+}$

pyrite water oxygen iron sulfate acid

Reaction 2: (Catalyzed by bacteria)

$Fe^{2+} + 1/40 + \mathbf{H^+} \rightarrow Fe^{3+} + 1/2H_2O$

Reaction 3:

$FeS_{2(s)} + 8H_2O + 14Fe^{3+} \rightarrow 15Fe^{2+} + 2SO_4 + \mathbf{16H^+}$

Reaction 4:

$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_{3(s)} + \mathbf{3H^+}$

(s) = solid

Figure ES-1. The chemistry of acid rock drainage. *Reaction 1)* A metal sulfide mineral (e.g. pyrite) reacts with water and oxygen producing acid. *Reaction 2)* Ferrous iron released from pyrite is oxidized to ferric iron, consuming some acid. *Reaction 3)* Ferric iron reacts with pyrite and water producing a large amount of acid. *Reaction 4)* Ferric iron reacts with water to produce a red precipitate and more acid.

What is often overlooked is the environmental impact from land areas that have little or no mining activity, but contain bedrock that was "hydrothermally altered" in the geologic past. Hydrothermal alteration is a process by which large volumes of bedrock are subjected to circulation of hot water in the subsurface. Volcanic activity and other movements of magma into the shallow crust of the earth initiate thermal groundwater circulation systems. These hydrothermal systems persist for thousands to millions of years – as long as anomalous heat remains in the shallow crust. Circulating thermal groundwater has high concentrations of dissolved solids with abundant dissolved metals and sulfur, partially contributed by magma-derived fluids. The thermal waters dissolve some minerals from the rock and simultaneously deposit other minerals into the rock. The resulting hydrothermally altered bedrock commonly has increased percentages of acid-producing sulfide minerals (e.g. pyrite) and is depleted in acid-buffering minerals (e.g. calcite).

Over geologic time, subsequent erosion and exposure of hydrothermally altered bedrock initiates natural acid rock drainage (NARD), a process that can affect whole landscapes. **Figure ES-2** shows two areas of eroded and exposed hydrothermally altered bedrock. Depending on the size of the original hydrothermal system, the area affected by NARD can range from small (0.5 km^2) alpine sub-basins to entire mountain ranges.

This study identified numerous headwater areas in Colorado characterized by eroded hydrothermally altered bedrock and NARD (**Figure ES-3**). These areas include:

- Silverton Caldera,
- Lake City Caldera,
- Platoro-Summitville caldera complex,
- Kite Lake (San Juan Mountains),
- East Trout Creek (San Juan Mountains),
- La Plata Mountains,
- Rico Mountains,
- Grizzly Peak Caldera,
- Ruby Range,
- Montezuma Stock,
- Red Amphitheatre,
- Rabbit Ears Range.

Figure ES-2 (a). Hydrotherally Altered Terrane.
Lookout Mountain in the upper Alamosa River basin. Erosion and exposure of hydrothermally altered bedrock enriched in sulfide minerals such as pyrite (FeS_2) causes natural acid rock drainage (NARD). The streams that flow out of these mountains are aptly named Iron Creek, Alum Creek, and Bitter Creek.

In large measure, the severity of NARD in an area depends on the grade of alteration. The primary hydrothermal alteration types are acid-sulfate, quartz-sericite-pyrite (QSP), argillic, and propylitic. These are listed in order of alteration intensity or grade. The first three types are capable of producing NARD. The highest grade alteration types are acid-sulfate and QSP. These have the highest percentage of sulfide minerals, generally ranging from 5 to 15 percent of the rock volume. In some acid-sulfate and QSP systems, sulfide mineral abundance can range to more than 20 percent, such as in the Silverton caldera, Lake City caldera, and Summitville caldera areas of Colorado. Argillic alteration zones also produce acid drainage, but the clays present in the rock offer some minimal acid-neutralizing capacity. Propylitic alteration zones are located

Figure ES-2 (b). Hydrotherally Altered Terrane.
Red Mountain #2 south of Ouray in the San Juan Mountains. Both natural and mining-derived acid rock drainage contribute to increased metal concentrations in the Uncompahgre River.

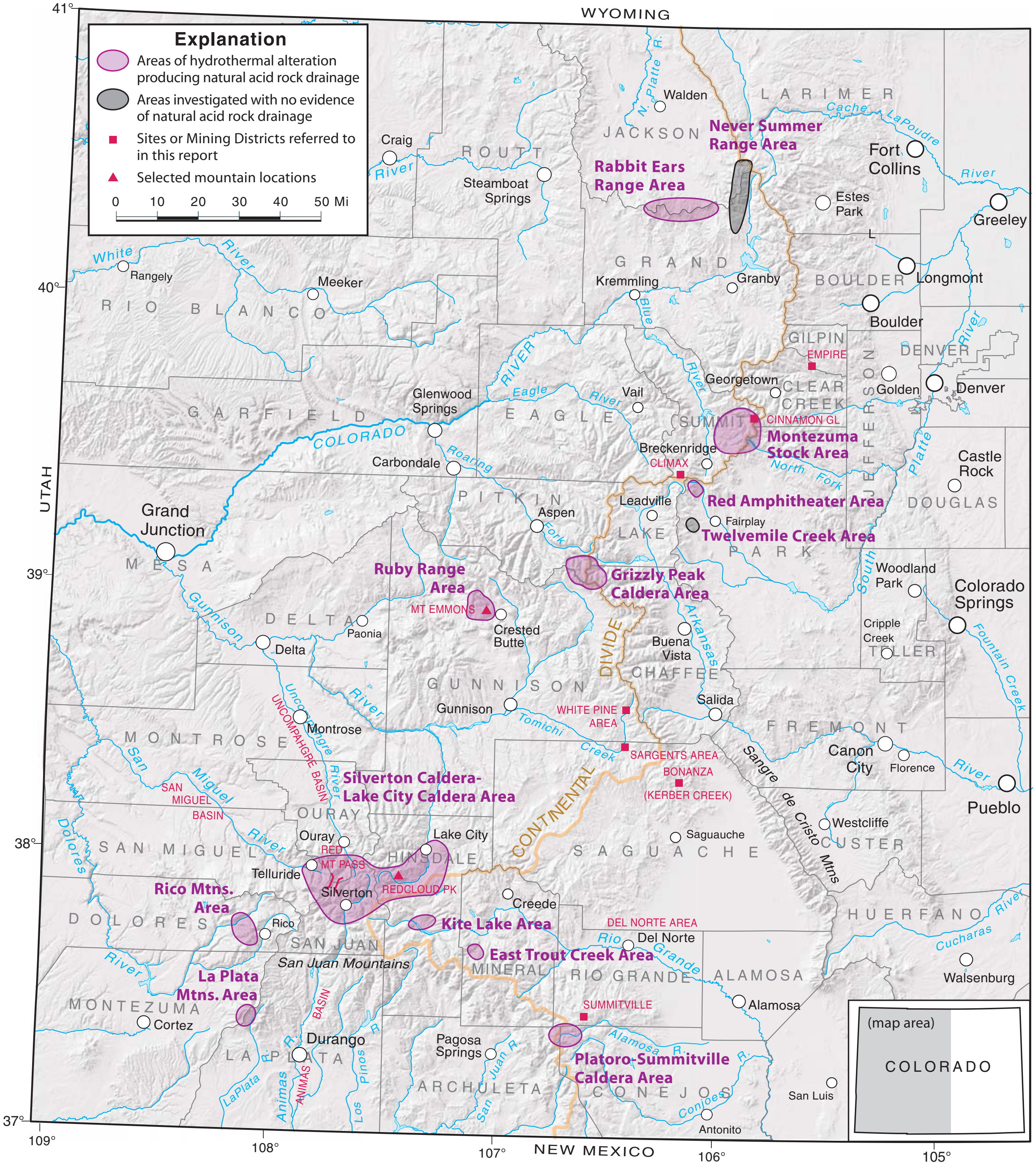

Figure ES-3. Map showing hydrothermally altered areas described in this report.

on the periphery of the higher grade alteration zones. This type of alteration contains acid-neutralizing minerals and can partially mitigate acidic water produced in higher grade alteration zones.

This report contains comprehensive water quality data on 101 sites in Colorado where bedrock is characterized by past hydrothermal alteration, NARD is prevalent, and anthropogenic disturbances are limited. Of these 101 sites, 86 are in areas that have no mining-related influence. The other 15 sites appear to be affected, in varying degree, by some type of human-induced water-quality impact such as old mining roads or nearby small mines and prospect diggings. Reconnaissance-level data (field pH and specific conductance) that allow a quick assessment of the general water quality are included for additional sites.

The water chemistry data program for this study was designed to evaluate the water quality associated with hydrothermally altered terrane, and to identify exceedances of the statewide water quality standards for metals and other constituents. As such, the majority of water chemistry data is for dissolved metals, with some analyses for total recoverable metals when either the water quality standard is dependent upon the total recoverable concentration, or the total recoverable concentration provides important information regarding metal solubility and transport (e.g., aluminum and iron). Major ion data are included for completeness, and to allow computation of water hardness. Statewide water-quality standards are used as the water quality reference in this report (instead of stream-segment standards) to facilitate comparison of water quality from one area to the next. Rock geochemistry data are presented for selected areas where more complete data were desired to determine the origin of metals in waters draining the affected areas.

Overall, 89 percent of the water samples collected were acidic (i.e., pH < 7) or had metal concentrations exceeding state standards, or both. Only 11 percent of the samples met statewide water quality standards for all of the tested parameters. Of the 86 samples with no apparent anthropogenic influence (**Table ES-1**), 66 samples had pH below the standard of 6.5. Concentrations of total recoverable aluminum exceeded the State hardness based standard in 65 of the 86 samples, and dissolved manganese exceeded the secondary (aesthetic) drinking water standard of 50 µg/L in 58 samples. Dissolved copper and zinc concentrations exceeded hardness-related State water quality standards in 50 samples each. Dissolved iron exceeded the secondary (aesthetic) drinking-water standard of 300 µg/L in 38 of 86 samples. Total recoverable iron exceeded the water quality standard of 1,000 µg/L in 35 samples. Cadmium also exceeded its hardness-based standard in 38 of 86 samples. Sulfate exceeded the secondary drinking-water standard of 250 mg/L in 14 samples, and lead exceeded its hardness-related standard in 11 samples. Nickel exceeded its hardness-related standard in 14 samples. Other parameters such as arsenic, thallium, chromium, silver, fluoride, and chloride exceeded standards five or less times each and these analytes were not detected in most samples.

This investigation indicates that dissolved aluminum and manganese concentrations generally exceed State water quality standards in NARD waters draining hydrothermally altered terranes (Table ES-1). Natural concentrations of copper, iron, cadmium, and zinc are typically elevated in hydrothermally altered areas around larger mining districts. **Table ES-2** summarizes specific areas exhibiting NARD, the respective statewide water quality standards exceeded, and the affected drainage basins.

Surface waters associated with hydrothermally altered areas vary significantly in chemical composition as a function of a number of parameters including: topography, host and country rock compositions, alteration type, volumetric extent, and ore deposit type. In all of the areas studied for this report, changes in water chemistry, from essentially unim-

Table ES-1. Summary of water chemistry data from sites with no known anthropogenic influence.
(Statewide table value standards are used)

Parameter	Number exceedances of water water quality standards (out of 86 samples)
pH	66
Aluminum (trec)	65
Antimony (trec)	0
Arsenic (trec)	3
Iron (trec)	35
Thallium (trec)	4
Zinc (trec)	2
Cadmium	38
Chloride	2
Chromium	2
Copper	50
Fluoride	3
Iron	38
Lead	11
Manganese	58
Nickel	14
Silver	2
Sulfate	14
Zinc	50

pacted (near neutral pH/low metal) to NARD (acidic/high metal) water are readily related to changes in alteration type and intensity. In particular, changes from propylitic or unaltered rocks to acid-sulfate, QSP, or argillic altered zones are commonly reflected in dramatic changes in the local chemistry of tributaries and springs. Such behavior is expected based on inherent variations in the acid generating capacity and acid neutralizing potential of different alteration assemblages. Based on the full water sample dataset, NARD exhibits a strong inverse relationship between pH and aluminum, iron, manganese, copper, cadmium, zinc, nickel, and sulfate. As pH declines, concentration of these metals and sulfate increase, and vice versa. The metals and sulfate have a positive correlation indicating that as one analyte concentration increases, generally the others increase also.

Many of the areas examined during this study are in watersheds where both natural ARD and historic mining-induced ARD affect water quality. Detailed characterization of the natural and anthropogenic sources is especially important in drainage basins slated for mine-reclamation projects so that realistic remediation goals can be defined.

Table ES-2. Summary of water quality standard exceedances by area. (Statewide table value standards are used)

Area	Drainage Basin	Standard Exceedances
Carson Camp	Lake Fork of the Gunnison	Al, Mn, Fe, Cu, Zn
East Trout Creek	Rio Grande	Al, Mn, Fe, SO4
Grizzly Peak Caldera	South Fork Lake Creek	Al, Mn, Fe, Cu, Zn, Cd, Ni, SO4
Kite Lake	Rio Grande	Al, Mn, Fe, Cu, Zn, Cd, Ni
La Plata Mountains	La Plata River	Al, Mn, Fe, Cu, Zn, Cd, F, Pb
La Plata Mountains	East Mancos River	Al, Mn, Fe, Cu, Zn, Cd, As, Tl, Ni, Cr, SO4
Lake City Area, Red Cloud	Lake Fork Gunnison	Al, Mn, Fe, Cu, Zn, Mo (Miller, 1998)
Montezuma	North Fork South Platte River	Al, Mn, Fe, Cu, Zn, Cd, Ni, Cr, SO4
Montezuma	Snake River	Al, Mn, Fe, Cu, Zn, Cd, Pb, Tl, Ag
Never Summer Mountains	Illinois River	As (limited sampling)
Platoro-Summitville	Alamosa River	Al, Mn, Fe, Cu, Zn, Cd, As, Tl, SO4
Rabbit Ears Range	Colorado River	Al, Mn, Fe, As
Red Amphitheatre	Middle Fork South Platte River	Al, Mn, Zn, Cd, F
Red Mountain Pass	Red Mountain Creek	Al, Mn, Fe, Cu, Zn, Cd, Pb, As, Tl, Ag
Rico Mountains	East and West Dolores Rivers	Al, Mn, Fe, Cu, Zn, Cd, SO4
Ruby Range	Gunnison River	Al, Mn, Fe, Pb, Cu, Zn, Cd, As, Ag, Cl, SO4
San Juan Mountains	San Miguel River	Al, Mn (limited sampling)
Slumgullion	Lake Fork of the Gunnison	Al, Mn, Fe, Cu, Zn, SO4, F, Cl
Twelvemile Creek	South Platte River	(no samples)

1

INTRODUCTION

The abundance of mineral deposits in Colorado is well known, with mineral production dating back to the 1860's. The environmental impacts of the mining industry have been, and will likely continue to be, the subject of investigation, remediation, debate, and litigation. Adverse impacts on watersheds are common in Colorado from mining-induced acid rock drainage (ARD), also called acid mine drainage. Many of Colorado's ore deposits were formed by hydrothermal processes associated with episodic volcanism and magma intruding the crust over time scales of millions of years. The most visible source of environmental impact from an abandoned mine is typically the mine adit (tunnel) discharging discolored water. However, hydrothermal activity often creates zones of mineral alteration that extend well beyond the immediate location of concentrated ore. In fact, large areas of hydrothermally altered terrane extend from mined areas to areas without any associated mineral production. Mineral alteration can be a source of hydrologic contamination on a scale that is not immediately evident. Thus, the extent of environmental impact derived from hydrothermally altered areas unaffected by economic mineral production or other significant anthropogenic influence is a subject that historically has not received much attention. The goal of this report is to provide the regulatory community, mining industry, environmental professionals, and the public with an appreciation of the magnitude of hydrologic impacts from ARD in Colorado derived strictly from natural geologic processes.

This report is the culmination of a study conducted by the Colorado Geological Survey (CGS), to evaluate natural acid rock drainage associated with hydrothermal alteration in Colorado. It supercedes the CGS report "Naturally Degraded Surface Waters Associated with Hydrothermally Altered Terrane in Colorado" (Open File Report 00-16), which was a reconnaissance-level investigation of naturally degraded waters in the state. In this report we have replaced the term "naturally degraded water" with the more precise term "natural acid rock drainage" (NARD), which identifies the cause of poor water quality in the affected areas. These waters have acidic or low pH (<6.5) and have dissolved or suspended constituent concentrations of metals and other constituents (i.e. Al, Fe, Zn, SO_4) exceeding State of Colorado water quality standards.

Many of the areas investigated during this study were initially identified by field measurements of pH and electrical conductivity (EC), during an abandoned mine land (AML) inventory conducted by CGS for the U.S. Forest Service (USFS) from 1991 through 1998 (Sares and others, 2000). Observations of the surrounding geology helped to reveal the impressive magnitude and extent of natural ARD in Colorado, and led to the decision that a more detailed investigation was warranted.

Areas of Colorado included in this investigation are shown in **Figure 1**. In each of these areas several water tests were conducted measuring pH, conductivity, and temperature. At most sites, a water sample was collected for laboratory analyses that included a suite of dissolved and total recoverable metals. This report includes all of the data and findings from the previous open-file report, but also includes significantly more detailed work for several locations that are considered important in terms of size, historical significance, environmental impact, amount of published information available, or other factors. At these locations, geology, structure, and hydrothermal alteration were mapped, and rock samples were collected for detailed chemical analyses. Additional water samples were collected at selected locations where supplemental data were desired. In total, 101 water samples were collected for this investigation.

Locations with historical or environmental significance typically have more information available in the literature than the less significant locations. For these areas, we have tried to incorporate as much information as possible to give the reader a more complete background. Areas that have new research and enhanced discussion include: Red Mountain Pass District, Slumgullion Slide, Allard Stock in the La Plata Mountains, Grizzly Peak Caldera, Montezuma Stock area, and Red Amphitheatre.

Personnel from the U.S. Geological Survey, the Colorado Division of Reclamation, Mining and Safety,

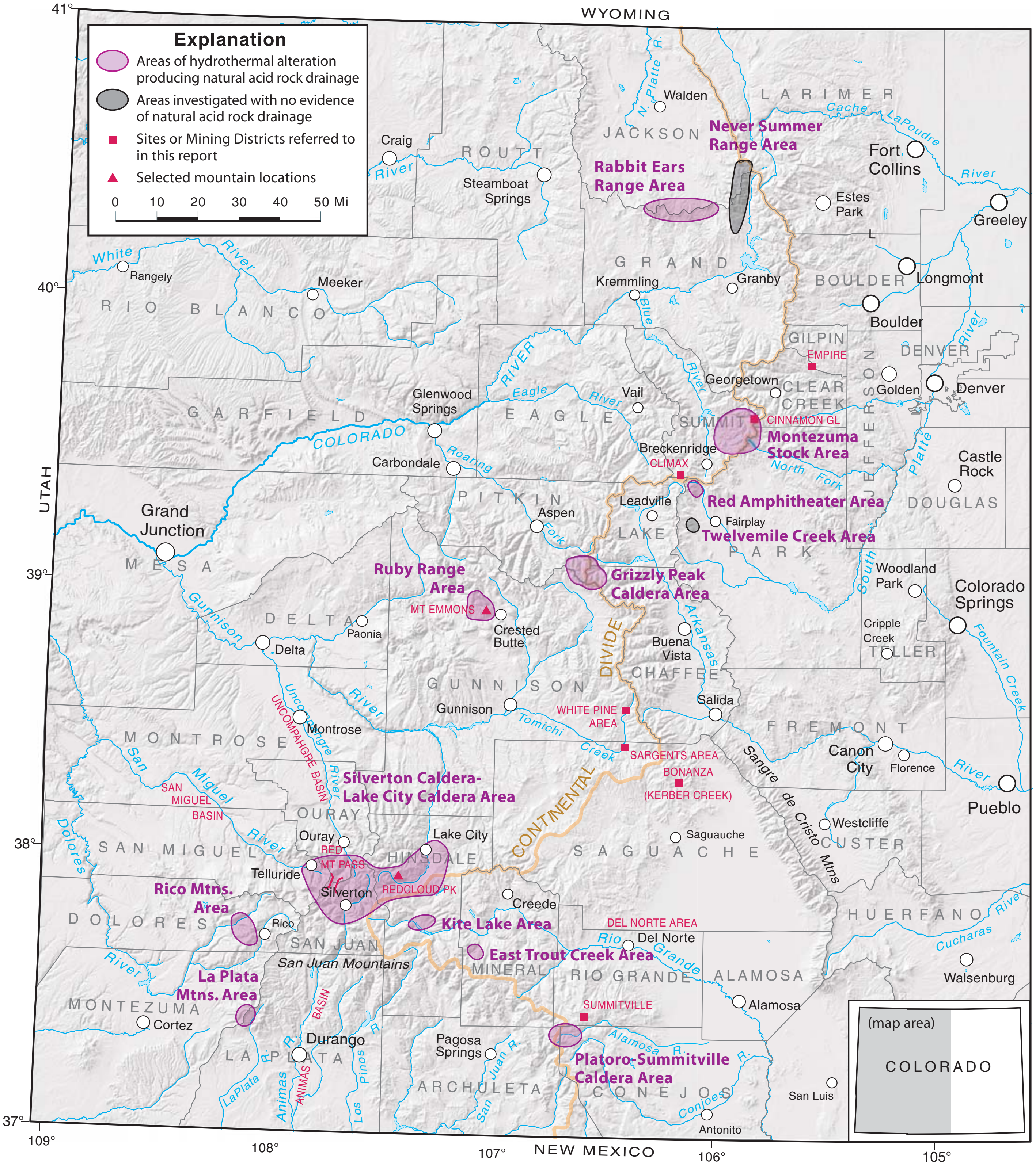

Figure 1. Index map showing hydrothermally altered areas described in this report.

and Colorado State University were important sources of preliminary information. A publication on iron occurrences in Colorado (Harrer and Tesch, 1959) was also used as a reference, because it describes numerous bog-iron deposits, many of which are associated with natural ARD.

A number of individual samples in several natural ARD areas contain near neutral pH, but still exhibit elevated concentrations of metals and sulfate. These samples may be indicative of acid neutralization processes downgradient of ARD and upgradient of the sampling site. Some entire areas sampled for this report yield dominantly near neutral pH waters with elevated metals and sulfate. The acid neutralizing capacity of the rocks in these areas appears to have been sufficient to neutralize the acid waters generated in the hydrothermally altered terrane.

Although this study does not characterize every hydrothermally altered area in Colorado, it does cover a significant portion of the Colorado mineral belt (Tweto, 1968), and the most prominent areas in which natural ARD occurs. The study can serve as a guide to identify other areas of Colorado that may be characterized by ARD, and provide general information regarding water chemistry in these areas. Several areas described in this report have been the subject of detailed studies characterizing geology and watersheds to better understand the natural and anthropogenic processes affecting groundwater and surface-water chemistry. Such studies were completed in the San Juan Mountains (Church and others, 2007; Bove and others, 2007; Mast and others, 2000a), Summitville area (Bove and others, 1996; Posey and others, 1995), Montezuma stock area (Caine and others, 2006; Bird, 2003; Fey and others, 2002), and Grizzly Peak caldera area (Bird and others, 2005; Sares and others, 2004).

Findings from this study are useful for regulatory agencies in setting stream water-quality standards and mine reclamation standards. In particular, data contained herein are useful in identifying stream reaches "impaired" by irreversible natural processes in addition to, or instead of, reversible human-induced processes. This distinction is crucial in the definition of impaired stream reaches that must be identified and listed by regulatory agencies in compliance with section 303(d) of the Clean Water Act. The data and findings may also be useful for determining remediation goals for past and future mining operations. Recognition of the natural ARD contributions to metal loads in streams, which are also contaminated by past mining activities, is important in establishing realistic clean-up goals. This study highlights the need for comprehensive baseline investigations to determine background conditions in watersheds prior to human development – including mines, home subdivisions, water diversions, reservoirs, and roads, among others.

2

METHODS OF INVESTIGATION

Sites with potential for natural acid rock drainage (NARD) in surface water were identified using the sources discussed previously and by using a variety of literature references. Using published maps and information from the Colorado Geological Survey abandoned-mine inventory of USFS-administered lands, sites with little or no known upstream mining activity were selected for the study. In the field, visual evidence such as precipitate, ferricrete or ferrosinter deposits, or turbid water, in conjunction with reconnaissance water testing (measurements of pH and electrical conductivity (EC)), were used to screen sites for geochemical sampling. Low pH (i.e., less than 6) or elevated EC (i.e., several hundred µS/cm) were regarded as potential indicators of ARD and were used as the main criteria to warrant collection of a sample for laboratory water quality analysis. Metals are generally more soluble and mobile at lower pH ranges (< 5), hence acidic water can have elevated concentrations of metals if a source is available. EC is proportional to the concentration of charged ions in the water, hence is generally proportional to total dissolved solids (Hem, 1985).

Many of the sample sites and the associated hydrothermally altered slopes around them were photographed. Maps of hydrothermal alteration assemblages were compiled in several areas where such mapping had not been previously conducted or was not readily available in published form. Where available, AVIRIS (Airborne Visual Infrared Imaging Spectroscopy) remote sensing data were used to aid in the compilation of the alteration assemblage maps. Field mapping, sampling, and laboratory analyses were also used to define alteration types in selected areas.

Filtered (0.45 µ) and unfiltered water samples were collected from selected streams and springs for laboratory analyses. In some locations, depending on factors such as inclement weather or nightfall, a large container would be filled at the sample site, and subsampled into filtered (dissolved) and raw (total recoverable) aliquots either at the vehicle or indoors. Samples were refrigerated until delivered to the lab. Field sampling protocols, laboratory analytical methods, and QA/QC information are in Appendix A.

At locations where a sample of running water was collected (e.g., stream, spring, or workings with flowing discharge), efforts to measure discharge were made using either a portable Baski cutthroat flume or instream flowmeter. Where the use of either the flume or flowmeter was impractical due to channel conditions or low flow, discharge was estimated visually or with a catchment such as a 5-gallon bucket.

For consistency in reporting data from different stream segments, analytical results were compared to statewide water quality standards established by the Colorado Water Quality Control Commission (CDPHE, 2011).[1] Specific stream-segment standards were not used. The relevant standards are shown in the table containing the laboratory analytical data in **Appendix A**. The most stringent of either the domestic-water-supply standard or the aquatic-life standard is shown.

Aquatic life standards for dissolved cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), silver (Ag), zinc (Zn), and total recoverable aluminum are dependent upon the hardness of the water. Thus, each water sample will have a unique set of water quality standards for those metals, which will be a function of the hardness of the water sample. Hardness, expressed as milligrams per liter of calcium carbonate ($CaCO_3$) equivalent, is calculated from the concentrations of calcium (Ca) and magnesium (Mg) as follows:

$$\text{Hardness (as } CaCO^3 \text{ mg/L)} = 2.5 \times (\text{Ca mg/L}) + 4.1 \times (\text{Mg mg/L})$$

The hardness reported in the tables is calculated from the Ca and Mg concentrations, rather than measured analytically, so no error is introduced by hardness contributed by ions other than Ca and Mg. Also, water quality standards based on hardness do not adjust for hardness above 400 mg/L.

The aquatic life standard for manganese (Mn) also depends on hardness, but will always be above the secondary (aesthetic) drinking water standard of 50 µg/L unless the hardness is less than 0.003 mg/L, which is not likely. Thus, to provide a more stringent basis for comparison, the secondary drinking water standard for manganese is used for reference in this

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[1] Regulation 31-Basic Standards and Methodologies for Surface Water available at http://www.cdphe.state.co.us/op/regs/waterqualityregs.asp)

report instead of the aquatic life standard. The aquatic life standard (chronic) for aluminum (Al) is based on total recoverable concentration and is complex. Above pH=7 it is based on the hardness-related equation. Below pH=7, the standard is based on the equation or 87 µg/L, whichever is more restrictive. The aquatic life standard (chronic) for iron (Fe) is 1,000 µg/L, and is based on total recoverable concentration. The dissolved iron standard (300 µg/L) referenced in this report is the more restrictive secondary (aesthetic) drinking water standard. The zinc aquatic life standard is based on hardness, but the equation is more resrictive if the stream hosts sculpin fish. The non-sculpin equation was used in this report to allow comparison statewide. The chromium (Cr) standard used is that of hexavalent chromium (VI). In most cases it is more restrictive than the trivalent chromium (III) standard. **Table 1** lists the constituents analyzed, the corresponding State water quality standard for each, and if the standard is related to hardness.

Tables that show the results of water chemical analyses and water quality standards (appendices) also include columns for "factor above standard" and "approximate load." The factor above standard is obtained by dividing the concentration of the constituent by the standard for the constituent. The approximate load is obtained by multiplying the concentration of the constituent by the flow rate, with appropriate unit conversions.

To substantiate field observations and verify assumptions about mineral solubility controls, selected water analytical data were modeled using the USGS software program PHREEQC (Parkhurst and Appelo, 1999) to calculate saturation indices of possible mineral phases.

Table 1. Constituents analyzed and corresponding water quality standards.

Parameter	Water Quality Standard	Basis
pH	6.5 – 9.0	Aquatic Life
Aluminum (trec)	87 µg/L or $e^{(0.3695[\ln(\text{hardness})]-0.1158)}$	Aquatic Life
Antimony (trec)	6 µg/L	Domestic Water - primary
Arsenic (trec)	10 µg/L	Domestic Water - primary
Iron (trec)	1,000 µg/L	Aquatic Life
Thallium (trec)	0.5 µg/L	Domestic Water - primary
Zinc (trec)	2,000 µg/L	Agricultural
Aluminum	None	n/a
Cadmium	$(1.101672 - [\ln(\text{hardness}) \times (0.041838)]) \times e^{(0.7998[\ln(\text{hardness})]-4.4451)}$	Aquatic Life
Chloride	250 mg/L	Domestic Water - secondary
Chromium	11 µg/L (Cr VI)	Aquatic Life
Copper	$e^{(0.8545[\ln(\text{hardness})]-1.7428)}$	Aquatic Life
Fluoride	2 mg/L	Domestic Water - primary
Iron	300 µg/L	Domestic Water – secondary
Lead	$(1.46203 - [\ln(\text{hardness}) \times (0.145712)]) \times e^{(1.273[\ln(\text{hardness})]-4.705)}$	Aquatic Life
Manganese	50 µg/L	Domestic Water - secondary
Molybdenum (trec)	210 µg/L	Domestic Water - primary
Nickel	$e^{(0.846[\ln(\text{hardness})]+0.0554)}$	Aquatic Life
Silver	$e^{(1.72[\ln(\text{hardness})]-10.51)}$	Aquatic Life
Sulfate	250 mg/L	Domestic Water - secondary

3

GEOLOGIC OVERVIEW

Most of the mineralization and hydrothermal alteration within the areas examined for this study was produced by Late Cretaceous and Tertiary-age (95–1.8 Ma) igneous events. Circulating hydrothermal fluids associated with these past volcanic or igneous intrusive events often formed metal ore bodies. These hydrothermal fluids also deposited metallic minerals, especially pyrite, over much larger areas surrounding the ore deposits.

Today, acidic, metal-rich surface waters are commonly associated with mining districts and, as this study demonstrates, are also frequently associated with nearby areas of hydrothermally altered bedrock having little or no mining activity. Oxidation of pyrite is generally the primary source of acidity and sulfate in naturally acidic, metal-rich streams. Oxidation of other sulfide minerals, such as chalcopyrite, marcasite, and enargite, can also contribute acidity as well as metals.

The sulfide minerals present in the bedrock react with water and atmospheric oxygen to begin a chemical reaction process called "acid rock drainage" (ARD). When associated with mining it is often called "acid mine drainage." When this process occurs in unmined, natural settings, it is called *natural* ARD or NARD. The chemistry of ARD is multifaceted, but is explained by the following four reactions:

Reaction 1:

$FeS_{2(s)} + H_2O + 7/2O_2 \rightarrow Fe^{2+} + 2SO_4 + \mathbf{2H^+}$

pyrite water oxygen iron sulfate acid

Reaction 2: (Catalyzed by bacteria)

$Fe^{2+} + 1/40 + \mathbf{H^+} \rightarrow Fe^{3+} + 1/2H_2O$

Reaction 3:

$FeS_{2(s)} + 8H_2O + 14Fe^{3+} \rightarrow 15Fe^{2+} + 2SO_4 + \mathbf{16H^+}$

Reaction 4:

$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_{3(s)} + \mathbf{3H^+}$

(s) = solid

In Reaction 1, a metal sulfide mineral (e.g. pyrite) reacts with water and oxygen producing acid. Bacteria catalyze Reaction 2, in which, ferrous iron is released from pyrite and is oxidized to ferric iron, consuming some acid. The bacteria thrive in acid environments and greatly accelerate the rate of this reaction. The released ferric iron then reacts with pyrite and water (Reaction 3) producing a large amount of acid –16 moles of acid for each mole of pyrite available. In Reaction 4, ferric iron is hydrolyzed to produce a reddish iron precipitate and more acid. This precipitate is often found coating streambeds in ARD affected watersheds, whether natural or mining induced.

The NARD process has been active in Colorado for at least thousands, possibly millions of years. Natural ARD is common in bedrock in or near the margins of calderas and igneous stocks. Hydrothermally altered, pyritized, and fractured intrusive igneous rocks are favorable host rocks for sources of NARD.

OVERVIEW OF HYDROTHERMAL ALTERATION

There are three principal types of base and precious metal ore deposits/occurrences prevalent in Colorado that are associated with the majority of natural ARD. These three types of deposits have distinctive ore mineralogy as well as characteristic spatial distributions of the alteration assemblages. They also have distinctive regional geologic settings and important differences in the sizes of the mineralized and altered districts. The three principal ore deposit types of interest for the present study are 1) acid-sulfate, 2) porphyry molybdenum (Mo) or Mo/Cu systems, and 3) polymetallic vein deposits. These ore deposit types found in Colorado were formed millions of years ago, long before the geologically recent erosion and ARD process caused acidic, metal-rich surface waters.

Well known Colorado examples of the acid-sulfate ore deposit type are Summitville, Red Mountain Pass, and Red Mountain near Lake City, Colorado (Stoffregen, 1987; Bove and others, 1990; Mast and others, 2000a).

Examples of porphyry molybdenum deposits include the high silica granite to rhyolite systems at Climax, Henderson, and Mount Emmons, (White and others, 1981; Mutschler and others, 1981b). Numerous subeconomic granodiorite to dacite Mo and Mo/Cu porphyry systems are also present throughout Colorado, including examples such as Mount Moly near Ophir and in the Montezuma area (Bove and others, 2001; Bove and others, 2004). Polymetallic vein deposits are present to some extent in nearly every mining district within Colorado, but the best known districts are Central City (Sims and others, 1963), Creede (Steven, 1968) and veins of the Silverton caldera and Lake City caldera (Burbank and Luedke, 1968).

ACID-SULFATE DEPOSITS

In terms of genesis, the acid-sulfate type of deposit in Colorado is typically present in intermediate to felsic volcanic rocks on the margins of Tertiary-age calderas. These alteration systems formed from highly acidic and sulfate-rich fluids that contained residual magmatic volatiles. Acid-sulfate deposits are associated with pervasive and areally extensive zones of highly pyritic and altered rock (Gray and Coolbaugh, 1994; Bove and others, 1996; Bove and others, 1990; Bove and others, 2000). In Colorado, most of these deposits are deeply rooted, are vertically and laterally extensive, and formed from magmatic-derived sulfate-rich hydrothermal fluids. Acid-sulfate zones are typically located above deeper quartz-sericite-pyrite (QSP) zones. One of the most distinctive mineralogic features of these deposits is the presence of alunite along with pyrophyllite and dickite.

Acid-sulfate deposits show lateral progression of alteration from inner silicified zones and alunite-bearing acid-sulfate assemblages outward to argillic altered rock (with lesser sericite) and finally into propylitic altered rock. Acid-sulfate altered rock may be marked by extreme acid leaching of nearly all host rock minerals resulting in a texture known as "vuggy silica" in the ore zone.

In terms of metal abundances, the acid-sulfate type deposits tend to be Cu, As, and Pb rich, as at Summitville and Red Mountain Pass (Plumlee and others, 1999; Bove and others, 1996; Bove and others, 2000; Bove and Knepper, 2000). However some acid-sulfate deposits in Colorado, such as Red Mountain near Lake City, do not have high sulfidation (high sulfur to metal ratio) Cu-As-Pb ores associated with them.

PORPHYRY MO AND MO/CU DEPOSITS

Porphyry Mo and Mo/Cu deposits are quite large deposits characterized by disseminated and veinlet-controlled mineralization that is deposited throughout very large volumes of altered rocks. These deposits formed dominantly from magmatic hydrothermal fluids related to late stages of magmatism in an area (Lowell and Guilbert, 1970; White and others, 1981).

The typical host intrusive for granite-type Mo systems is a granitic rock enriched in silica and fluorine. The main porphyry Mo orebodies consist of stockwork veinlets of quartz and molybdenite with associated pyrite and fluorite. The central parts of porphyry Mo deposits are typically poor in base metal sulfides such as sphalerite, galena and chalcopyrite, but zinc and lead sulfides along with calcite and manganese carbonate generally increase in abundance away from the core (Mutschler and others, 1981b; White and others, 1981).

The typical host intrusive for the Mo/Cu deposits is an intermediate composition (granodiorite to quartz monzonite) intrusive rock, generally low in fluorine compared to the high silica granite porphyry Mo systems. The primary ore minerals in porphyry Mo/Cu deposits are pyrite, molybdenite and chalcopyrite with lesser scheelite near the central core. In addition, an alkalic variety of porphyry Cu deposit is known in Canada (Barr and others, 1976) and at the Allard stock in the La Plata Mountains of Colorado (Werle and others, 1984) among other locations. The principal primary ore minerals in porphyry Cu deposits are pyrite and chalcopyrite with lesser bornite, enargite and molybdenite.

Wallrock alteration assemblages associated with porphyry Mo and Mo/Cu deposits form broad zones progressing from a core of potassic alteration marked by potassium feldspar, biotite, and anhydrite. The potassic altered rocks are surrounded by a broad QSP alteration zone, and the more distal portion of the deposit is characterized by propylitic alteration of the country rocks surrounding the host intrusion. The propylitic assemblage typically contains epidote, chlorite, calcite and some pyrite. The upper portions of the QSP alteration zone in porphyry deposits may show argillic alteration due to interaction of meteoric fluids as the hydrothermal system cooled. In some Mo/Cu deposits, an acid-sulfate alteration zone may overlie deeper porphyry deposits (Bove and others, 1990; Bove and others, 1996). In deeper levels of granitic porphyry Mo type deposits, wall rocks are typically altered to "greisen" assemblages of quartz, muscovite and topaz (White and others, 1981).

The high-silica granite, Mo-porphyry deposits are generally molybdenum, fluorine, and tin rich while the porphyry Mo/Cu deposits tend to be rich in Mo and/or Cu with associated tungsten. Peripheral Pb-Zn and Au-Ag veins are common to all porphyry systems.

POLYMETALLIC VEIN DEPOSITS

Polymetallic veins have mostly formed in the epithermal environment in the Colorado Mineral Belt. Such veins generally form where surficial waters mix with deeper, heated, saline waters in a lateral flow regime, high above and probably offset from an intrusive heat source at depth. These hydrothermal systems have many features in common with present day geothermal systems such as at Yellowstone and Broadlands, New Zealand (Heald and others, 1987; Sillitoe, 1993). The epithermal deposits form within a few kilometers of the surface and are characterized by veins, stockworks and mineralized breccias typically within a volcanic host rock. Polymetallic vein deposits can also form at slightly greater depths than the epithermal veins and are characterized by veins and stockworks in highly variable host rocks. The polymetallic veins are generally composed of quartz, pyrite, chalcopyrite, sphalerite and galena with occasional arsenopyrite and sulfosalts. In most districts, sphalerite, galena and vein carbonates increase in abundance toward the outer margins of the district (Sims and others, 1963). The principal gangue minerals are quartz, carbonates, adularia, and sometimes fluorite and/or barite.

Epithermal systems are marked by strong lateral and vertical variation in wallrock alteration assemblages with silicification and argillic alteration closest to the veins and propylitic alteration farther away from the veins. QSP alteration and propylitic alteration of the wallrocks generally occurs in narrow envelopes that are up to several times the vein width. Somewhat broader areas of alteration can occur associated with breccia bodies. Polymetallic vein deposits may be dominated by any base metal and may have significant associated manganese minerals.

All three deposit types form in structurally complex environments that typically have several generations and orientations of faults and fractures. For the acid-sulfate type deposit, the most common regional structural setting is near caldera margins (the ring fracture area). Typical examples of such caldera settings in the present study are: Summitville-Platoro caldera complex, Red Mountain Pass in the Silverton caldera, Lake City caldera; and the Grizzly Peak caldera. Porphyry Mo/Cu systems may be found in caldera settings in Colorado as well. Examples in the present study are known in the Grizzly Peak caldera (Cruson, 1973; Bove and others, 2004) and the Summitville caldera (Bove and others, 1996). The polymetallic vein type deposits may also be found in caldera settings within Colorado, such as those in the Silverton (Burbank and Luedke, 1968), Creede (Steven, 1968), and Lake City (Burbank and Luedke, 1968) calderas.

Another distinctive feature of the three deposit types is the size of the "productive" district and of the altered area. The acid-sulfate type in Colorado tends to form a relatively equidimensional volume of altered and mineralized rock and to have a similar extent of altered rock volume as that related to porphyry Mo and subeconomic porphyry Mo/Cu systems.

Polymetallic vein systems tend to have relatively narrow alteration envelopes but may have vein lengths that extend over several miles. Examples in the present study are the large altered volumes in the acid-sulfate systems at Red Mountain Pass and the large altered area in the porphyry Mo/Cu system at Montezuma. The Red Amphitheatre area provides the simplest example of a polymetallic vein system of limited extent in the present study.

COLORATION OF ALTERATION ZONES IN THE WEATHERING ZONE

Some generalizations about typical coloration of alteration zones can be made to allow the reader to make some interpretations of probable pyrite abundance and alteration assemblage in those areas where no hydrothermal alteration mapping was compiled and descriptions of alteration are solely based on rock coloration observed from a distance.

The acid-sulfate, QSP, and argillic assemblages commonly weather to various colors of bright red, orange, and yellow. The QSP alteration zone is typically gray where pyrite is unoxidized, or yellowish (jarosite) where partially oxidized (Swayze and others, 2000). Areas of argillic alteration are typically marked by more extensive erosional features due to the low quartz content compared to acid-sulfate and QSP zones. The color of argillically altered rocks is variable from light gray to light yellow to light orange. It often has a bleached appearance because of the presence of light-colored clays.

The propylitic alteration zone is generally various shades of green depending on chlorite and epidote abundance. Surfaces may be stained dark brown to black by iron and manganese oxide coatings.

PYRITE ABUNDANCE

Pyrite abundance tends to be quite variable in the different alteration zones typically ranging from 5 to over 15% by volume (Bove and others, 2000; Bove and others, 1990; Bove and others, 1996). The sericitic alteration zone in many cases contains the highest percentage of pyrite of the alteration zones present, where it can range to over 20% by volume. In several acid-sulfate systems in Colorado (Summitville, Red Mountain-Lake City, Silverton), pyrite abundance is very high (>20 vol. %) in the acid-sulfate zone (Bove and others, 2000; Bove and others, 1990; Bove and others, 1996). The propylitic alteration zone generally contains the lowest percentages of pyrite.

ACID NEUTRALIZATION POTENTIAL

The presence of carbonate and hydroxyl-bearing minerals serve to neutralize some ARD. Although the details of the acid neutralization process are fairly complex (Lawrence and Wang, 1997; Plumlee and others, 1999; Bove and others, 2000; Mast and others, 2000a; Jambor and others, 2000) some broad generalizations can be made. In most deposits, the silicic zone has essentially no minerals available to contribute to acid neutralization, unless there are carbonates present in the veins. The typical coarse-grained potassic assemblage in porphyry systems is fairly unreactive and provides little acid neutralization (Plumlee and others, 1999). The minerals of the argillic assemblage also have minimal potential to neutralize acidity unless montmorillonite (mixed layer illite/smectite) is present. Even in this case, the abundance of pyrite generally results in this zone being an acid-generating assemblage (Plumlee and others, 1999). Both the acid-sulfate and QSP zones are acid generating (Bove and others, 2000; Mast and others, 2000a). Any chloritic zone present will generally have limited acid neutralizing potential. Only the propylitic zone has any significant acid neutralizing potential, with the degree mainly dependent on the carbonate content. Unaltered country rocks may also act as acid neutralizers with the strength depending on the feldspar and particularly the carbonate content of the rocks.

IMPLICATIONS FOR NATURAL ACID ROCK DRAINAGE

Acid-sulfate type deposits generally have low acid neutralization potential because the basic ions are leached during the pervasive alteration. These rocks also have high acid-generating potential due to an abundance of finely disseminated pyrite and therefore waters interacting with these rocks are commonly acidic and have high concentrations in iron, aluminum, and sulfate. Pyrite and other sulfide minerals are typically oxidized and leached in the upper portions of high-level acid-sulfate zones. Waters draining rocks when exposed and oxidized generally have low pH and are low in dissolved metal concentrations (Plumlee and others, 1999; Bove and others, 1996; Bove and others, 2000). Although typical volcanic host rocks for acid-sulfate systems have fairly limited acid neutralization potential, acid-sulfate systems in Colorado are situated in caldera environments that generally have regional zones of propylitic- altered rock that commonly contain calcite surrounding the acid-sulfate system. Thus, there is some potential for acid neutralization on the periphery of these systems. Porphyry Mo and Mo/Cu systems are areally extensive with large areas of QSP altered rock that has significant acid generating potential due to the abundance of disseminated pyrite. The central portions of porphyry Mo and Mo/Cu systems tend to produce ARD with relatively low base-metal contents because they are generally lower in abundance in such systems (Plumlee and others, 1999). For the porphyry Cu systems, like the Allard stock in the La Plata Mountains, the ARD typically has a higher concentration of copper than zinc (Plumlee and others, 1999). The peripheral propylitic alteration zone in all porphyry systems has moderate acid neutralization potential but is usually far removed from the central areas where ARD is generated. Highly variable acid neutralization potential may exist on the periphery of the porphyry system depending on the composition of the wall rocks (e.g., presence or absence of carbonates).

Polymetallic vein deposits, have small alteration haloes generally no more than 1–2 times vein width, with fairly low potential for acid generation, especially where the veins have not been disturbed by mining. The country rocks are typically unaltered and have some acid neutralization potential. The close proximity of propylitically altered vein envelopes to the vein sulfides suggests that acid neutralization should be common in most vein systems. Veins have a high availability of metals but the source of acidity is limited due to the low surrounding volume of altered and pyritic rock, as well as the general acid-neutralizing capacity of the unaltered wall rocks. (Bove and others, 2000, Mast and others, 2000c).

The highly variable base metal content of polymetallic veins implies that any metal could be leached from these deposits and become a problem in streams down gradient, although zinc tends to be the most mobile of the base metals over a wide range of pH.

The presence of propylitic alteration zones does allow for some acid neutralization in all three deposit types. The ability of the propylitic zone to have significant acid neutralizing effects is largely dependent on its carbonate content as well as the spatial relations of this alteration zone to the area where naturally degraded waters are generated.

RELATIONSHIP BETWEEN TYPES OF HYDROTHERMAL ALTERATION AND SURFACE-WATER CHEMISTRY

This study corroborates the findings of several recently completed compilations (Plumlee and others, 1995; Plumlee and others, 1999; Church and others, 2007) that investigated relationships between hydrothermal alteration/mineralization and surface-water quality. These compilations demonstrated that waters draining mineral deposits with similar geologic characteristics tend to generate similar metal concentrations and pH values, and that suites of metals present in mine-drainage waters typically reflect the same characteristic suite of metals contained in the mineral deposits

(Smith and others, 1994; Plumlee and others, 1993; Plumlee and others, 1992; Ficklin and others, 1992). The following paragraphs describe the most common types of hydrothermal alteration observed in the areas evaluated for this investigation, and the quality of water expected to be draining from these alteration types.

Acid-Sulfate

The sulfide minerals in the quartz-alunite-pyrite and quartz-kaolinite-pyrophyllite-pyrite zones of the acid-sulfate alteration assemblage can produce acidic runoff. Acid-sulfate alteration assemblages also tend to occur at the top of hydrothermal systems and therefore frequently appear on or near the tops of peaks. Generally, acid-sulfate altered rocks are somewhat metal-poor due to intense hydrothermal leaching. Such hydrothermal leaching also removes essentially all acid neutralizing capacity from the altered rocks (Plumlee and others, 1999). However, the associated (peripheral and underlying) altered rocks are commonly metal-enriched, and can release significant metal and sulfate loadings to watersheds.

Quartz-Sericite-Pyrite (QSP)

The QSP alteration assemblage is common in hydrothermal systems and generally contains the most pyrite of any alteration assemblage. Surficial weathering typically converts these altered rocks to quartz plus sericite plus jarosite, hematite, or goethite. Metals are frequently enriched in QSP altered rocks. Acidic water, sulfate, silica, aluminum, iron, and other metals can be released to watersheds from QSP-altered rocks.

Argillic

The alteration assemblage is characterized by the presence of kaolinite or dickite that have replaced primary rock-forming minerals, other than quartz. Associated minerals may include pyrite or jarosite, which contribute to acid runoff, as well as goethite, sericite, and hematite. This assemblage provides minor acid neutralization capacity during weathering or interaction with acid rock drainage (Plumlee and others, 1999). The argillic assemblage is typically peripheral to ore-bearing zones. Aluminum, silica, sulfate, and iron are typical weathering products released to watersheds.

Propylitic (Or Chloritic)

The propylitic assemblage, typically consisting of calcite-biotite-chlorite-epidote with feldspar, can provide significant acid neutralization. Experimental studies indicate that many of the minerals in this assemblage have some potential to neutralize acid (Lawrence and Wang, 1997; Jambor and others, 2000). However, calcite is by far the strongest acid-neutralizing agent in these rocks, and unlike the other propylitic minerals such as chlorite and epidote, its solubility is not restricted above the low pH ranges ($pH < 4$ to 4.5) (Bove and others, 2000). Waters draining this assemblage typically have high pH values (> 5 to 8), measurable alkalinity, and low dissolved metal concentrations (Mast and others, 2000a; Bove and others, 2000; du Bray, 1995). A common signature of propylitically altered rocks is manganese enrichment (Rose and others, 1979). These altered rocks are commonly stained black by manganese oxide coatings, especially along fractures. Elevated manganese concentrations in associated surface waters may be a feature of this alteration assemblage. Because the propylitic assemblage generally is peripheral to and may overlie more intense alteration (such as QSP), the acidic, metal-rich waters that sometimes occur in propylitic terrane are likely to be caused by sulfide-bearing alteration in the shallow subsurface.

4

SOUTHWESTERN COLORADO

Natural ARD is documented in many watersheds in southwestern Colorado (Church and others, 2007; Neubert, 2000; Bove and Knepper, 2000; Mast and others, 2000a; Bove and others, 2000; Miller and McHugh, 1998). Most of these areas with natural ARD are associated with intrusive activity in, and adjacent to, Tertiary-age calderas; whereas some are related to Laramide-age intrusives. Hydrothermal fluids associated with the igneous activity frequently formed localized to pervasive alteration zones, ore deposits, and widespread sub-economic mineralization.

SAN JUAN MOUNTAINS

The San Juan Mountains are primarily comprised of Tertiary volcanic rocks that are remnants of a volcanic field that covered most of the southern Rocky Mountains. The initial volcanic activity began about 35 to 40 Ma and was primarily andesitic in composition. Beginning about 30 Ma, silicic ash flows, lavas, and breccias buried large areas of the older andesitic rocks. Throughout the San Juan volcanic field, rapid extrusion of large volumes of silicic rocks from near-surface magma chambers resulted in collapse of the overlying rocks and formation of calderas. At least 15 calderas are documented in the San Juan Mountains (Steven and Lipman, 1976). Nesting and overlapping of the calderas are common.

Silicic volcanism leading to formation of calderas initially began in the northeastern (Bonanza) and southern areas (Summitville) of the San Juan volcanic field (Figure 1). In the western and central parts of the field, silicic eruptions and caldera formation began about 29 and 28 Ma, respectively. Silicic volcanic activity and subsequent caldera formation may be related to emplacement of shallow, highly silicic plutons above a batholith that is postulated to underlie most of the San Juan volcanic field (Steven and Lipman, 1976).

Varying degrees of mineralization and hydrothermal alteration are associated with the calderas and the related intrusive activity. In addition, nested and overlapping calderas create complex hydrologic, stratigraphic, and structural geologic conditions. Large hydrothermally altered areas are associated with the Silverton, Lake City, and Platoro/Summitville caldera complexes. Other smaller, isolated areas with poor-quality water are scattered throughout the San Juan Mountains

SILVERTON CALDERA AREA

The Silverton caldera is in southwestern Colorado in the western San Juan Mountains (Figure 1). The caldera is approximately 10 mi in diameter (Steven and Lipman, 1976, Figure 2). The town of Silverton lies near the southern boundary of the caldera **(Figure 2)**. Historically, this area was extensively mined for silver, gold, and base metals. Mining-related, poor quality stream effluent is evident in some areas of the mining district.

Within and adjacent to the Silverton caldera, the headwaters and tributaries of the Animas River have been the subjects of extensive studies pertaining to geology, water quality, abandoned mine and watershed characterization, reclamation technology, and the contribution of natural ARD to the acidic, metal-rich streams in the drainage basin. The U.S. Geological Survey has been the primary agency conducting investigations (Bove and others, 2000; Burbank and Luedke, 1969; Fisher and Leedy, 1973; Mast and others, 2000a,b; Ransome, 1901; Steven and Lipman 1976; Wright and Janik, 1995). Church and others (2007) compiled 33 papers documenting integrated inter-disciplinary studies of the Animas River watershed performed between 1995 and 2007.

General Geology

The Silverton caldera is one of four closely spaced or overlapping calderas that have been documented in the northwestern San Juan Mountains (Figure 2). The Silverton, San Juan, and Uncompahgre calderas formed within a period of 2 million years, extruding ash-flow tuffs of similar composition. The San Juan and Uncompahgre calderas formed simultaneously. The Silverton caldera is slightly younger and most of it is nested within the San Juan caldera. The Lake City caldera formed about 5 million years later, in the Pliocene, and most of it is nested within the Uncompahgre caldera (Steven and Lipman, 1976).

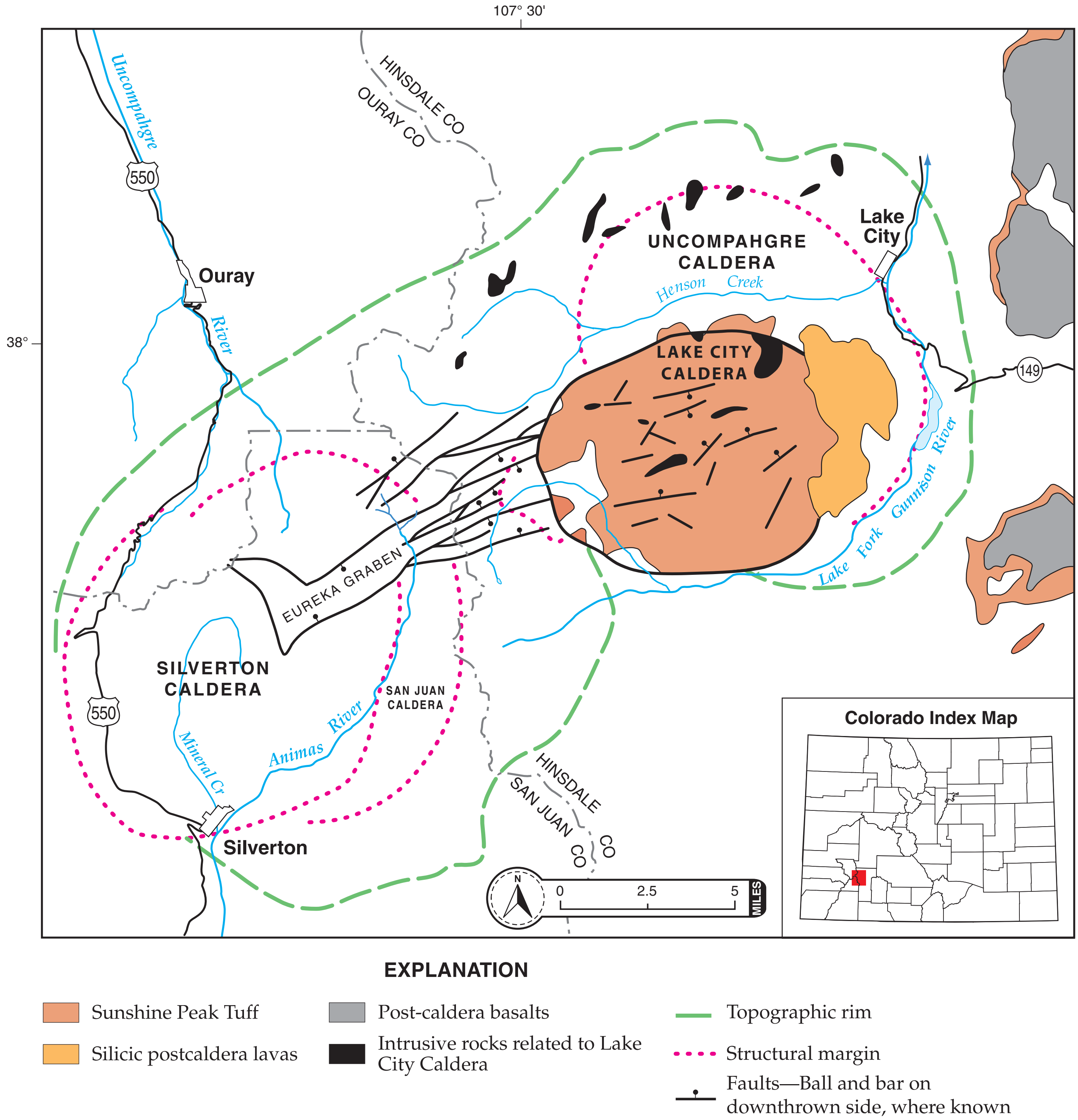


Figure 2. Generalized geology of the western San Juan caldera complex showing distribution of rocks related to the Lake City caldera. (modified from Steven and Lipman, 1976)

During and after formation of the San Juan caldera, small stocks, dikes, and sills intruded the volcanic rocks. Resurgent doming, followed by extrusion of the Crystal Lake Tuff from the San Juan caldera, led to localized subsidence, forming the Silverton caldera and the related mineralized Eureka graben (Figure 2). During the multiple episodes of subsidence, resurgence, and intrusive activity, numerous faults and fractures formed within and adjacent to the San Juan/Silverton calderas, providing zones of weakness for later intrusions and channels for circulating hydrothermal fluids (Steven and Lipman, 1976). Some of these faults and fractures currently act as conduits for surface water and groundwater affected by ARD.

About 6 to 10 million years after the Silverton caldera became structurally complete, silicic igneous magmas intruded zones of weakness along some of the caldera-related faults and fractures. These post-caldera igneous intrusions were associated with metal-rich, hydrothermal fluids responsible for most of the mineralization and alteration spatially related to the Silverton caldera (Steven and Lipman, 1976). Within and adjacent to the Silverton caldera are several types of mineral deposits, including veins, chimneys, replacements, stockworks, and disseminations. Pyrite and sulfides/sulfosalts of copper, lead, and zinc are abundant in all of these types of deposits. The mineralized rocks also contain manganese carbonates, manganese silicates, rare sulfates (barite and gypsum) and fluorite. The stockwork and disseminated deposits are indicative of highly fractured rock that is especially accessible to both mineralizing fluids and later surface-water leaching.

In addition to depositing economic grades of metallic minerals in some locations, hydrothermal fluids from post-caldera intrusions altered much of the surrounding host rock (Bove and others, 2007). At many locations, the original composition of the rock is difficult to ascertain because of the intensity of alteration. Propylitic, argillic, sericitic, and acid-sulfate alteration types are present, and pyrite is abundant in host rocks at many localities. Oxidation of pyrite, a process continuing today, has created large areas of deep red iron-staining, hence names such as Red Mountain.

Geology Of The Red Mountain Pass Area

The Red Mountain Pass district (Plate 1) is the site of one of the largest acid-sulfate systems in the western United States (7.8 mi^2) and was host to historic silver-copper-gold production from breccia pipe and fault-controlled mineral deposits (Burbank and Luedke, 1969; Fisher and Leedy, 1973; Bove and others, 2000). The Red Mountain Pass district is recognized as a world-class example of alteration zoning, owing to its shallow depth of emplacement that created steep pressure and temperature gradients (Guilbert and Park, 1986). This mineralized acid-sulfate system was localized along the structurally complex northwest margin of the 27 Ma Silverton caldera. Some of the richest ores in the Silverton area were mined from small, silicified breccia pipes associated with the extensive acid-sulfate hydrothermal system in the Red Mountain Pass district. These high sulfidation (high sulfur to metal ratio) deposits, which mainly formed within the oxidized portions of the breccia pipes, were irregular in shape and typically consisted of carbonates of lead and iron, as well as lead sulfates, iron oxides, sphalerite, and miscellaneous arsenates (Fisher and Leedy, 1973). Below the oxidized zone, sulfide ores composed of pyrite, enargite and lesser chalcopyrite, galena, tetrahedrite, and sphalerite were present as irregular masses in altered volcanic rocks.

Ore deposits of similar age are found in the vicinity of Prospect, Dry, Georgia, and Corkscrew Gulch (Ransome, 1901; Nash, 1975; Bove and others, 2001, Plate 1). However, in comparison to the Red Mountain Pass deposits, ore minerals in these localities are more confined to preexisting faults and spatially associated hydrothermal breccias zones (Bove, Yager and others, 2007). Although hydrothermal breccias are common (Bove and others 2000; Nash, 1975; Fisher and Leedy, 1973), surficial exposures of the classic mineralized breccia bodies are only seen in the Red Mountain Pass area and are largely absent in the others (Bove and others, 2000). Geologic relations and isotopic age determinations indicate that ore mineralization, hydrothermal brecciation, and pervasive hydrothermal alteration in the Red Mountain Pass district are intimately associated with episodic intrusion of dacite porphyry magma, all of which took place at about 23 Ma (Bove and others, 2001).

Hypogene Hydrothermal Alteration Types

Detailed alteration mapping was conducted in the Red Mountain Pass area for this investigation. During the mapping effort, the following alteration types were characterized.

Acid-Sulfate Alteration

The Red Mountain Pass acid-sulfate system formed in response to sulfate-rich, low pH vapor plumes emanating from shallow dacitic magmas. The plumes were localized along zones of hydrothermal brecciation and intense fracturing related to magmatic high-pressure fluids (Bove and others, 2001). The acid-sulfate mineral assemblage formed dominantly from the replacement of the original volcanic host by these low pH, sulfate-rich solutions. The evidence for such replacement is revealed by the preservation of the original porphyritic rock textures after replacement by the acid-sulfate mineral assemblage.

Excellent rock exposures in the Red Mountain Pass area have allowed detailed zonation studies of alteration assemblages within this complex acid-sulfate hydrothermal system (Bove and others, 2000; Dalton and others, 2000; Mast and others, 2000a). Surface mapping and careful studies of paragenetic sequences demonstrate that structurally controlled zones of quartz-alunite alteration grade outward into pyrophyllite, dickite, and farther outward into smectite, and (or) propylitically-altered rock. Sericite is generally not a component of the lateral zonation. Mineralogical data from exploration drilling in the vicinity of Red Mountain No. 3 (just east of sample NW-10) and adjacent Prospect Gulch (draining the southeast side of

Red Mountain #3) (Plate 1) (Bove and others, 2000), demonstrate that the acid-sulfate alteration zones have roots extending at least 1,000 ft beneath the ground surface.

Alteration minerals within the quartz-alunite-pyrophyllite (QAP) zones include quartz, alunite, pyrophyllite, natroalunite, dickite, diaspore, and pyrite, with minor to trace amounts of zunyite, sulfur, and tridymite. Pyrite, which is present as disseminations and along tiny fracture networks, varies in abundance from 20–30 weight percent within these altered rocks.

Zones of silicification, which are spatially associated with the inner quartz-alunite-pyrophyllite zones, typically formed as replacements along mineralized, pipelike to tabular, hydrothermally brecciated masses, and along brecciated faults and fracture zones. The mineral assemblage is comprised of gray to dark-gray microcrystalline quartz, with pyrite and minor alunite, pyrophyllite, diaspore, leucoxene, and rutile. Within the breccias, quartz is cryptocrystalline or forms anhedral microcrystalline grains in both the groundmass and within clasts. Small crystals of quartz commonly line cavities. Copper-silver-arsenic-lead-rich sulfide minerals within the silicified breccia deposits of the Red Mountain Pass district were localized in vugs and cavernous breccias (Ransome, 1901; Fisher and Leedy, 1973; Nash, 1975; Bove and others, 2000).

Bleached argillic zones, which form the broad outer margins around the inner QAP and silicic zones, are characterized by the presence of dickite and quartz with varying amounts of pyrite. These zones are poorly to moderately indurated, and are commonly recognized in the field by the presence of soft, waxy textured clays. Zones of smectitic alteration are similar in appearance to the argillic zones, but are characterized by smectite, chlorite, and metastable feldspar grains.

Quartz-Sericite-Pyrite Alteration

The collective acid-sulfate zones are commonly superimposed over broad intervening expanses of QSP-altered rock (Bove and others, 2000). Pervasive QSP-altered rocks are commonly exposed up to the tops of many high ridges in the Red Mountain Pass area, and in places reflects a zonation upward and outward from a deeper, potassic alteration assemblage typical of mineralized Mo porphyry systems (Gilzean, 1984). The QSP alteration assemblage is characterized by the complete replacement of plagioclase and potassium-feldspar phenocrysts by 25–50 volume percent fine-grained pervasive quartz, illite (sericite), and 10–20 percent finely disseminated and fracture-filling pyrite. Kaolinite may be present in varying abundance in some localities. Rocks typically have a bleached appearance and are variably oxidized. Thin stockwork quartz veinlets are locally present within this assemblage.

The weak sericite-pyrite alteration assemblage generally reflects a weaker style of alteration than that characterized by the QSP assemblage. Rocks affected by this style of alteration are found in areas of dense veining and also are present on the outer margins of broad QSP zones (Bove and others, 2000). The weak sericitic assemblage contains 5–25 percent quartz, illite, and greater than 5–10 volume percent pyrite. This assemblage is characterized by the presence of weakly altered to unaltered plagioclase, and contains chlorite, which, along with plagioclase, is usually absent in the typical strong QSP assemblage.

Propylitic Alteration Assemblage

Nearly all the rocks in the area were affected by low-grade regional metamorphism or propylitization due to thermal events related to the San Juan and Uncompahgre calderas(28 Ma), and later Silverton caldera. The timing of this alteration event is roughly constrained to about 28.2–27.5 Ma, and is similar to the ages of these respective calderas, but preceded most ore mineralization by 5–15 Ma (Lipman and others, 1976; Bove and others, 2001). The propylitic mineral assemblage consists of varying abundance of chlorite, epidote, calcite, and illite, in the presence of metastable to stable primary feldspar crystals. However, coexisting mineral phases of the propylitic assemblage can be quite variable dependent on several factors including rock type and degree of alteration. Incipient to weak stages of propylitic alteration are generally marked by the replacement of ferromagnesian minerals (biotite, pyroxene, and hornblende) by fine-grained chlorite, calcite, quartz, iron oxides, and/or epidote. In contrast, calcite and illite replace plagioclase, mostly along cleavage planes and micro-fractures, leaving the internal portions of the grains relatively unaltered. As noted by Burbank and Luedke (1969), the weakly altered rocks have been identified in the dark-colored lavas of the Henson Member of the Silverton Volcanics (Henson Member), which cap many of the high ridges within the study area. The weakly propylitized Henson Member is also characterized by the presence of hematite along microfractures and as microscopic granular disseminations.

Rock-Water Interactions

Combined geologic and geochemical studies (Bove and others, 2000; Mast and others, 2000a) emphasize that the degree of metal mobilization and acid production in natural ARD systems correlates well with the type of hydrothermally altered rock, and the structural features in which these waters interact. The concentrations of most dissolved solids in the waters increase incrementally in conjunction with increasing intensity of alteration of the associated host rocks (Mast and others, 2000a; Yager and others, 2000; Bove and others, 2000).

Previous Water Quality Investigations

Extensive water quality investigations have been conducted in the upper Animas watershed area as a part of an interdisciplinary effort focusing on abandoned mine land issues (Church and others, 2007; Church and others, 2002). Areas of naturally occurring ARD are mostly associated with volumetrically extensive and highly pyritic zones of hydrothermally altered rock around two large acid-sulfate systems and a weak Mo-Cu porphyry system (Church and others, 2002; Bove and others, 2000; Mast and others, 2000a). Loading calculations indicate that natural ARD in these areas contributes a majority of the acidity, aluminum, iron, and sulfate load to the surrounding streams, whereas zinc loads, although substantial in some areas, are mostly attributed to anthropogenic sources (Kimball and others, 2002; Mast and others, 2000a; Church and others, 2002; Wirt and others, 2001).

CGS personnel collected a water sample from a tributary of Middle Fork Mineral Creek **(Plate 1)** in 1995. The stream, the easternmost major tributary draining into Middle Fork Mineral Creek from the south, is unaffected by mining. Other studies call this stream the "Red Trib" because of its distinctive color (Wright and Janik, 1995; Mast and others, 2000a). Bedrock in the upper reaches of the tributary has been intensely altered, and is stained red from oxidation of disseminated pyrite. Water sampled from the tributary exceeded State standards in aluminum, iron, and cadmium. Manganese, sulfate, and zinc concentrations were also elevated. The stream was flowing at an estimated rate of 500 gpm with pH of 3.66 (Sares, 1996; Lovekin and others, 1997). This area was studied extensively by USGS abandoned mine land studies (Mast and others, 2000a; Yager and others, 2000; Wright and Janik, 1995).

Present Water Quality Investigation

The focus of CGS work in the southwest San Juan Mountains was the headwaters of the Red Mountain Creek drainage basin. In addition, one sample was collected from the headwaters of Howard Fork of the San Miguel River. The Animas River drainage basin was not included in this investigation because the USGS previously worked on similar issues in the area (Church and others, 2007; Church and others, 2002; Bove and others, 2000; Mast and others, 2000a).

The results of chemical analyses and measurement of field parameters for samples collected during this statewide investigation are given by area in **Appendices A-1 through A-11** and numerically in **Appendix B**. Twenty samples were collected from the Red Mountain Creek drainage basin (Plate 1 and Appendix A-1). With the exception of sample NW-1, from the upper basin of Corkscrew Gulch, all samples were collected upstream of all mines of significant size and water discharge. During fieldwork in 1999, a draining adit above the site of water sample NW-1 was covered with snow and was not visible. Fehlmann (1997) reported that 20 gpm of poor-quality water (pH of 2.2; EC of 5,600 µS/cm) emerged from this mine. Water samples of mine effluent collected by Fehlmann (1997) contained high concentrations of aluminum, arsenic, copper, iron, sulfate, and zinc.

Sample NW-1 had pH of 2.31 with EC of 821 µS/cm and a streamflow of about 300 gpm in late June of 1999. The water exceeded State standards in aluminum, cadmium, copper, iron, lead, manganese, nickel, silver, sulfate, and zinc (Appendix A-1). Although some of the elevated metal concentrations are attributable to mine drainage, the large exposures of acid-sulfate and QSP-altered bedrock and talus in the basin (Plate 1) likely also contribute acidic, metal-rich runoff and seepage. Wirt and others (2001) and Bove and others (2000) suggest that acidity, Fe, Al and sulfate are likely to have substantial input from the large altered areas while base metals such as zinc, copper and lead are probably dominantly mining-related.

Samples NW-2 through NW-8 are from the west and northwest sides of Red Mountain No. 1, from tributaries of Corkscrew Gulch. No significant mines or draining adits are known above the sample sites. Red Mountain No. 1 is stained red, yellow, and brown from the oxidation of disseminated pyrite within intense QSP and acid-sulfate altered rocks in this area **(Figures 3 and 4; Plate 1)**. Fine-grained disseminated pyrite, was common in the stream sediments at most of these sample sites. In addition, fragments of ferricrete and traces of malachite were visible in the stream gravels at sample site NW-3 **(Figure 3)**. In general, streams draining from Red Mountain No. 1 into Corkscrew Gulch carried clear water that showed no visual indications of ARD **(Figure 5)**. However, pH values ranged from 2.59 to 4.73, while EC measurements were usually less than 250 µS/cm, with the exception of NW-8, which was 639 µS/cm. These data demonstrate that visual observations cannot be used as reliable indicators of ARD conditions. Water samples had relatively low hardness, ranging from 3 to 11 mg/L (as $CaCO_3$), with the exception of sample NW-8 at 49 mg/L (Appendix A-1). For several metals, the low hardness created situations in which the detection limit of the analytical method was higher than the resulting hardness-dependent State water quality standard, so that comparison of the sample analyses with stream standards was not possible. Sample NW-8 had the highest metal content with dissolved aluminum concentration of 17,000 µg/L and iron of 4,700 µg/L. Samples NW-2, through NW-7, also showed influence from ARD (i.e., low pH and elevated Al, Fe and Mn) (Appendix A-1).

Figure 3. Water sample sites NW-3 to NW-5 on the west side of Red Mountain No. 1

Figure 5. Spring on northwestern slope of Red Mountain No. 1 at water sample site NW-7.

Figure 4. Water sample site NW-3 on the quartz-sericite-pyrite and acid-sulfate altered western slope of Red Mountain No. 1.

State water quality standards for aluminum were exceeded in all samples collected on the west and northwest side of Red Mountain No. 1 (Plate 1 and Appendix A-1) with concentrations ranging from 160 to 16,000 µg/L. Copper ranged from <4 to 38 µg/L in these samples and exceeded its hardness-related water quality standard in five of the seven samples. Iron and manganese, with ranges of 42 to 4,700 µg/L and 5 to 320 µg/L, respectively, exceeded standards in four samples. Zinc concentrations ranged from <10 to 95 µg/L, and exceeded standard in four samples. Lead was only detected in one sample (NW-5), at a concentration of 3 µg/L, which exceeded the aquatic life standard (Appendix A-1).

On the east side of Red Mountain No. 1, in the upper reaches of Gray Copper Gulch and above any significant mining influence, sample NW-66 (Plate 1) was collected from a stream lined with well-indurated ferricrete. The slopes to the northwest are highly fractured and stained red, brown, and yellow due to oxidation of pyrite within the acid-sulfate and QSP altered rocks **(Figure 6 and Plate 1)**. Immediately upstream from the sample site, brown iron oxide staining is prevalent.

Fine-grained disseminated pyrite commonly appears in the fine gravels in the streambed. The creek was flowing at 4 gpm with pH of 2.66 and EC of 1,265 µS/cm. This water had relatively high concentrations of several ions including aluminum, chloride, copper, iron, lead, and zinc. Dissolved calcium concentration in this sample was below analytical detection limits (<4 mg/L). Because calcium concentration was below detection limits, the hardness could not be calculated, and the hardness-related water-quality standards could only be assigned upper limits.

Farther south and east of Red Mountain No. 1, sample NW-64 was collected from the discharge of a tarn (glacial lake) on the Cement Creek side of the drainage divide (Plate 1). Rocks in the stream channel had minor red-brown iron staining. Streamflow at this site was 12.5 gpm, while pH and EC values were 6.34, and 38 µS/cm, respectively (Appendix A-1). As shown in Table 2, this circumneutral stream sample had metal concentrations below State water quality standards. The composition of this water reflects the preponderance of regional propylitic-altered rocks on the slopes upgradient of this site, and lack of influence from the strongly altered and pyritic slopes of Red Mountain No. 1, to the west (Plate 1).

Samples NW-9 to NW-13 were collected from streams flowing from Red Mountain No. 2 **(Plate 1; Figures 7 and 8)**. All samples were collected above any known large mines or draining adits. Analytical results of water samples indicate that most of the non-mining-related runoff from Red Mountain No. 2 is influenced by ARD (Appendix A-1). The sampled streams had flows ranging from 50 to 280 gpm, pH from 2.16 to 3.92, and EC from 18 to 1,640 µS/cm. Sulfate and aluminum concentrations ranged from 8 to 550 mg/L and 180 to 27,000 µg/L respectively.

The stream from which sample NW-12 was collected, flows on the northern edge of a large land-

Figure 6. East side of Red Mountain No. 1.

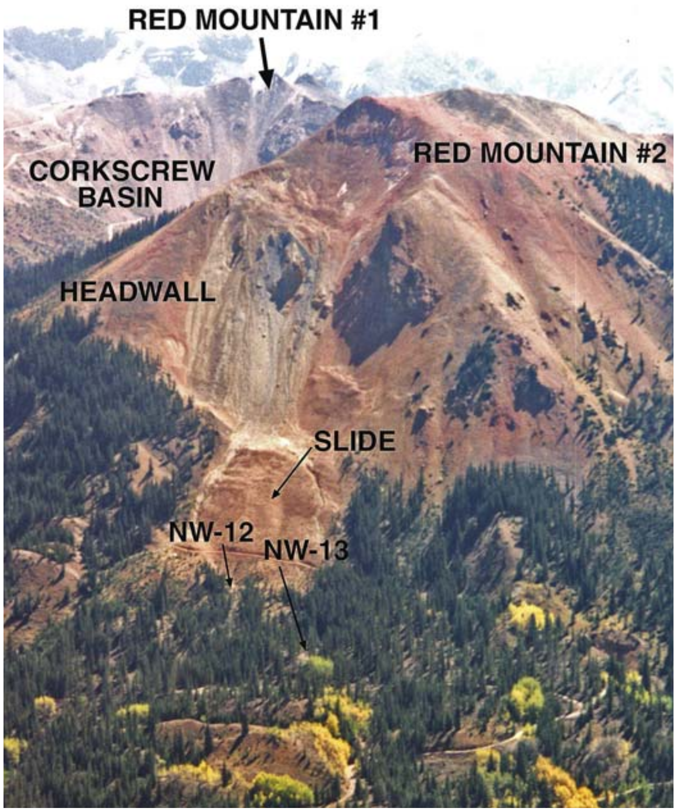


Figure 7. Water sample sites NW-12 and NW-13 on the west slope of Red Mountain No. 2.

slide with acid-sulfate altered rock exposed on the fresh headwall (Figure 8). The stream was turbid and carried suspended solids **(Figure 9)**. The large differences between concentrations of dissolved and total recoverable iron and aluminum suggest that the suspended solids were mostly phases of iron and aluminum (Appendix A-1), although PHREEQC simulations indicate that gypsum, chalcedony, and amorphous silica are also near saturation and could be precipitating. Orange-red and gray precipitates were plentiful along the stream channel.

Sample NW-13 from a stream on the south side of the landslide had the lowest pH and the highest metal concentrations of all samples collected near Red Mountain No. 2, with pH of 2.16, EC of 1640 µS/cm, and elevated aluminum, cadmium, copper, iron, manganese, thallium, and zinc (Appendix A-1). However, the water was relatively clear and no precipitate was apparent. At the sample site, the low pH apparently kept most metals in a dissolved state, but ponds within 100 ft downstream of the site contained abundant light-green precipitate that coated the substrate and attached to the algae. The color of the precipitate may indicate the presence of copper as the dissolved concentration of copper in the water was 150 µg/L.

Sample sites NW-10 and NW-11 had red-brown precipitate in the stream channels, but the water was clear. PHREEQC geochemical simulations indicate that the water was oversaturated with respect to silica phases, but no iron phases. Iron phases may precipitate during periods of higher pH conditions within the stream reach.

Figure 8 Photograph showing slide and headwall above water sample sites NW-12 and NW-13.

Sample NW-9 (pH 3.93) was slightly turbid, but had no associated precipitate and had the lowest concentrations of aluminum and iron of all samples from this area. This site drained areas that are primarily affected by argillic and propylitic alteration. QSP alteration is present only in the uppermost reach of the drainage (Plate 1). The low iron and other metal concentrations in this sample may reflect the fact that these waters largely drain near-surface rocks or surficial deposits where pyrite and other sulfides are largely oxidized (Bove and others, 2000).

Aluminum concentrations were above State water quality standards in all five samples from the streams draining Red Mountain No. 2 (Appendix A-1), ranging from 180 µg/L in sample NW-9 to 27,000 µg/L in NW-13. Concentrations of copper and manganese exceeded State water quality standards in all samples except NW-9, varying from <4 to 150 µg/L for copper and 43 to 3,600 µg/L for manganese. Iron, ranging from 72 to 90,000 µg/L, exceeded standard in two samples, and zinc, ranging from <10 to 270 µg/L, exceeded standard in three samples. Lead was above detection level only in sample NW-10, at 2 µg/L, but exceeded the State water quality standard because of the low hardness of the sample. Thallium and sulfate concentrations exceeded standards in sample NW-13. Thallium and arsenic exceeded standards in NW-12.

Water samples from the west side of U.S. Highway 550 (Plate 1, samples NW-60, NW-61, NW-62, and NW-65) had widely varying compositions. The two most acidic and metal-rich samples were from the middle segments of deeply eroded gulches with strongly altered wall rocks (NW-60 and NW-62). Both samples were turbid and had high aluminum concentrations (Appendix A-1). The significant differences between total versus dissolved aluminum indicate that aluminum phases are present as suspended solids

QSP alteration, exhibited as brown-yellow and light-yellow rocks, containing white clay in fractures, are exposed in upper Governor Gulch, above sample site NW-60 **(Figure 10; Plate 1)**. In addition to aluminum, sample NW-60 contained elevated concentrations of cadmium 2 µg/L manganese (4,000 µg/L), sulfate (440 mg/L), and zinc (590 µg/L) (Appendix A-1).

Red precipitate was observed at sample site NW-62 in Monument Gulch (Plate 1). Stream water contained high concentrations of iron, with the concentration of total iron considerably greater than dissolved. The concentrations of aluminum, iron, cadmium, copper, manganese, and zinc exceeded State water quality standards (Appendix A-1). This sample site was an area of intense QSP alteration related to the large veins that intersect in the drainage.

Relatively clean (lower metal concentration) water samples (NW-61 and NW-65 in Appendix A-1) were collected west of U.S. Highway 550 at higher elevations, in areas surrounded by grassy slopes with weak alteration. Concentrations of all analyzed parameters were below State water quality standards in sample NW-61 (Appendix A-1), which was from an unnamed stream west of Red Mountain Pass. Weak, regional propylitic alteration is present in the majority of the drainage basin in which this sample was collected (Plate 1).

Figure 9. Turbid water at water sample site NW-12.

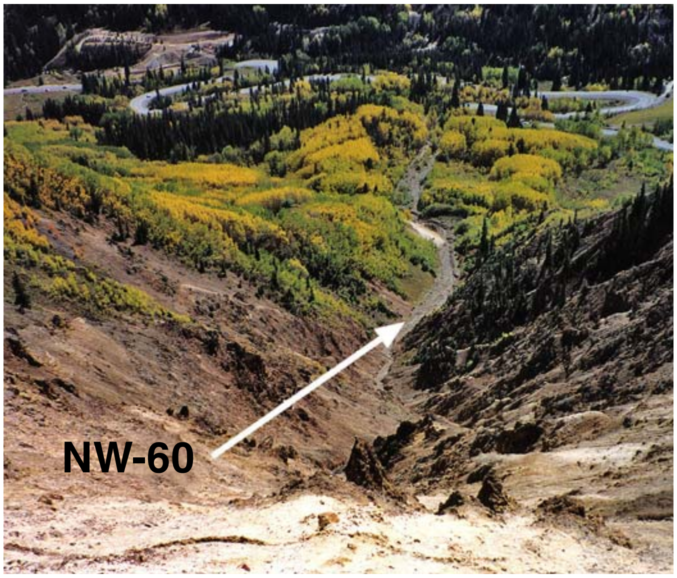
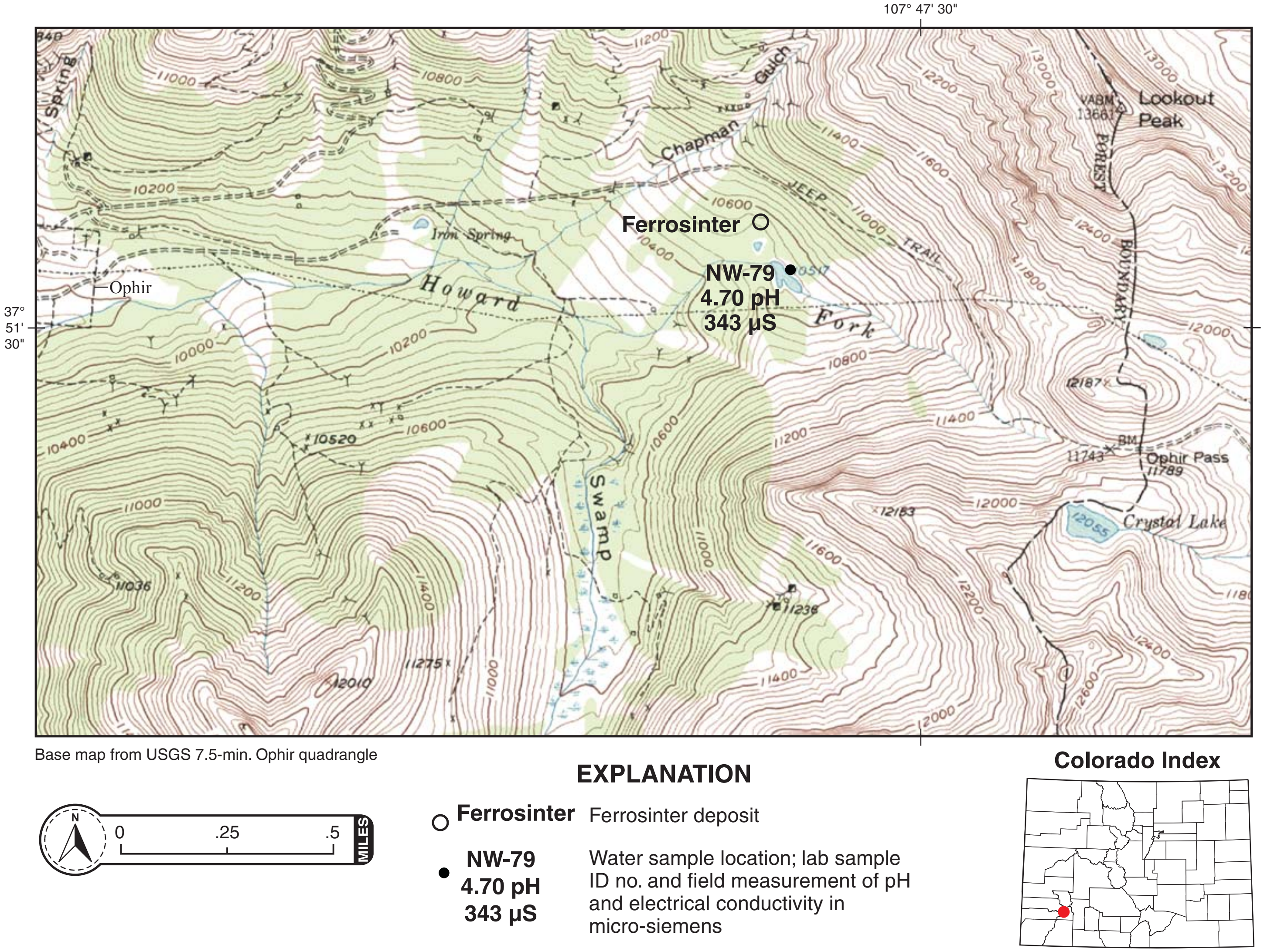


Figure 10. Water sample site NW-60 and headwaters of Governor Gulch.

Sample NW-65, from McIntyre Gulch just upstream of the Greyhound Mine (Plate 1), contained nickel well above standard at 1,700 µg/L (Appendix A-1). The high nickel concentration appears to be anomalous relative to other samples from the area and may represent a laboratory error. Chloride concentration was also elevated (120 mg/L), but within the standard of 250 mg/L. Rocks in the stream channel showed propylitic alteration, consistent with the dominant alteration in the drainage basin. The rocks contained moderate amounts of calcite, chlorite, epidote, and minor disseminated pyrite. White precipitate, presumably aluminum hydroxide, coated the gravel and algae in the stream.

The stream in the upper reaches of Brooklyn Gulch (Plate 1, sample NW-63), above all significant mining activity, was flowing at 3 gpm with pH of 6.68 and EC of 222 µS/cm. The water was clear with no apparent precipitate. Nearby alluvium and colluvium included some hydrothermally altered rock fragments, and probably represent a source of acid-sulfate alteration at the headwall of the drainage (Plate 1). However, most of the upstream portion of this drainage basin was grass-covered and showed no obvious or intensely altered bedrock. Despite the pristine appearance, aluminum, cadmium, zinc, and lead concentrations exceeded State water quality standards (Appendix A-1)

In 1999, the southernmost sample in the Silverton area (NW-79) was collected from a lake with a bluish tinge near the headwaters of Howard Fork of the San Miguel River, west of Ophir Pass **(Figures 11 and 12)**. No surface water was observed entering the lake, but the lake was discharging at a rate of about 420 gpm, indicating a large inflow of groundwater from the red-



Base map from USGS 7.5-min. Ophir quadrangle

Figure 11. Map showing water sample site NW-79 and a nearby ferrosinter deposit in the headwaters of Howard Fork of the San Miguel River.

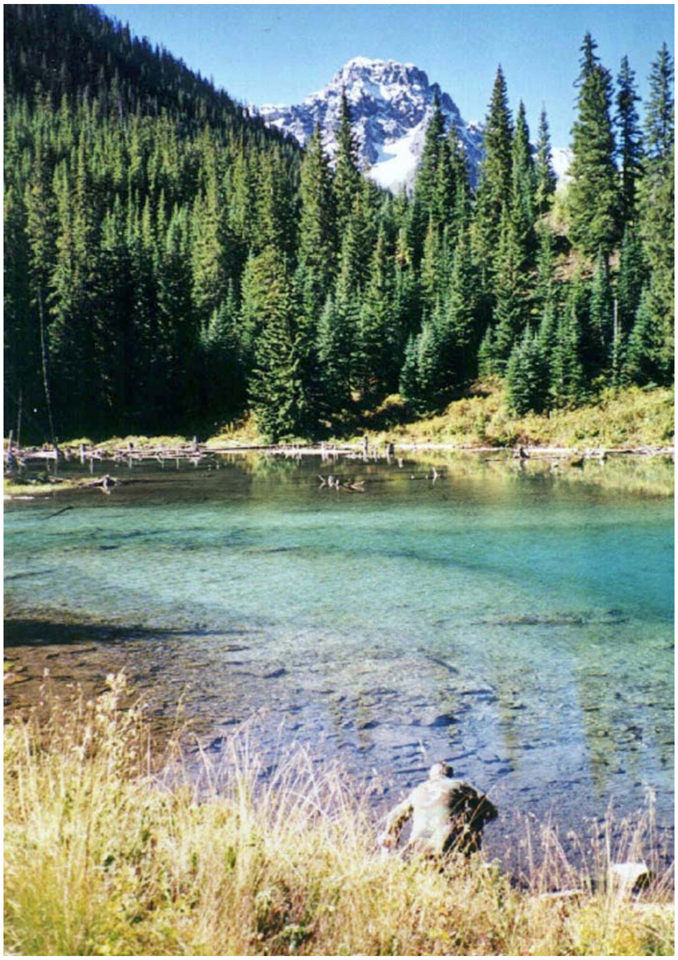


Figure 12. Blue-green water in lake near headwaters of Howard Fork at water sample site NW-79.

stained, altered slopes near Ophir Pass. EC was 343 μS/cm and pH was 4.7 (Appendix A-1). Aluminum and manganese exceeded State water quality standards (Appendix A-1), although small brook trout were swimming in the lake. A small ferrosinter deposit, from which minor amounts of water seeped, is exposed north of the lake (Figure 11). The ferrosinter deposit was probably deposited by water originating from the red-stained, altered, southwestern slopes of Lookout Peak.

Bog-Iron and Ferricrete Deposits of the Silverton Caldera Area

Bog-iron and "ferricrete" deposits in the Silverton caldera area are composed of goethite, ferrihydrite, and schwertmannite, and have accreted down gradient from hydrothermally altered zones containing abundant pyrite (Wirt and others, 2002). Subbasins having the highest percentages of acid-sulfate and QSP mineral assemblages (Plate 1) are directly upgradient from the most abundant bog iron, iron spring, and ferricrete deposits (Wirt and others, 2002). Most of these ferricrete deposits formed throughout recent post-glacial history, providing geologic evidence for pre-mining ARD conditions. Adits were driven into some of them during mineral exploration activities. Differences in the composition of the bog-iron deposits should reflect changes in the chemical composition of surface water after mining. Additional studies are required to determine whether water chemistry changes over time have created compositional changes in the bog-iron deposits.

Ferricretes of the Animas Basin

Ferricrete deposits are present along much of Cement Creek (Plate 1; Yager and others, 2002). Additional smaller, distinctly separate deposits are associated with springs along four miles of Cement Creek downstream from Gladstone. Active mineral precipitation is occurring at most of these sites. Ferricretes associated with these springs are 500 to 1,000 ft long, 25 to 300 ft wide, and very thin (Harrer and Tesch, 1959). Undoubtedly, mine effluent affects some of the springs and surface flow and contributes acidity and metals to Cement Creek. During the 1990's, USGS personnel conducted numerous studies in the Cement Creek drainage basin (Bove and others, 2000; Dalton and others, 2000; Mast and others, 2000a,b).

Ferricrete deposits are associated with an active spring at about 9,800 ft elevation near Burro Bridge, on the west side of Mineral Creek, 1.5 mi south of Chattanooga (south of Red Mountain map area). The spring water formed an apron of iron-rich precipitate that extends to Mineral Creek (Harrer and Tesch, 1959).

About 0.75 mi south of Chattanooga, at an elevation of about 9,800 ft on the west side of Mineral Creek (south of map area), a spring has deposited a triangular-shaped deposit of ferrosinter that extends to Mineral Creek. The fan of precipitate associated with the spring is about 575 ft long, 300 ft wide at the base, and 3 to 10 ft thick (Harrer and Tesch, 1959).

Much of Mineral Creek contains alluvial bog-iron deposits (Harrer and Tesch, 1959). Most of these deposits are probably related to upwelling of poor-quality groundwater and interaction with the acidic, metal-rich surface water. No individual springs are known in this area, although some probably exist. Similar to Cement Creek, Mineral Creek is strongly influenced by both natural and mining-related ARD.

The general distribution of ferricrete deposits of the upper Animas Basin is shown in Plate 1. Recent mapping by Yager and others (2002) provides a more detailed distribution of these deposits.

Ferricretes of the Uncompahgre Basin

In Ouray County, on the north side of Red Mountain Pass in the Red Mountain Creek drainage basin (Plate 1), an iron-rich spring discharges water on the northwest-facing hillside above the Guston Mine (Harrer and Tesch, 1959). The iron deposits at this spring were known prior to 1882 and presumably predate mining in this area. Cross and others (1905, as cited in Harrer and Tesch; 1959) report that the limonite "precipitated from water issuing from the hillside about 150 ft above the Guston mine and from a mine tunnel driven into the limonite. Limonite has been deposited downslope from the mine and also has cemented the mine dump into a firm ferruginous mass."

Much of Ironton Park (Plate 1) contains a ferricrete deposit formed by ferruginous springs prior to mining. The deposit covers a large area, but is thin (Harrer and Tesch, 1959).

Iron-rich springs located north of Ironton Park (north of Plate 1 map area), on the eastern side of Uncompahgre Park, about 2 mi southeast of Ridgway, have deposited a thin layer of ferricrete that covers several acres (Harrer and Tesch, 1959). These springs are related to post-caldera igneous intrusions and related hydrothermal alteration zones that are located north of the Silverton caldera (Steven and Lipman, 1976). None of the iron deposits in this area were sampled or tested for this study.

Ferricretes of the Howard Fork of the San Miguel Basin

Metal-rich springs west of the Silverton and San Juan caldera boundaries are present in the Howard Fork of the San Miguel River, in San Miguel County (Figure 11 west of Plate 1 map area). These springs are located near Ophir in the Iron Springs mining district. Ferricrete is presently forming in and adjacent to the town of Ophir and iron-rich precipitates are abundant along the streambed of the Howard Fork (Harrer and Tesch, 1959).

At least two metal-rich springs emerge between Chapman Gulch and the town of Ophir (Figure 11). Although mine workings exist above these springs, precipitates associated with the springs apparently predate mining because the Iron Springs mining district near Ophir was named for the spring with the largest precipitate deposit. The Iron Springs deposit is about 1,500 ft long and extends to Howard Fork. Both the ferric oxide (adjacent to and west of Iron Springs) and the Iron Springs deposits are actively forming at present, and both have deposited precipitate into the streambed of Howard Fork (Harrer and Tesch, 1959). Chapman Gulch contains several ferruginous springs and a flowing artesian drill hole. Water from these sites is characterized by high metal concentrations (Neubert and Harris, 1996). Isolated, actively weathering ferricrete deposits line the banks of Chapman Gulch in the vicinity of these sites. Groundwater discharging from the drill hole had a pH of 6.62 and EC of 2,170 µS/cm, with concentrations of iron, fluoride, sulfate, and silver that exceeded state water quality standards (Neubert and Harris, 1996). Water from the drill hole had relatively high calcium (1,400 mg/L) and sulfate (1,300 mg/L) concentrations (Neubert and Harris, 1996) and saturation indices calculated by PHREEQC indicated slight oversaturation with respect to gypsum. Mast and others (2000a) suggest that gypsum dissolution contributes to the high calcium and sulfate concentrations in waters of the nearby Mt. Moly area. Mt. Moly is in a similar geologic environment to Chapman Gulch. These findings suggest that samples with high combined Ca (i.e Ca > 500 mg/L), and sulfate concentrations in the Howard Fork may be related to gypsum dissolution.

On the south side of the Howard Fork, an unnamed tributary of Swamp Canyon (Figure 11) shows evidence of natural ARD. The tributary drains hydrothermally altered rocks on the north side of South Lookout Peak. Ferricrete deposits are present along a stream channel, near some small mines that were developed near the break in slope that separates the upper basin from the steep gulch descending toward Swamp Canyon. Upstream from all known mines, the stream was flowing at a rate of 300 gpm in June of 1996 with pH of 3.88 and EC of 288 µS/cm (Neubert and Harris, 1996). A water sample was collected near the base of the steep gulch (sample number 254/4192–1.306, described in Neubert and Harris, 1996), upstream of a small mine that was discharging 0.3 gpm with pH of 6.0 and conductivity of 644 µs/cm (Neubert and Harris, 1996). The sample exceeded State standards in aluminum, iron, manganese, and zinc. The stream below the mine was flowing about 1,000 gpm with pH of 4.78 and EC of 403 µS/cm (Neubert and Harris, 1996). In August 1996, the discharge at this same site was 86 gpm and the pH and EC were 3.35 and 515 µs/cm, respectively. This water exceeded standards in iron, aluminum, manganese, and zinc. A white precipitate, presumably aluminum oxyhydroxide, was observed near the beaver ponds between the sample site and Swamp Canyon, and the water had a bluish hue (Figure 12). The low volume of effluent discharging from the small mines in this drainage basin, and the existence of water with low pH and high EC above all known mines, suggests that much of the ARD in this unnamed tributary could be natural in origin, although anthropogenic input to groundwater can not be ruled out (Neubert and Harris, 1996).

LAKE CITY CALDERA AREA

The Lake City caldera area is in the northwestern part of the San Juan Mountains (Figure 1). CGS personnel investigated three possible sources of natural ARD in 1999, two on a reconnaissance level (Redcloud Peak and the Carson Camp area), and one in detail (Slumgullion Slide). Most of the hydrothermally altered rocks associated with the ARD in the Lake City area are spatially related to intrusions within and along the margins of the Uncompahgre/Lake City nested calderas.

The Lake City caldera is nested within the larger Uncompahgre caldera, but formed about 5 million years later (Bove and others, 2001). Eruption of the Sunshine Peak Tuff accompanied the collapse of the Lake City caldera. Emplacement of a shallow granite porphyry pluton caused resurgent doming within the caldera (Steven and Lipman, 1976; Hon, 1987).

Several ages of mineralization are known in the Lake City area (Lipman and others, 1976; Hon, 1987; Bove and others, 2001). Small, subeconomic base and precious-metal deposits are present in the cores of volcanoes of intermediate-composition that predated the caldera-forming eruptions of the present San Juan volcanic field. Larger deposits of vein and disseminated ore minerals were emplaced in the northern part of the Uncompahgre caldera prior to development of the Lake City caldera. Younger vein and disseminated ores formed in and adjacent to the Lake City caldera. Mineralized veins hosted in faults of the Eureka graben on the west side of the Lake City caldera probably postdate caldera formation and may be as young as 15 Ma (Lipman and others, 1976; Steven and Lipman, 1976).

Much of the Uncompahgre/Lake City caldera complex and surrounding area have been affected by hydrothermal alteration. The most intensely altered rocks are within the Lake City caldera near the margins of the shallow granite porphyry intrusion that caused resurgent doming, along the eastern caldera margin, and the Red Mountain acid-sulfate complex (Steven and Lipman, 1976; Hon, 1987; Bove and others, 1990).

REDCLOUD PEAK AREA

Redcloud Peak is about eight miles southwest of Lake City (Figure 1). It lies on the north side of Lake Fork of the Gunnison River within and near the margin of the Lake City caldera.

Geology

In the Redcloud Peak area of the Lake City caldera, about 100 quartz veins have been identified. Of those 100 veins, 30 are more than 2,000 ft long. Veins within the caldera are composed primarily of quartz and pyrite with minor amounts of galena, chalcopyrite, sphalerite, tetrahedrite, and rhodochrosite (Steven and Lipman, 1976; Sanford and others, 1986; Hon, 1987). Only limited mining has been attempted near Redcloud Peak with very minor production (Sanford and others, 1986; Hon, 1987).

Previous Water Quality Investigation

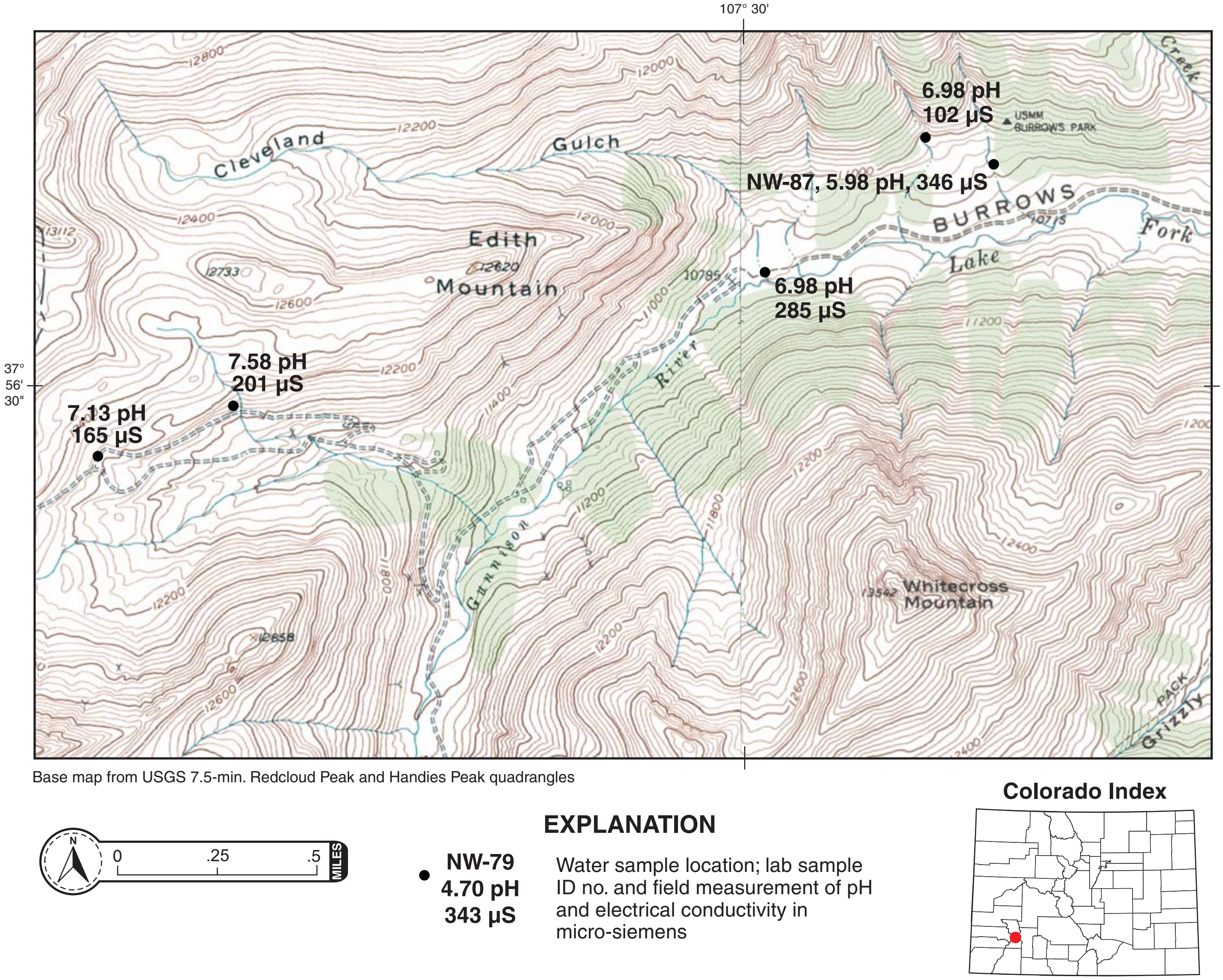
No significant acidic mine drainage is documented in the Redcloud Peak area of the Lake City caldera, however natural acid-rock drainage has been documented in recent studies (Miller, 1998; Miller and McHugh 1998; and Bove and Knepper, 2000). In July 1994, Miller (1998) conducted a detailed study of natural ARD in selected streams in the Redcloud Peak area southwest of Lake City (Miller, 1998; Miller and McHugh, 1998) (Figure 1). The project included surface-water samples from 32 stream or lake sites and one spring, and was designed to determine geochemical baselines in an intensely mineralized but essentially unmined area. The results of the study are summarized below.

White precipitate, presumably aluminum hydroxide minerals, coats rocks in the streams at most of the sample sites where analyses indicated elevated aluminum concentrations. Iron precipitates are apparent at some localities, but appear to be less common than aluminum precipitates. Five of 33 water samples had pH below 5. Sulfate concentration generally ranged from 20 to 50 mg/L and exceeded 100 mg/L in two samples, including the sample from the one spring site. The concentration of aluminum was greater than 1,000 µg/L in six samples; manganese was above 50 µg/L in nine samples; zinc was above 50 µg/L in nine samples; and molybdenum was at least 2 µg/L in eight samples. Iron concentrations were as high as 450 µg/L, but usually ranged from 10 to 40 µg/L. Many of the samples with high concentrations of metals were collected from streams draining the northwest side of Redcloud Peak and from the spring in lower Alpine Gulch, northeast of Redcloud Peak (Miller, 1998).

Miller (1998) suggests that water with low pH and high sulfate results from near-surface oxidation of sulfides, and that water with neutral pH and high sulfate results from subsurface oxidation of sulfides. Alternatively, acid neutralization could occur along the surface-water course due to interactions with acid neutralizing minerals. Acid produced by sulfide oxidation may be neutralized by calcite formed during the widespread propylitic alteration that occurred in this area.

Present Water Quality Investigation

In 1999, sample NW-87 was collected from a south-flowing tributary of Lake Fork in Burrows Park **(Figure 13)**, slightly west of the area studied by Miller (1998). The slopes above the sample site were stained brown, red and yellow from pyrite oxidation. Locally, rocks had been bleached, and mapping by Hon (1987)



Base map from USGS 7.5-min. Redcloud Peak and Handies Peak quadrangles

Figure 13. Map showing water sample site NW-87 and nearby water test results in the upper Lake Fork of the Gunnison River drainage basin.

indicates that these rocks are QSP- and argillic-altered. The tributary was flowing at 5 gpm, with pH of 5.98 and EC of 346 µS/cm. All of the tested parameters fell within State water quality standards, and most metals were below detection limits, although zinc was slightly elevated (77 µg/L) **(Appendix A-2)**. Water tests farther upstream in the Lake Fork drainage basin had pH values ranging from 6.98 to 7.58, and EC ranging from 102 to 285 µS/cm, suggesting minimal influence of ARD. Some of the waters with higher electrical conductivities may indicate upstream processes of acid-neutralization, similar to that in NW-63 in the Red Mountain Pass area, but no additional upstream samples were collected to evaluate this hypothesis. No significant ARD was identified by this limited reconnaissance testing in the headwaters of Lake Fork upstream of the area studied by Miller (1998).

Slumgullion Slide

The Slumgullion Slide **(Figures 14 and 15)** is a large earthflow on the eastern side of Lake Fork of the Gunnison River. The headwall of the slide is about 5 mi east of Lake City. State Highway 149 traverses and parallels the lower part of the slide. Areas of hydrothermally altered rock in the headwall area of the slide were mapped by Diehl and Schuster (1996) and their mapping is reproduced for this investigation **(Figure 15).**

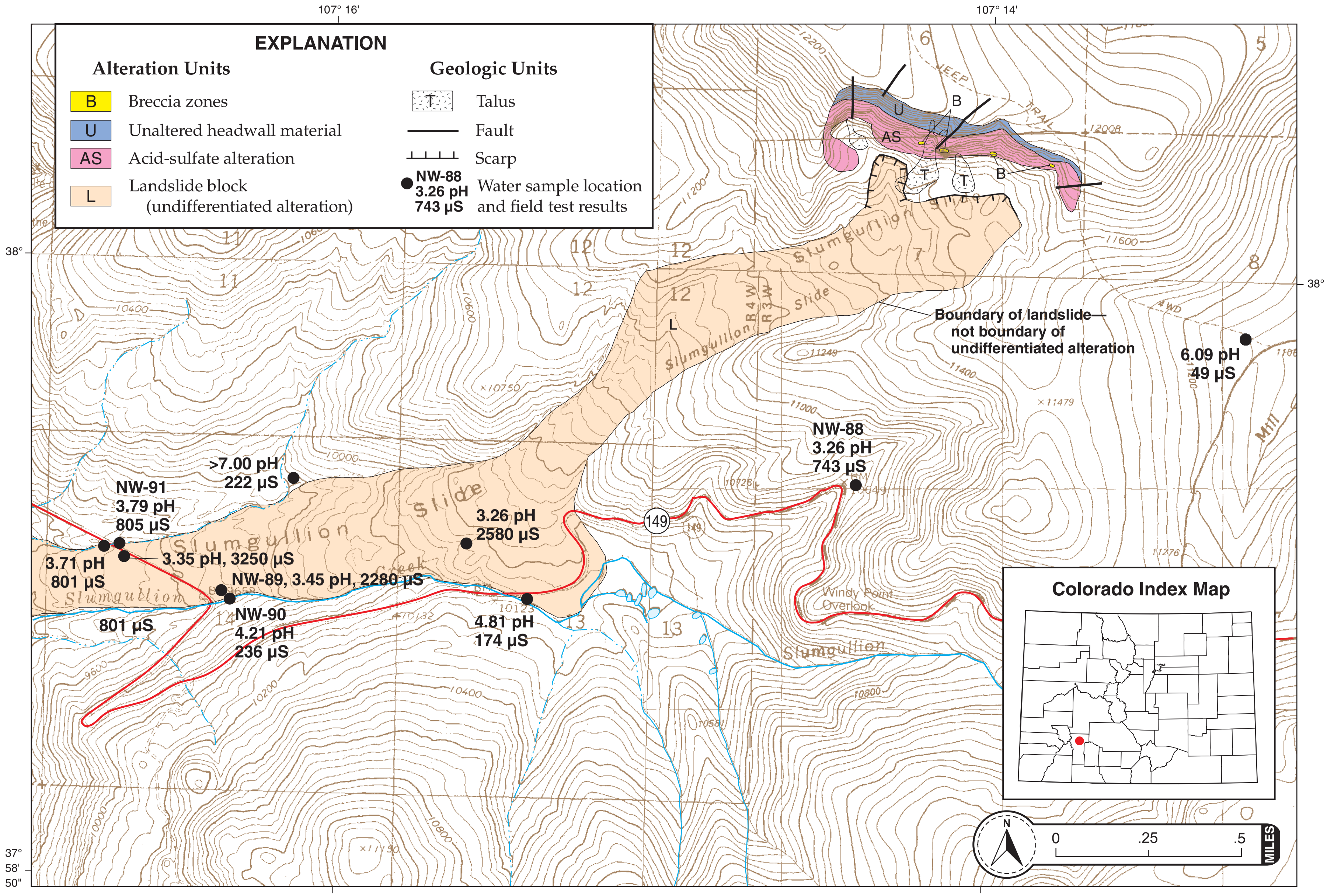
The Slumgullion slide is composed of hydrothermally altered Tertiary volcanic rock material and consists of a younger active flow moving over an older, inactive flow (Varnes and Savage, 1996). The older section, which dammed the Lake Fork of the Gunnison River and formed Lake San Cristobal, is about 700 years old (Varnes and Savage, 1996), and is about 4 mi long and 0.25 mi wide. At the toe of the slide in the valley of Lake Fork, material was dispersed upstream about 0.25 mi and downstream about 0.5 mi from the main body of the slide (Savage and others, 1992). A younger and still active portion of the slide lies within and above parts of the older slide. Radiocarbon and tree-ring geochronology indicate that the younger, active flow is approximately 300 years old. It is about 2 mi long and one-eighth to one-quarter mile wide, and is moving at a rate of about 7 to 20 ft per year (Savage and others, 1992). The composite landslide mass has a volume of approximately 6 billion ft^3 and is the largest landslide in Colorado.

Geology

The main head-wall scarp of the Slumgullion slide is near the eastern margin of the San Juan-Uncompahgre caldera complex, and at the eastern edge of regionally limonitically altered rhyolitic rocks (Lipman, 1976). The main scarp consists of relatively unaltered and nearly horizontal, foliated basalt flows and welded ash-flow tuffs that overlie acid-sulfate altered andesitic to rhyolitic flows (Diehl and Schuster, 1996). These units were intruded near the scarp by pyritic porphyritic rhyolites and are cut locally by masses of hydrothermal breccia (Figure 15). A small intrusion, probably of pre-caldera age, is exposed about a mile south of the headwall (Lipman, 1976). The intense alteration and steep topography, in conjunction with numerous structural features cutting the scarp area, are considered to be the main factors causing the original failure of the rock that initiated the landslide (Diehl and Shuster, 1996). The main scarp failed in areas affected by wide zones of argillic-altered rock that surround breccia masses and intrusions.

Within the main scarp area, hydrothermal alteration is most intense adjacent to breccia bodies (Figure 15). Hydrothermal alteration is zoned around the breccia masses, and contacts are transitional outward from vuggy silica to quartz-alunite and into argillic-altered rock. Pyrite is present within veins and tiny fractures and is also disseminated throughout the altered rocks. Other hydrothermal minerals in the breccia matrix and adjacent rocks include chalcedony,

Figure 14. Headwall and upper reaches of Slumgullion Slide.



Alteration from D. Bove, 2001, unpublished USGS data

Base map from USGS 7.5-min. Lake City, Cannibal Plateau, Lake San Cristobal, and Slumgullion Pass quadrangles

Figure 15. Map showing geology, alteration, water sample sites NW-88 to NW-91, and water test results from the Slumgullion Slide area.

sericite, smectite, kaolinite, jarosite, and alunite (Diehl and Schuster, 1996). The weathering of sulfides has lead to the precipitation of surficial alteration crusts such as gypsum and limonite, which are abundant throughout the headwall scarp and the rest of the slide mass. Unpublished studies (E. Anderson, USGS, oral commun., 2000), indicate that the jarosite and some clays in the upper few feet of the landslide may be related to in situ supergene leaching of sulfide minerals. However, much of the jarosite and clays are undoubtedly derived from hydrothermally altered rocks in the headwall area.

Much of the body of the slide is composed of soft, wet, unstable clay cut by numerous gullies. Two main types of clay-rich materials are exposed on the active surface of the landslide and are easily differentiated by color (Chleborad and others, 1996). These two materials (one yellow, the other reddish-brown) form much of the matrix of the landslide debris and also form local masses within the deposit. Slender selenite needles as much as 10 cm long are common on the surface of the yellow material. These crystals were rarely seen in, or on, surface exposures of the reddish-brown material. Chleborad and others (1996) determined that the yellowish material contains only a smectitic clay and is relatively rich in sulfur and calcium. In contrast, the reddish brown material contains both discreet smectite and kaolinite, and is generally higher in iron than the yellowish material and lower in calcium and sulfate. The surficial portions of the slide thus contain gypsum, kaolinite, smectites, jarosite, oxidized sulfides and variably altered volcanic rock fragments.

Present Water Quality Investigation

Sample NW-88 was collected from a stream draining altered rocks south of the slide (Figures 14 and 15). Water samples NW-89 to NW-91 were collected from streams within or bordering the Slumgullion Slide. The pH of these four samples ranged from 3.26 to 4.21, EC ranged from 236 to 2,280 µS/cm, and hardness ranged from 54 to 897 mg/L (as $CaCO_3$). Aluminum, iron, and manganese concentrations exceeded State standards in all four samples (Appendix A-2).

At sample site NW-88, partly eroded ferricrete formed the banks of the stream in some areas. Alluvium was mostly argillized or acid-sulfate-altered porphyry with yellow and red staining. Fragments of ferricrete, brick-red, fine-grained volcanic rock, and yellow- and brown-stained silicified rocks also appeared as alluvium. Flow was about 4 gpm, pH was 3.26, and EC was 743 µS/cm. Aluminum, iron, manganese, copper, chloride, and zinc concentrations exceeded standards (Appendix A-2). The chloride concentration (1,400 mg/L) was significantly higher than in all other samples collected for this study. The sample has a poor ionic balance, biased towards anions, suggesting that the chloride concentration could be a laboratory error. If the chloride value is correct, it could be explained by the very near proximity of the sample site to Highway 149 (Figure 15) and potential road salt application, although neither sodium, magnesium, nor potassium concentrations for this sample were high compared to other Slumgullion waters.

Sample NW-89 was collected from a milky and turbid tributary of Slumgullion Creek, just upstream of its confluence with Slumgullion Creek and State Highway 149. This stream drains much of the active portion of the slide. Flow was 340 gpm, pH was 3.45, and EC was 2,280 µS/cm. Aluminum, manganese, iron, fluoride, copper, and sulfate exceeded State water quality standards. Silica, chloride, sodium, zinc, nickel, and hardness were elevated but below standards (Appendix A-2).

Concentrations of total aluminum and iron significantly exceeded dissolved concentrations, indicating that aluminum and iron phases comprise a large portion of the suspended solids in the stream. PHREEQC modeling indicates that gypsum, potassium jarosite, jurbanite, and various silica phases are near saturation. Because of the fairly high flow rate and high metal concentrations, this stream contributes significant metal loads to Slumgullion Creek and the Lake Fork of the Gunnison.

Sample NW-90 was collected from Slumgullion Creek immediately above its confluence with the milky tributary sampled at NW-89. At this site, Slumgullion Creek receives surface flow from the southern boundary of the slide, but run-off from the slide is considerably diluted by the much larger flow from the upper part of Slumgullion Creek, south of the slide. A water test of upper Slumgullion Creek revealed some evidence of natural ARD, with pH of 4.81 and EC of 174 µS/cm (Figure 15), but no sample was collected from upper Slumgullion Creek during this investigation. At sample site NW-90, the water was slightly cloudy, and a red precipitate coated some of the stream gravel. Flow was 450 gpm, pH was 4.21, and EC was 236 µS/cm. Aluminum, iron, and manganese exceeded standards at this site, but concentrations were considerably lower than in NW-89. The large difference between concentrations of total (1,600 µg/L) and dissolved (540 µg/L) iron in sample NW-90 indicates the presence of suspended iron phases (Appendix A-3).

Sample NW-91 was collected from a creek near the northwestern border of the slide **(Figure 16)**. A few small, dry mines had been driven into bedrock north of the slide and within the drainage basin, but probably have little effect on the water quality downgradient. Red-orange precipitate coated the streambed (Figure 16). Flow was 72 gpm, pH was 3.79, and EC

Figure 16. Water sample site NW-91 near the northwest margin of Slumgullion Slide.

was 805 µS/cm. Aluminum and manganese concentrations significantly exceeded State water quality standards, and iron exceeded standards to a lesser extent (Appendix 2). Much of the high EC may be explained by relatively high concentrations of sulfate, and major cations, such as calcium, magnesium, and sodium.

Sample NW-91 showed effects of ARD, despite the diluting effect of an unnamed tributary that joined this stream from the north, about 0.5 mi upstream. A water test from the northern tributary had neutral pH and EC of 222 µS/cm. A water test in some wetlands near site NW-91, on the south side of State Highway 149, had pH of 3.35 with EC of 3,250 µS/cm (Figure 16).

Water sample data indicate derivation from strongly acid-sulfate and argillically-altered rocks where much of the sulfide has broken down to release ARD. The large volume and unconsolidated nature of the slide implies that ARD will continue to be released from this area for the foreseeable future.

CARSON CAMP AREA

Carson Camp **(Figure 17)** was a turn-of-the-20th century mining settlement about 10 mi south of Lake City near the headwaters of Wager Gulch, a tributary of Lake Fork of the Gunnison River. The Carson mining district straddles the Continental Divide, and large mines lie in the upper basins of Wager Gulch on the north side of the divide, and along the western side of a tributary of Lost Trail Creek on the south side of the divide.

Geology

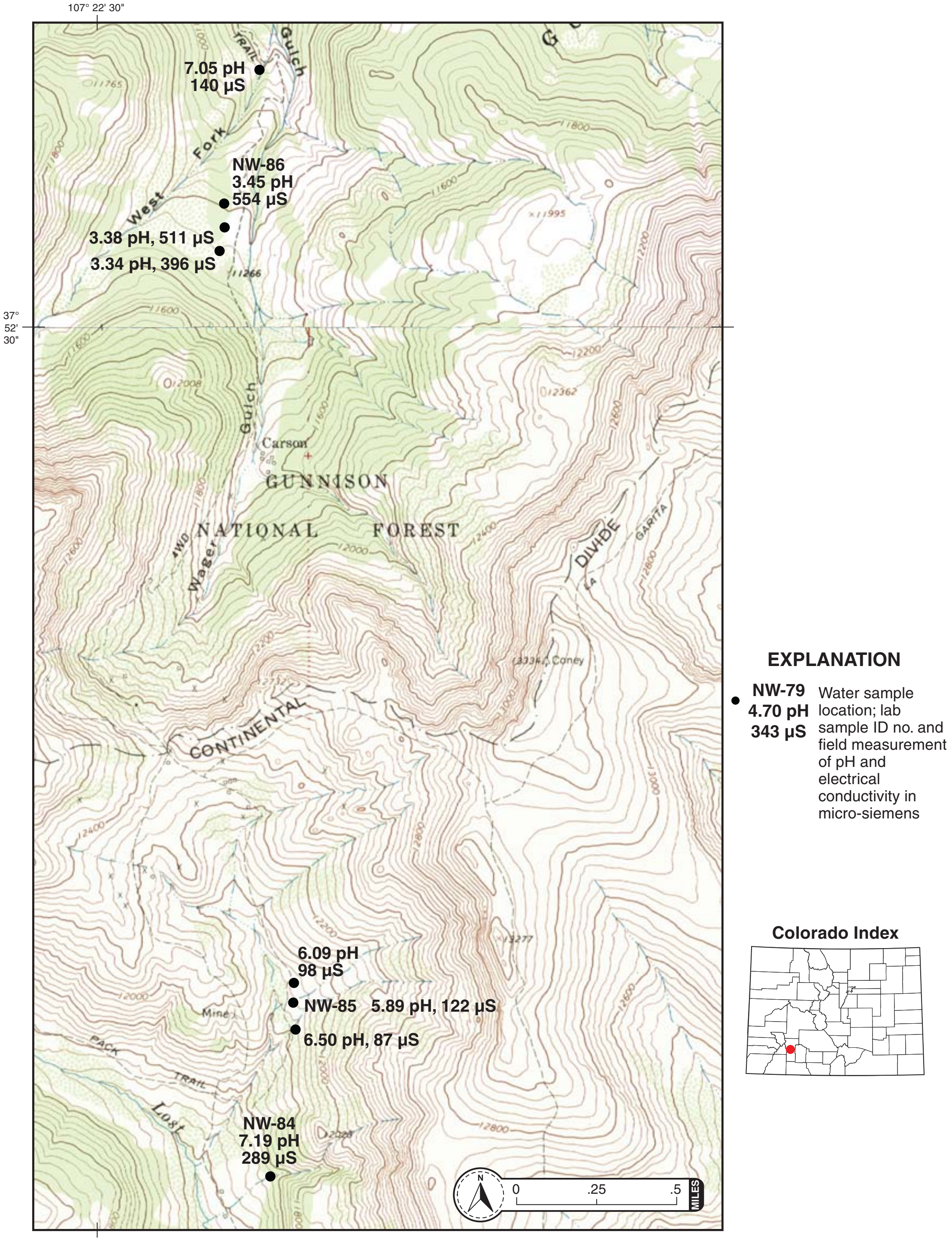
Large areas of altered rocks are exposed along the Continental Divide in and near the Carson mining district (Bove and Knepper, 2000). The alteration is spatially related to the Carson volcanic center, a 29-million-year-old volcano that predates the formation of the nearby Uncompahgre/Lake City and the inferred Lost Lake calderas (Steven and Lipman, 1976). The core of the volcano is now exposed as a porphyritic andesite stock. Intermediate-composition lavas and volcaniclastic rocks surround the stock. Hydrothermal alteration has affected parts of the stock and the surrounding extrusive and volcaniclastic rocks (Lipman, 1976; Steven and Lipman, 1976).

Mines in the Carson mining district were developed on numerous discontinuous veins that cut the stock and surrounding volcanic rocks. Minor amounts of gold and silver were produced from the veins, which also contained barite, quartz, enargite, pyrite, chalcopyrite, sphalerite, galena, and marcasite (Larsen, 1910). Mineralization and alteration in the Carson area may have resulted from late-stage hydrothermal activity associated with the pre-caldera Carson volcano, or it may be related to later, nearby caldera-forming events.

In upper Wager Gulch, iron-rich springs emerge in a wetland between Wager Gulch and the West Fork of Wager Gulch. No mines are known to exist above this series of springs. Water from the springs has formed an active bog-iron deposit with yellow, red, and brown precipitates, presumably ferrihydrites and sulfates (Harrer and Tesch, 1959). Bedrock exposed immediately above the springs is gray volcanic rock that appears to be only weakly altered. Lipman (1976) mapped undifferentiated hydrothermally altered volcanic rocks higher on the ridge.

Present Water Quality Investigation

Sample NW-86 was taken from a stream flowing across the ferrosinter deposit described above in upper Wager Gulch **(Figures 17 and 18)**. Within and near the stream channel, most of the ferrosinter was fresh and hard with a thin coating of soft precipitate. An oily sheen of unknown composition appeared on the ferrosinter surface in shallow areas of the stream and near seeps. Away from the channel, the deposit is weathered to a dark, red-brown soil. Flow was 15 gpm, pH was 3.45, and EC was 554 µS/cm. Aluminum, manganese, and iron



Base map from USGS 7.5-min. Finger Mesa and Lake San Cristobal quadrangles

Figure 17. Map of water sample sites NW-84 to NW-86 and water test results from the Carson Camp area.

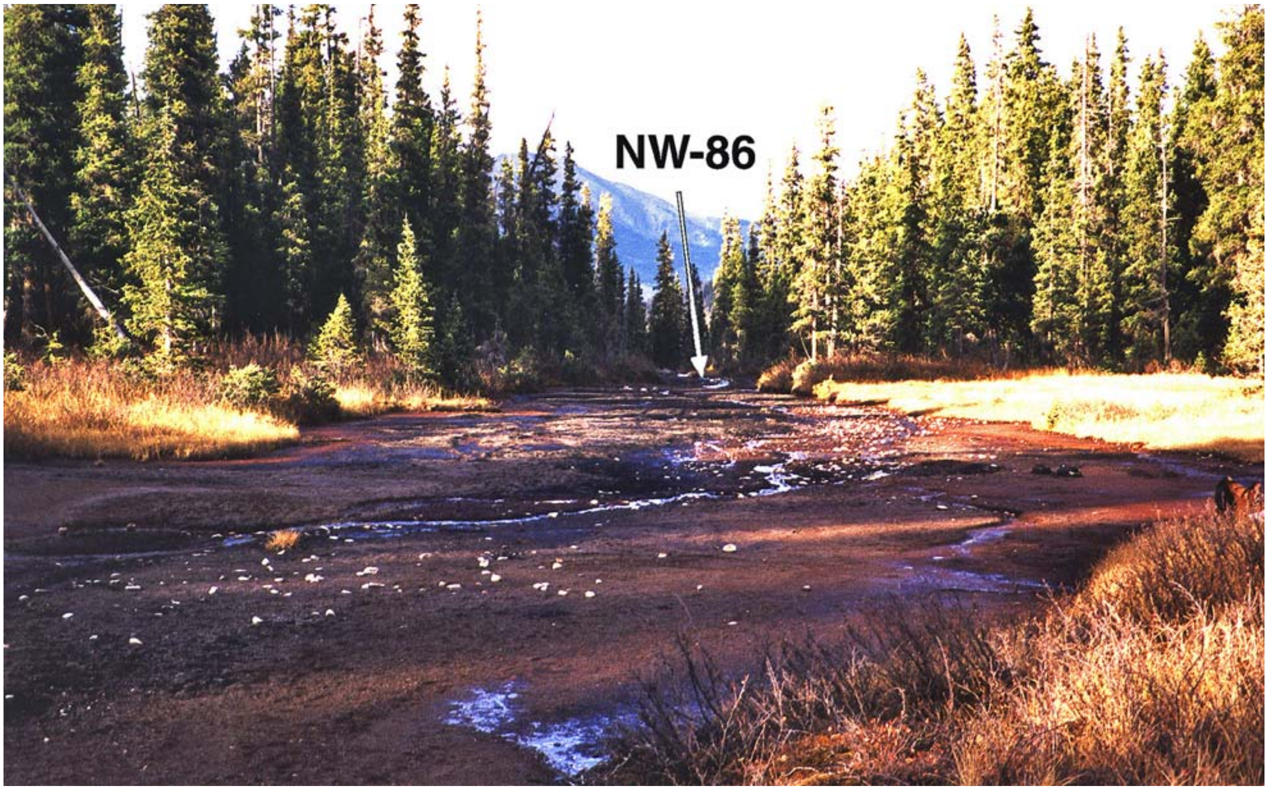


Figure 18. Water sample site NW-86 and ferrosinter deposit near Wager Gulch.

concentrations significantly exceeded State water quality standards (Appendix A-2).

Copper and zinc concentrations were elevated, but within State water quality standards due to the high hardness of the water. Where the stream flowed across the active ferrosinter deposit, pH remained fairly constant, but EC gradually increased downstream (Figure 17). ARD from the springs merged with West Fork of Wager Gulch. The West Fork, below the confluence with the acidic springs and above its confluence with Wager Gulch, had a pH of 7.05 and EC of 140 µS/cm. Additional sampling would be required to characterize the chemistry of this spring and its effects on Wager Gulch.

In a tributary of Lost Trail Creek on the south side of the Continental Divide (Figure 17), large abandoned mine workings were visible almost to the ridgeline (Figure 17), therefore, this tributary is likely affected by mine runoff. Because of the historic mining activity in the main tributary, two water samples (NW-84 and NW-85) were collected from smaller, unmined tributaries flowing from the ridge east of Lost Trail Creek (Figure 17). Bedrock exposed on the slopes above the sample sites include weakly altered and iron-stained volcaniclastic and extrusive rocks (Lipman, 1976). Stream gravel was composed of argillized and propylitized rocks, along with fresh andesite porphyry.

The water at sample site NW-84 (35 gpm flow, 7.19 pH, 289 µS/cm EC) was mostly clear. However, small amounts of light-yellow precipitate, which was visible in some of the pools, clogged the filter during sampling, indicating that some material was in suspension. The water exceeded the State water quality standard for manganese concentration (Appendix A-2), and sulfate was slightly elevated (62 mg/L) compared to other water samples from this area. Total concentrations of aluminum and iron exceeded dissolved concentrations, indicating the presence of suspended aluminum and iron phases. PHREEQC simulations indicated numerous phases near or over saturation, including alunite and basaluminite; various forms of aluminum hydroxide including boehmite, diaspore, and gibbsite; chalcedony, amorphous ferric hydroxide, K-jarosite, jurbanite, and various clays.

Sample NW-85 was from a small tributary with flow of 1 gpm, pH of 5.89, and EC of 122 µS/cm. Despite the slightly acidic pH, this sample was within State water quality standards for all analyzed parameters (Appendix A-2). Water tests from other springs and streams in this area showed no signs of significant ARD and were not sampled (Figure 17).

PLATORO-SUMMITVILLE CALDERA COMPLEX

The Platoro-Summitville caldera complex is in the southeastern San Juan Mountains (Figure 1). Alamosa lies about 40 mi to the east; Pagosa Springs is about 20 mi to the west-southwest; and Wolf Creek Pass is about 10 mi to the west-northwest. Because of the well-documented and on-going environmental issues at the Summitville Mine, this area has been the focus of numerous water quality studies involving mining-affected and naturally-occurring ARD. CGS conducted a reconnaissance level investigation of naturally occurring ARD in the area for this study.

Geology

The Platoro caldera began forming about 30 Ma and is one of the oldest of the San Juan volcanic field. Pre-caldera andesitic volcanoes of the Conejos Formation were deeply eroded and the terrain was relatively flat when extrusion of the silicic Treasure Mountain Tuff and caldera formation began. Resurgence of the caldera followed, and the moat surrounding the resurgent core filled with lava and volcaniclastic rocks of the lower member of the Summitville Andesite. The Summitville Andesite is similar in composition to the Conejos Formation and may represent a reactivation of the pre-caldera volcanism (Steven and Lipman, 1976).

After the Platoro caldera moat was nearly filled with Summitville Andesite, subsequent extrusion of upper members of the Treasure Mountain Tuff, between 29 and 30 Ma, formed the Summitville caldera. The Summitville caldera is nested in the northern part of the Platoro caldera. The Summitville caldera probably had no resurgence and soon filled with upper members of the Summitville Andesite (Steven and Lipman, 1976).

Later extrusive and intrusive igneous activity and mineralization were concentrated near the margins of both calderas. At least five post-caldera igneous episodes occurred between 29 and 20 Ma (Steven and Lipman, 1976). Hydrothermal alteration and base- and precious-metal deposits are related to some of these post-caldera igneous events, especially where the Summitville and Platoro ring fractures intersect a regional northwest-trending fault zone along the western margin of the Summitville caldera (Steven and Lipman, 1976; Stoffregen, 1987; Gray and Coolbaugh, 1994).

Faults associated with the Platoro-Summitville caldera complex served as structural zones of weakness for emplacement of intrusive stocks during post-caldera igneous episodes. Hydrothermal fluids associated with the Alamosa River quartz monzonite stock and the Jasper andesite porphyry stock are responsible for extensive alteration in the upper Alamosa River drainage basin. The Alamosa River stock exhibits QSP alteration **(Figures 19 and 20)** that extends into the overlying Summitville Andesite in the drainage basins of Iron, Alum, and Bitter Creeks. Intrusion of the Jasper stock caused the alteration of bedrock in Jasper and Burnt Creeks (Bove and others, 1995; Lipman, 1974; Meyer and others, 1996).

Figure 19. Alteration on the south side of Lookout Mountain, in the Iron Creek drainage basin.

The Iron, Alum, Bitter and Burnt Creek basins encompass roughly 11 km^2 of intensely altered and weakly mineralized rock that corresponds spatially with the northern margin of the Alamosa River stock and eastern margin of the Jasper stock **(Figure 20)** (Bove and others, 1995). A later phase of the Alamosa River stock, called the Alum Creek porphyry (Calkin, 1967) is the focus of the most intense alteration in this area and contains zones of anomalously high lead (up to 1,060 ppm), copper (up to 250 ppm), molybdenum (up to 600 ppm) and zinc (up to 600 ppm) (Sharp and Gualtieri, 1968; Calkin, 1967). A classic porphyry-style, QSP alteration assemblage is centered around Alum Creek porphyry and is characterized by stockwork quartz-pyrite veinlets containing sparse molybdenite (Bove and others, 1996). Pyrite, which occurs ubiquitously throughout the altered rocks in these four basins, is most prevalent in zones of QSP alteration, where it averages about 1 to 2 volume percent of the rock (Bove and others, 1996). Pyrite concentrations decrease outward in the peripheral weak argillic-sericitic and propylitic alteration assemblages. (Bove and others, 1995, 1996).

Previous Water Quality Investigations

Because of the vast amount of research done in the Summitville area during the last decade, no effort is made to document all of the studies involving water quality in the Alamosa River. Our work in this area was relatively brief because of the abundance of work that has already been done. The reader is referred to Posey and others, 1995; Bove and others, 1996; Calkin, 1967; Miller and McHugh, 1994; Moran and Wentz, 1974; Sharp and Gualtieri, 1968; Stroffregen, 1987; and Gray and Coolbaugh, 1994 for additional information on the Summitville area. A few examples of naturally acid, metal-rich springs in the area, previously

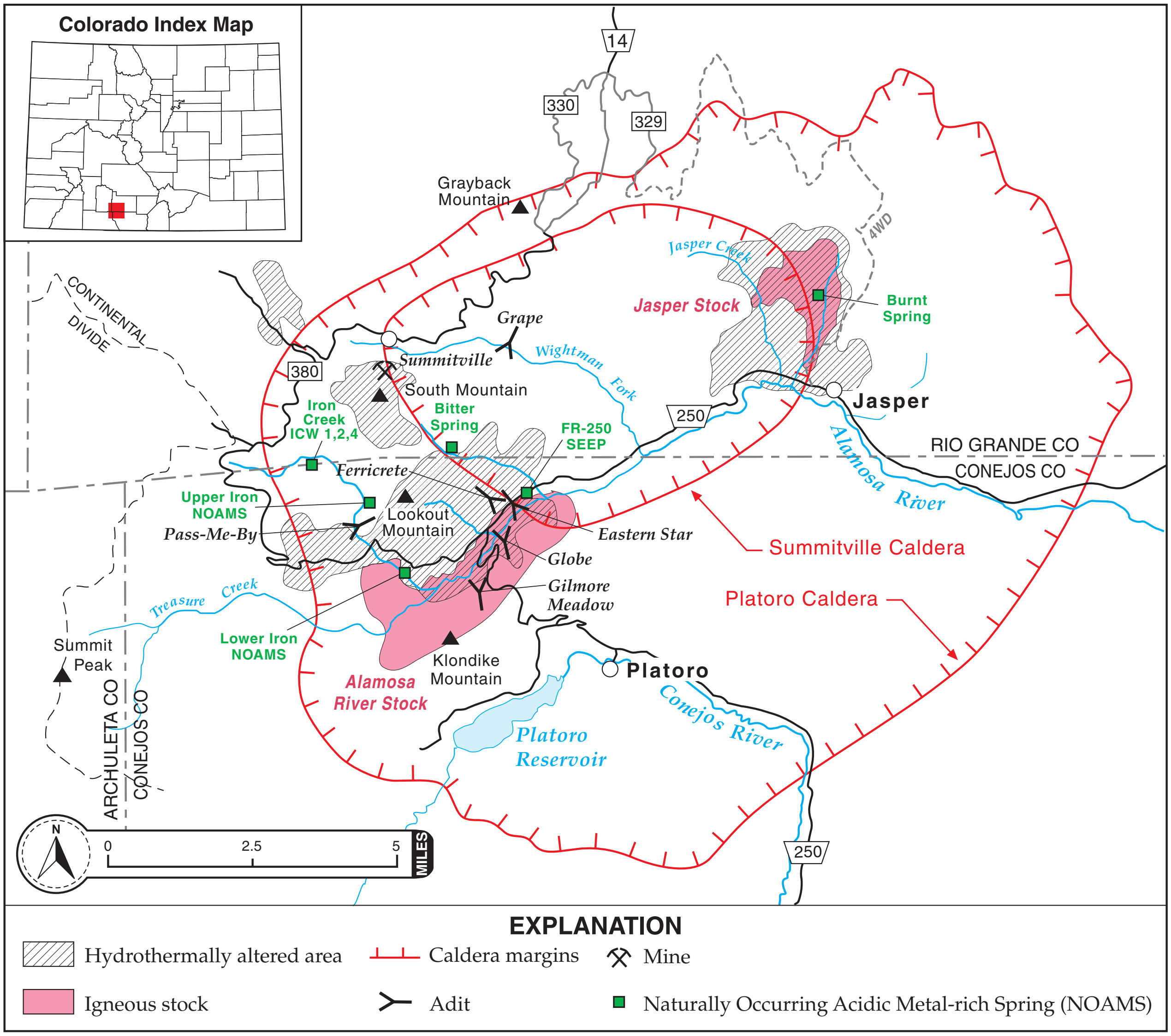


Figure 20. Map of the upper Alamosa River basin showing hydrothermally altered areas. (modified after Bove and others, 1995)

sampled by CGS personnel, are described and tabulated in the following paragraphs.

Numerous water tests for pH and EC were performed on mining-affected and natural waters during an abandoned mine inventory of USFS-administered land (Kirkham and Lovekin, 1995). A follow-up study (Kirkham and others, 1995) included collection of samples from five naturally acidic, metal-rich springs, or NOAMS (Naturally Occurring, Acidic, Metal-rich Spring) (Figure 20). All samples had pH<4 and contained elevated metal concentrations, most commonly aluminum, copper, iron, and zinc, and locally manganese. Flow rates on these springs varied from less than 2 gpm to about 20 gpm (samples from 1993 and 1994 in **Table 2**).

The Upper Iron NOAMS emerges from strongly altered Summitville Andesite in the Iron Creek drainage at an elevation of 11,380 ft (Figures 19 and 20). Water flows from a sub-horizontal fracture, down a precipitate-covered slope about 200 ft wide and 300 ft long (Sares, 1996). The spring water had a flow rate of 6.7 gpm with pH of 2.53 and elevated concentrations of aluminum, iron, copper, cadmium, lead, zinc, and sulfate **(**Table 2**)**. A NOAMS with similar pH and conductivity was noted by Kirkham and others (1995) at an elevation of 11,840 ft at the headwaters of an Iron Creek tributary at the south end of Cropsy Mountain.

The Lower Iron NOAMS occurs downstream from the Upper Iron NOAMS in the Iron Creek drainage in a post-caldera, monzonite intrusion immediately downslope from intensely altered Summitville Andesite and associated talus and colluvium (Figure 20). Water from the spring has formed a large ferrosinter mound (Sares, 1996). This spring has the largest flow identified among the NOAMS in the caldera complex, with a flow of about 20 gpm. The pH of the spring water was 2.94, and aluminum, iron, manganese, and zinc concentrations were elevated (Table 2). This NOAMS is located below the Pass-Me-By Mine and may have some mining-related impacts.

Meyer and others (1996) collected samples from springs and seeps in the Iron Creek drainage basin and from the Pass-Me-By Mine, which lies in the Iron Creek drainage basin below the seeps (Figure 20). No precise locations for the Iron Creek seeps are given in Meyer and others (1996), but ICW4 is described as 200 ft higher in elevation than the Pass-Me-By Mine at a comparable location to the "Upper Iron NOAMS" of Kirkham and others (1995). As shown on Table 2, waters from all of the seeps and the Pass-Me-By Mine

Table 2. Analytical data for selected water samples collected in the Platoro-Summitville caldera area prior to 1999. *Results are shown in dissolved concentrations and µg/L unless noted. Blank columns indicate the parameter was not analyzed or the results are not known. The 1993 and 1994 samples were reported in Kirkham and others (1995); the 1995 samples are reported in Meyer and others (1996, Table 4).*

Parameter	Upper Iron	Lower Iron	Bitter	FR-250 Seep	Main Burnt	Iron Creek ICW1	Iron Creek ICW2	Iron Creek ICW4	Pass-Me By-Mine
Date	8/5/93	8/27/93	6/18/94	8/11/93	8/31/93	9/14/95	9/14/95	9/14/95	9/14/95
Flow (gpm)	6.7	~20	1.6	3.9	~18				
pH	2.53	2.94	3.27	2.75	3.82	3.87	3.79	2.39	3.02
Conductivity (µS/cm)	2,590	622	214	2,600	2,040	433	624	3,610	1,225
Eh (millivolts)						173	175	247	214
Temperature (°C)						9	7.2	6.6	5.6
DO (mg/L)						0.6	0.1	0.4	0.5
TDS (mg/L)						218	314	1,810	613
Hardness (mg/L)	33	26	2	785	947				
Aluminum	120,000	9,000	1,422	38,000	31,000	7,500	18,000	270,000	59,000
Arsenic						4	<10	<10	33
Calcium (mg/L)	22	7	0.2	150	320	36	33	19	18
Cadmium	1.7	<20	<0.3	<20	<20	0.38	0.62	3	1.2
Copper	990	<40	77	350	58	<4	<8	2,500	110
Iron	160,000	26,000	1,920	70,000	72,000	48,000	90,000	500,000	160,000
Lead	7	<80	<3	<80	<80	<1	<1	<1	<1
Magnesium (mg/L)	2.6	2.0	0.3	100	42	5.9	5	3	2.4
Manganese	240	650	49	15,000	4,200	1,200	1,300	220	400
Mercury							<0.2	<0.2	<0.2
Nickel	<200	<40	<1	160	<40				
Potassium (mg/L)						4.6	5.1	<0.25	6.9
Silver	<0.2	<40	<0.6	<40	<40				
Sodium (mg/L)						2.7	0.94	0.14	0.3
Sulfate (mg/L)	1,380		25			180	310	3,200	640
Zinc	260	130	138	930	810	150	230	310	190

are acidic and contain high concentrations of aluminum (>1,000 µg/L), iron (>1,000 µg/L), and zinc (>100 µg/L).

The most acidic seep (Upper Iron) and the Pass-Me-By Mine water contain high concentrations of cadmium (>1 µg/L), copper (>100 µg/L), and sulfate (>600 mg/L). Arsenic (33 µg/L) exceeds State standards in the Pass-Me-By Mine effluent. Manganese exceeds 1,000 µg/L in the Main Burnt and two of the Iron Creek seeps, all of which have slightly higher pH than the other sample sites (Table 2). Higher concentrations of calcium, magnesium, and sodium in the seeps having higher pH may indicate a mild acid-neutralizing effect because of dissolution of carbonate or feldspar minerals (Meyer and others, 1996).

The Bitter NOAMS emerges from altered Summitville Andesite in the upper reaches of the Bitter Creek drainage basin at an elevation of about 11,300 ft (Figure 20). The spring flowed about 1.6 gpm with pH of 3.27 and high concentrations of aluminum (1,422 µg/L), copper (77 µg/L), iron (1,920 µg/L), and zinc (138 µg/L) (Table 2). Several other springs emerge at approximately the same elevation in this gulch, suggesting a permeability boundary in the flow units that compose the bedrock (Sares, 1996).

Several seeps discharge in a borrow pit along Forest Road #250 between Alum and Bitter Creeks at an elevation of about 9,900 ft (Figure 20). The borrow pit was excavated in a debris flow. Bedrock in this area is altered, post-caldera monzonite (Sares, 1996). The seep (sample labeled as “FR-250 Seep” on Table 2) flowed at about 4 gpm with pH of 2.75 and exceeded State water quality standards in aluminum, copper, iron, manganese, and zinc. Other metals with high concentrations included magnesium (100 mg/L), calcium (150 mg/L), and nickel (160 µg/L) (Table 2).

The Main Burnt NOAMS is in the middle to upper portion of the Burnt Creek drainage basin above all known mine workings at an elevation of 10,300 ft (Figure 20), and emerges from altered, intrusive, andesite porphyry of the Jasper stock. Precipitate deposited from the spring water has formed an overhanging ferrosinter mound composed of small, stair-stepped terraces holding shallow pools of water (Sares, 1996). The spring flowed at about 18 gpm and had a pH of 3.82. The water greatly exceeded standards in aluminum, iron, manganese, and zinc. Other metals with high concentrations included calcium (320 mg/L), magnesium (42 mg/L), and copper (58 µg/L)(Table 2).

To determine if the formation of precipitate mounds partly attenuates the ARD in waters of natural seeps and springs, Meyer and others (1996) sampled the precipitate in three of the mounds to analyze their metal content. The mounds were sampled immediately adjacent to the spring or seep to obtain “fresh” precipitate, and farther from the source for “older” material. With few exceptions, the “old” and “fresh” material in the same deposits were similar in composition. The mounds contained from 23% to 43% iron, and most of the metals were found at similar concentrations relative to iron as that in the adjacent seeps. Only arsenic appeared to show preferential enrichment in the mounds compared to the waters. These analyses show that abundant iron and significant quantities of trace metals are precipitated during formation of the ferrosinter deposits, and that development of these deposits may partly attenuate metal concentrations in natural ARD (Meyer and others, 1996).

Nearly all of the previous USGS and CGS studies cited above have consistently found natural ARD in the upper Alamosa River drainage basin (the Iron, Alum, Bitter and Burnt Creek drainages) with aluminum, iron, manganese, copper, zinc and sulfate concentrations exceeding state water quality standards. In the most concentrated seeps, the pH is lower and the conductivity is higher than the worst mine drainage in the area (Kirkham and others, 1995) suggesting that natural ARD in this area produces waters more “degraded” than that from mining.

No known hydrologic connection exists between the Summitville mine area and the natural ARD seeps sampled in these studies (Morrison Knudsen Corporation, 1997). The Reynolds adit, the main drainage point in the Summitville mine area located at the base of South Mountain, is at a lower elevation (11,320 ft) than the most concentrated natural seeps in upper Iron Creek (at 11,380 ft and 11,840 ft) so that it is extremely unlikely that any mining impacted waters from the Summitville mine could contribute to the high metal concentrations in many of the seeps affecting the upper Alamosa River.

Present Water Quality Investigation

Because of the extensive work already done by others in the Summitville area, only two samples (NW-83 and NW-95) were collected in 1999 from near the Platoro-Summitville caldera complex **(Figure 21)**. NW-83 was from Crater Creek, on the western side of the Continental Divide. Although alteration associated with intrusive activity reportedly exists in this area (Lipman, 1974; Steven and Lipman, 1976), none was obvious in the vicinity of the sample location. Veins containing zinc and other base metals were exposed and mined just downstream from the sample site. Stream gravel at the sample site included mostly relatively fresh andesite porphyry; lesser amounts of argillic-altered porphyry; siliceous, light-brown aphanitic volcanic or volcaniclastic rock; and traces of quartz veins with pyrite stringers. Water sample NW-83 was relatively clean, and analyses only showed a few trace metals, all in low concentrations **(Appendix A-3)**.

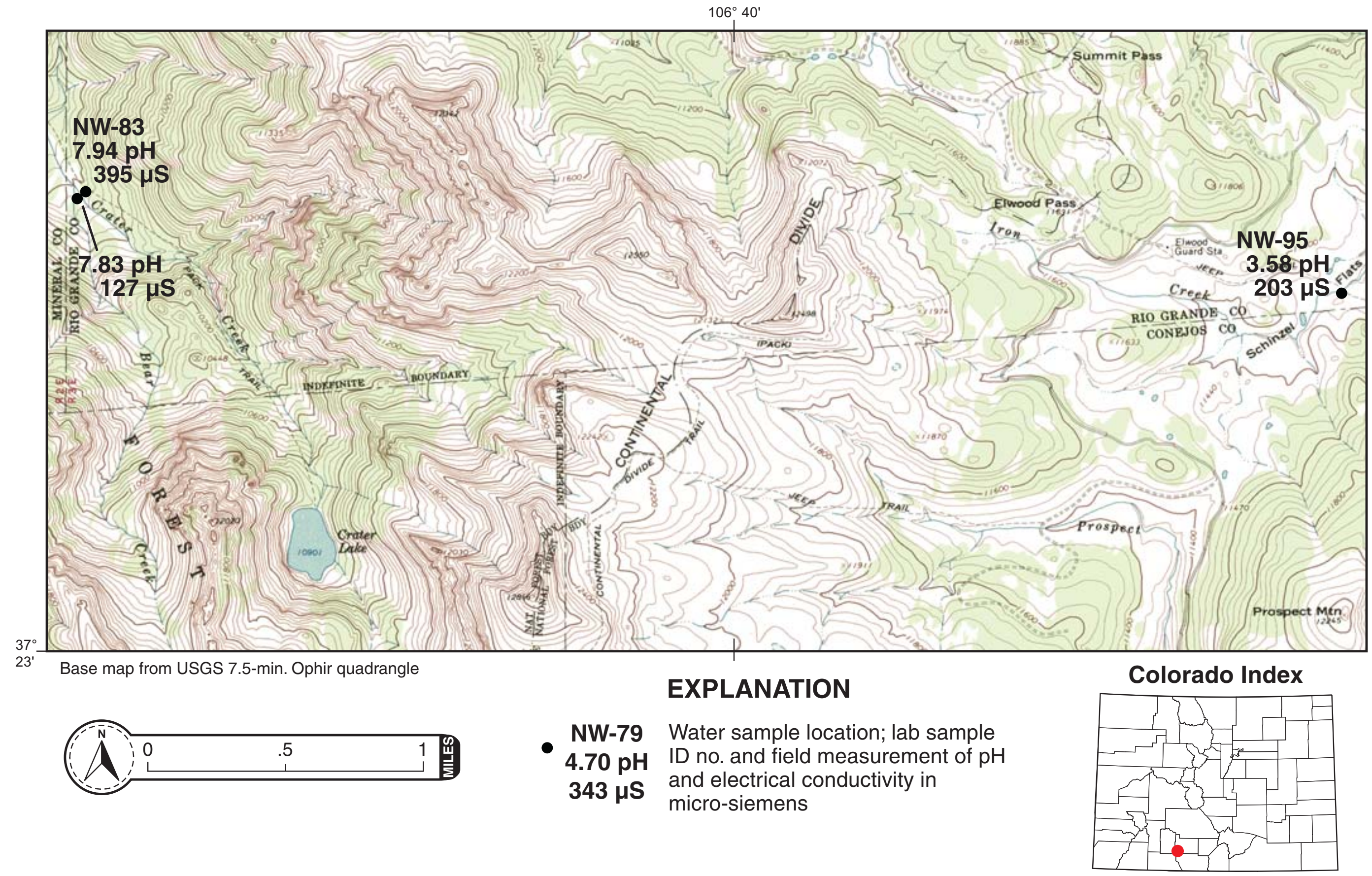


Figure 21. Map showing water sample sites NW-83, NW-95, and water test results from the Platoro-Summitville caldera area.

Water sample NW-95 was from a spring with an associated actively forming ferrosinter deposit **(Figure 22)** in Schinzel Flats, near the headwaters of Iron Creek, on the eastern side of the Continental Divide. A nearby shallow prospect pit was downgradient and was not considered to be a factor in the water quality of the spring. Bedrock exposed at a small waterfall about 200 ft downstream from the sample site comprised silicified and pyritized, gray, aphanitic volcanic rock.

Old[1], well-indurated ferricrete deposits, high above the active stream channel **(Figure 23)** on both sides of Iron Creek adjacent to sample site NW-95, suggest a history of ARD. Based on the numerous ferricrete deposits at higher elevation in the Iron, Alum, Bitter and Burnt Creek basins, several authors have suggested that ARD has been present in this area for thousands of years (Bove and others, 1995; Kirkham and others, 1995). A thin layer of red precipitate coated much of the channel of Iron Creek both upstream and downstream from the spring. The sampled spring was flowing at 3 gpm with pH of 3.58 and EC of 203 µS/cm. Aluminum, iron, copper, manganese, thallium, and zinc exceeded State water quality standards (Appendix A-3).

KITE LAKE AREA

Kite Lake is in the upper Rio Grande drainage basin, near the headwaters of Bear Creek and close to the Continental Divide (Figure 1). Abandoned mines related to the ghost town of Beartown are nearby. Water samples collected during the reconnaissance level investigation in 1999 are from sites above both known large mines and draining adits.

Geology

Acid rock drainage emerges near Kite Lake from Precambrian Uncompahgre Formation phyllite and quartzite. Disseminated pyrite commonly appears in some of the metamorphosed rocks of the Uncompahgre Formation. Unaltered volcanic rocks related to early Oligocene andesitic volcanism are

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[1] Criteria used in this report to designate a ferricrete or ferrosinter as either young or old are based on field observations such as degree of induration (actively forming deposits typically have a soft skin), erosion, position relative to the stream channel (i.e., "perched" above active seeps or surface water), inactive versus active, presence of lichen, and color (older ones have faded compared to young or active deposits).

Figure 22. Ferrosinter deposit at water sample site NW-95, adjacent to Iron Creek.

Figure 23. Ferricrete along upper Iron Creek near water sample site NW-95.

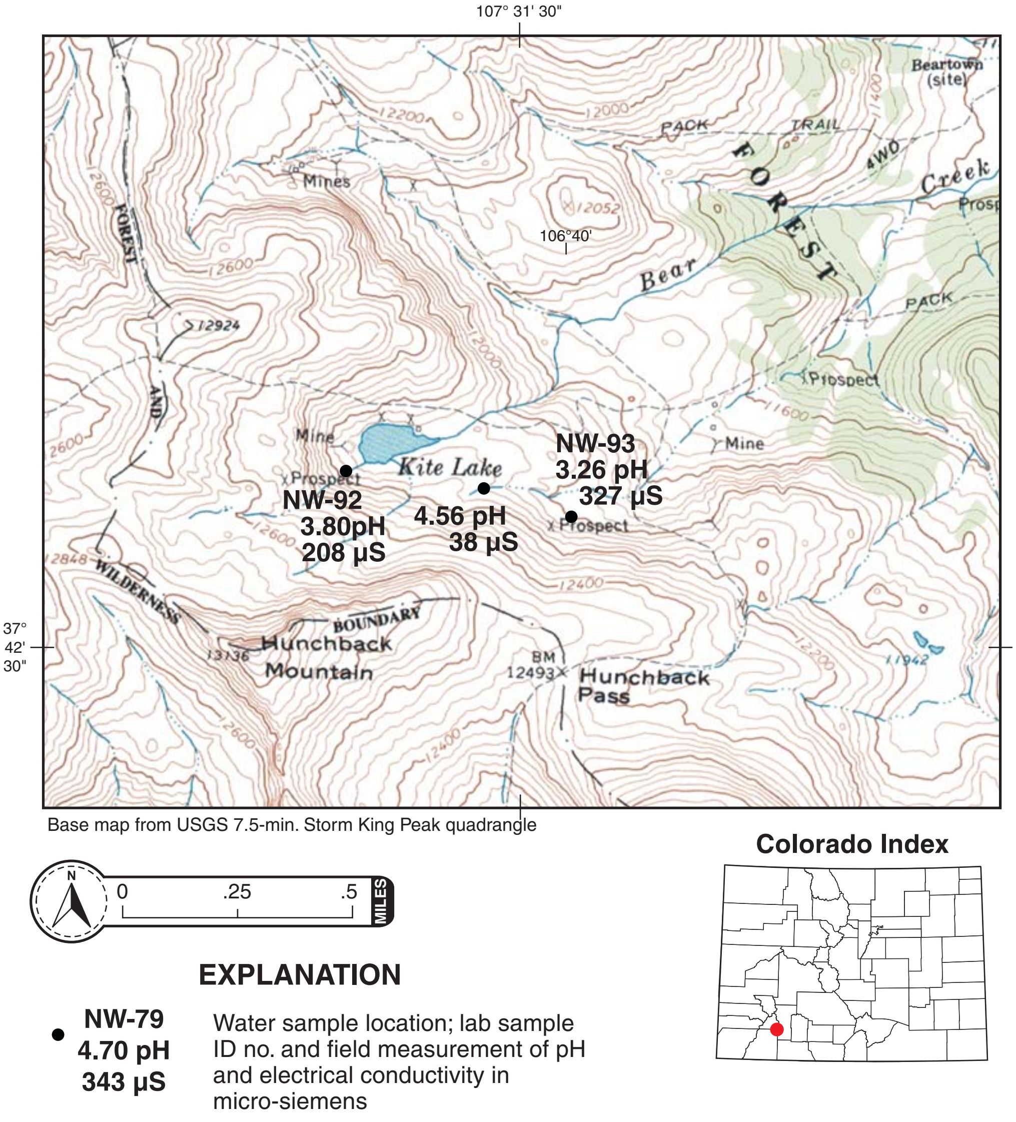
exposed to the north of an east-trending fault zone that lies immediately north of the sample sites (Steven and others, 1974). The disseminated nature of the pyrite and its intimate association with abundant carbon in the phyllite suggests that it is related to the Precambrian depositional environment, rather than a Laramide or later mineralization event. The inferred Ute Creek caldera of Tertiary-age is about three miles to the northeast (Steven and Lipman, 1976, Figure 5). It is not known whether ARD in this area is related to hydrothermally altered or mineralized areas near the margins of the caldera, or if it is related to weathering of Precambrian pyrite in the Uncompahgre Formation.

Previous Water Quality Investigations

Kirkham (1993) described acidic water in the stream draining into Kite Lake from the southwest **(Figure 24)**. Although a few small mines lie on private land near this creek, the mines apparently do not discharge water, and any drainage associated with them flows as groundwater directly toward Kite Lake, rather than into the stream. The stream channel is lined with red-orange precipitate in its upper reaches, upstream of the observed mines. When tested immediately upstream of Kite Lake in 1992, the water had pH of 4.75 pH and EC of 113 µS/cm.

Kirkham (1993) also discussed acidic, metal-rich springs and associated ferrosinter deposits on the north-facing slope east-southeast of Kite Lake. In 1992, a 15-gpm spring was observed emerging from a shallow, caved adit or prospect pit hosted entirely within a ferrosinter deposit. The prospect was probably driven to test the metal values of the ferrosinter deposit, and it is doubtful that the working itself affected water quality. The water had pH of 4.33, EC of 346 µS/cm, and contained high concentrations of iron (23,000 µg/L) and aluminum (5,200 µg/L). Metal concentrations exceeding State water quality standards included copper (43 µg/L), manganese (333 µg/L), zinc (98 µg/L), cadmium (0.5 µg/L), and nickel (51 µg/L). Sulfate, at a concentration of 120 mg/L, was elevated but within the State water quality standards (Kirkham, 1993). Samples were collected from the unnamed receiving stream, above and below its confluence with the spring. From upstream to downstream, flow in the creek increased from 20 to 35 gpm, pH dropped from 6.53 to 4.15, and EC increased from 33 µS/cm to 174 µS/cm. The upstream sample was within State water quality standards for the analyzed parameters. The downstream sample exhibited effects of ARD, exceeding State water quality standards in aluminum, iron, copper, manganese, zinc, and cadmium (unpublished CGS data).

Figure 24. Map showing water sample sites NW-92, NW-93, and water test results near Kite Lake and Hunchback Pass.



Base map from USGS 7.5-min. Storm King Peak quadrangle

Present Water Quality Investigations

Iron-stained phyllite and quartzite form the cliffs and talus slopes around Kite Lake. Disseminated pyrite is common, and the rocks are stained brown, with lesser amounts of red and yellow staining. Sample NW-92 was collected from the stream feeding Kite Lake from the southwest (Figure 24), and near the test site of Kirkham (1993) described above. The stream was flowing 2 gpm with pH of 3.80 and EC of 208 µS/cm. Aluminum, manganese, nickel, zinc, and copper exceeded State water quality standards **(Appendix A-4)**. No large mines are known to exist in the drainage basin above the sample site.

Small prospects and/or caved adits excavated in the ferrosinter deposits **(Figure 25)** described by Kirkham (1993) east-southeast of Kite Lake do not appear to affect the water quality of the springs that formed the deposits, even though seeps from the ferrosinter discharge ARD. Sample NW-93 was collected from one of the seeps below an icy cliff and had flow of 2 gpm, pH of 3.26, and EC of 327 µS/cm. Aluminum, iron, manganese, copper, nickel, and zinc exceeded State standards. Sulfate was elevated, but within standards (Appendix A-4).

EAST TROUT CREEK

East Trout Creek flows northward from the Continental Divide, eventually joining the Rio Grande River about 10 mi upstream of Creede (Figure 1). Natural ARD flows in a tributary of East Trout Creek, about 0.5 mi upstream from its confluence with West Trout Creek and about 20 mi south-southwest of Creede. CGS collected one sample during a reconnaissance-level investigation for this study.

Geology

Altered ash-flow tuffs with a chalky appearance are exposed along the ridge on the east side of East Trout Creek. A Tertiary intrusion is exposed about 3 mi downstream (Steven and others, 1974). The Creede caldera lies about 8 mi to the northeast, and the Mount Hope caldera is about 10 mi to the east (Steven and Lipman, 1976). Sulfur was mined at the nearby Sulphur Tunnel (Steven and Williams, 1984). The presence of the nearby sulfur mine **(Figure 26)** suggests fumarolic activity related to the localized hydrothermal alteration. The nearby Tertiary intrusion seems the most likely source for the hydrothermal fluids responsible for the alteration.

Present Water Quality Investigation

In 1992, Kirkham's (1993) water test in the unmined drainage basin north of the Sulphur Tunnel indicated pH of 3.88 and EC of 744 µS/cm. In 1999, sample NW-94 was collected from this stream near the site of Kirkham's test (Figure 26). Stream gravel consisted of gray andesite with minor brown and red staining;

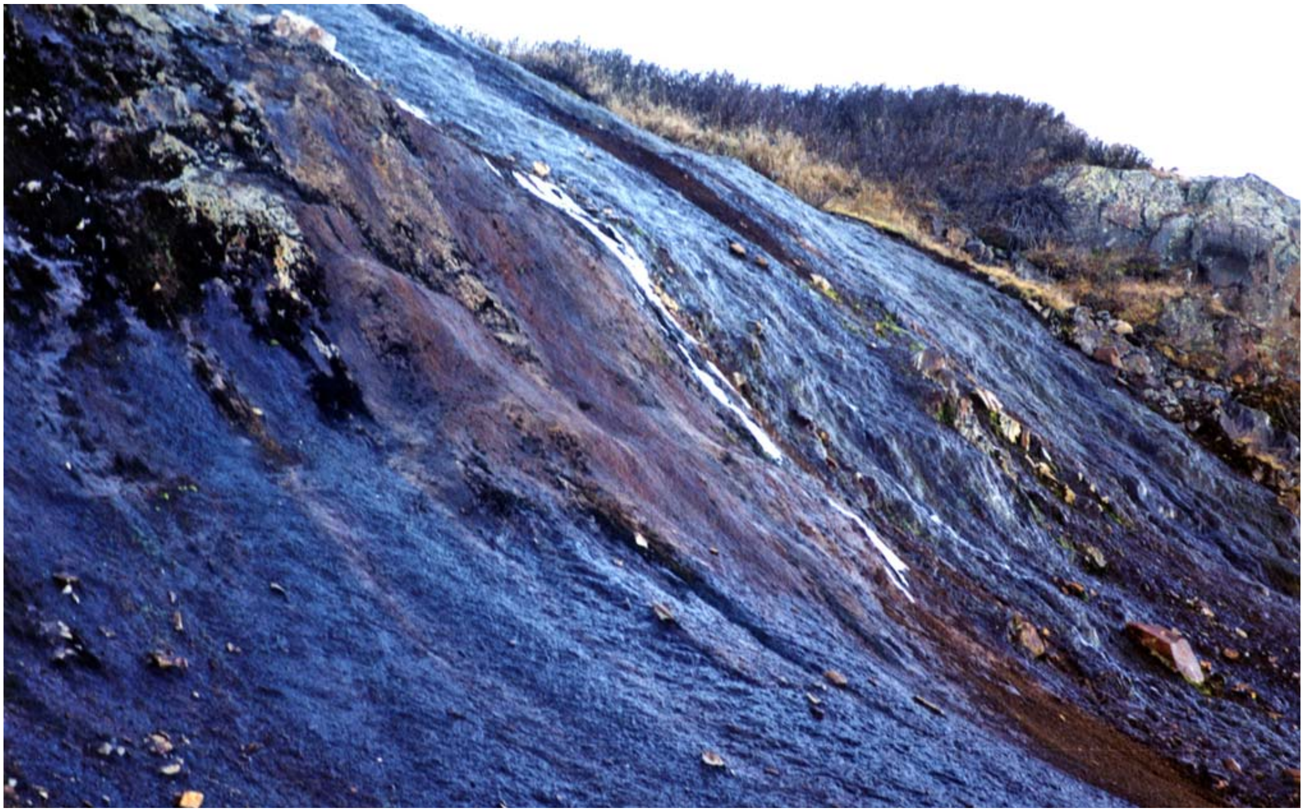


Figure 25. Ferrosinter deposit near water sample site NW-93, near Kite Lake.

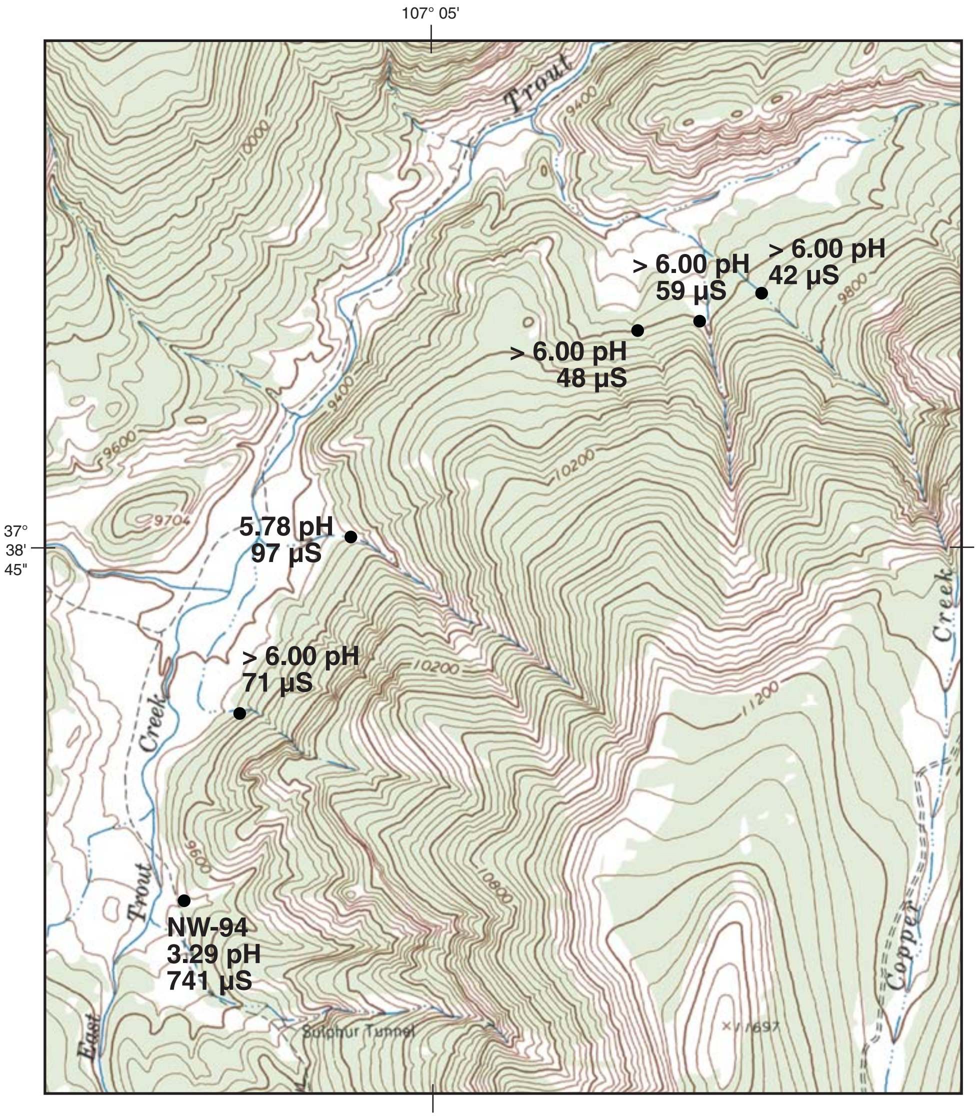
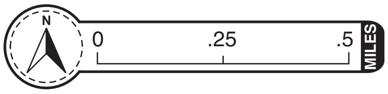
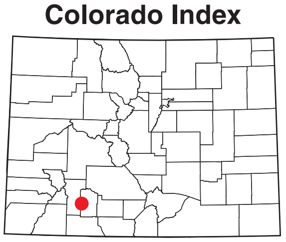


Figure 26. Map showing water sample site NW-94 and water test results near East Trout Creek.

Base map from USGS 7.5-min. Workman Creek quadrangle





EXPLANATION

● **NW-79** **4.70 pH** **343 µS**	Water sample location; lab sample ID no. and field measurement of pH and electrical conductivity in micro-siemens

pinkish, aphanitic porphyry with sparse disseminated pyrite; propylitically-altered, medium-grained intrusive rock with chlorite; bleached porphyry with a strong sulfur odor; and fragments of ferricrete. The stream had a flow of about 80 gpm with pH of 3.29 and EC of 741 µS/cm. Aluminum, iron, manganese, and sulfate exceeded State water quality standards (Appendix A-4). Other parameters with high concentrations included hardness (180 mg/L as $CaCO_3$), chloride (110 mg/L), silicon (24 mg/L), and sodium (8.2 mg/L).

Although rocks were altered on much of the ridge between Trout Creek and Copper Creek, water tests from tributaries of Trout Creek to the north, including Copper Creek, did not indicate significant influence from ARD (Figure 26), and no samples were collected for this investigation.

LA PLATA MOUNTAINS

The La Plata Mountains are about 10 mi northwest of Durango in La Plata and Montezuma counties, southwestern Colorado (Figure 1). Natural ARD emerges from several locations near the drainage divide between the La Plata and East Mancos Rivers. CGS mapped the hydrothermal alteration assemblages in an approximately 4 sq mi area **(Figure 27)**, and collected nine water samples and three rock samples in this study area.

GENERAL GEOLOGY

The La Plata Mountains represent the erosional remains of a domal uplift of about 6,000 vertical ft and about 15 mi in diameter. Doming resulted from the intrusion of several felsic to intermediate-composition stocks and sills during the Laramide Orogeny. In addition to the intrusive rocks, Pennsylvanian to Cretaceous sedimentary rocks are exposed. The sedimentary sequence has been subjected to folding, faulting, and localized areas of contact metamorphism (Eckel, 1949).

Geology And Hydrothermal Alteration of Allard Stock

The Allard stock, near the headwaters of Bedrock Creek (Figure 27), is one of the major intrusions of the La Plata Mountains (Figure 1). This multi-phase syenite stock hosts a sub-economic disseminated copper deposit that is partly exposed at the surface (Werle and others, 1984). Potassic, silicic, QSP, and argillic alteration are widespread and extend into country rock beyond the stock. Pyrite and chalcopyrite are abundant and are the dominant metallic minerals. Gold, silver, platinum, and palladium are present, primarily as telluride minerals (Eckel, 1949).

The area contains a sequence of westerly dipping Permian to Jurassic sedimentary rocks of the La Plata dome that have been intruded, metamorphosed, and altered by a series of Laramide diorite-monzonite porphyry sills and dikes and a large syenite stock (Eckel, 1949), named the Allard Stock by Werle and others (1984). Sedimentary rocks in the area include: the Permian Cutler Formation, composed of red, calcareous, limy shale, sandstone, and arkosic conglomerate; the Triassic/Jurassic Dolores Formation, composed of red shale and mudstone with sandstone and limestone conglomerate; the Jurassic Entrada sandstone, a ridge-former composed of massive, white, cross-bedded sandstone; the Jurassic Wanakah Formation which includes a marl member, a sandstone member, and the Pony Express Limestone Member; and the Jurassic Junction Creek Sandstone which is a massive, medium to fine-grained sandstone. Within the area, the sedimentary rocks are primarily composed of strongly silicified sandstones, or shales metamorphosed to hornfels. The marl beds were typically converted to contact metamorphic mineral assemblages of pyroxene, epidote, garnet, and quartz.

Near all of the syenite contacts, the silicified sedimentary rocks are fractured, brecciated, pyritized, and veined. Minor associated copper mineralization is common. Locally the thin Jurassic limestone beds (Pony Express Limestone member of the Wanakah Formation) are converted to massive coarse-grained pyrite and quartz with traces of chalcopyrite. This occurs on both sides of Burwell Peak and the east-west trending ridge north of Gibbs Peak (Figure 27).

Dikes and sills of diorite-monzonite porphyry are present in the area adjacent to the syenite stock. The diorite-monzonite porphyry is typically poorly exposed and argillically altered on the East Mancos River side of the drainage divide.

The syenite typically exhibits weak argillic and sericitic alteration with disseminated pyrite and chalcopyrite. Local QSP alteration is associated with prominent copper mineralization **(sample AS-1 in Tables 3 and 4)** and quartz-pyrite-calcite-fluorite veins (Figure 27). This alteration and veining is especially prominent in upper Bedrock Creek, above the Allard Tunnel (sample AS-4B in Figure 27; Tables 3 and 4). Copper mineralization extends up to the top of the ridge and is exposed in a large area near the head of Bedrock Creek. Local areas of visible copper mineralization were also identified near the head of Madden Creek (sample AS-3) and north of Gibbs Peak (locations 9, 11, and 12). At most locations with QSP alteration and veining, a zone of marginal argillic alteration with disseminated pyrite is also well developed (sample AS-2, locations 9 and 10).

Other than the Allard Tunnel, driven for exploration purposes, no significant mining has taken place in the area above the Copper Hill Mine (elevation 10,000 ft) just above the La Plata River in the Bedrock Creek drainage. No significant mining took place on the southeast side of the upper East Mancos River drainage. The Doyle group of mines, on the north side of the upper East Mancos River drainage and the south side of Jackson Ridge (located just due west of sample site NW-77, west of Figure 27), produced minor amounts of ore from pyritic gold deposits in veins and limestone replacement deposits (Eckel, 1949). All water and rock sampling done for this investigation was conducted in areas that appear to be hydrologically unaffected by the Doyle group of mines.

Geochemical anomalies in copper, arsenic, and fluorine (Werle and others, 1984) are prominent in the vicinity of the syenite stock. The anomalies appear to reflect the abundance of copper sulfides, copper

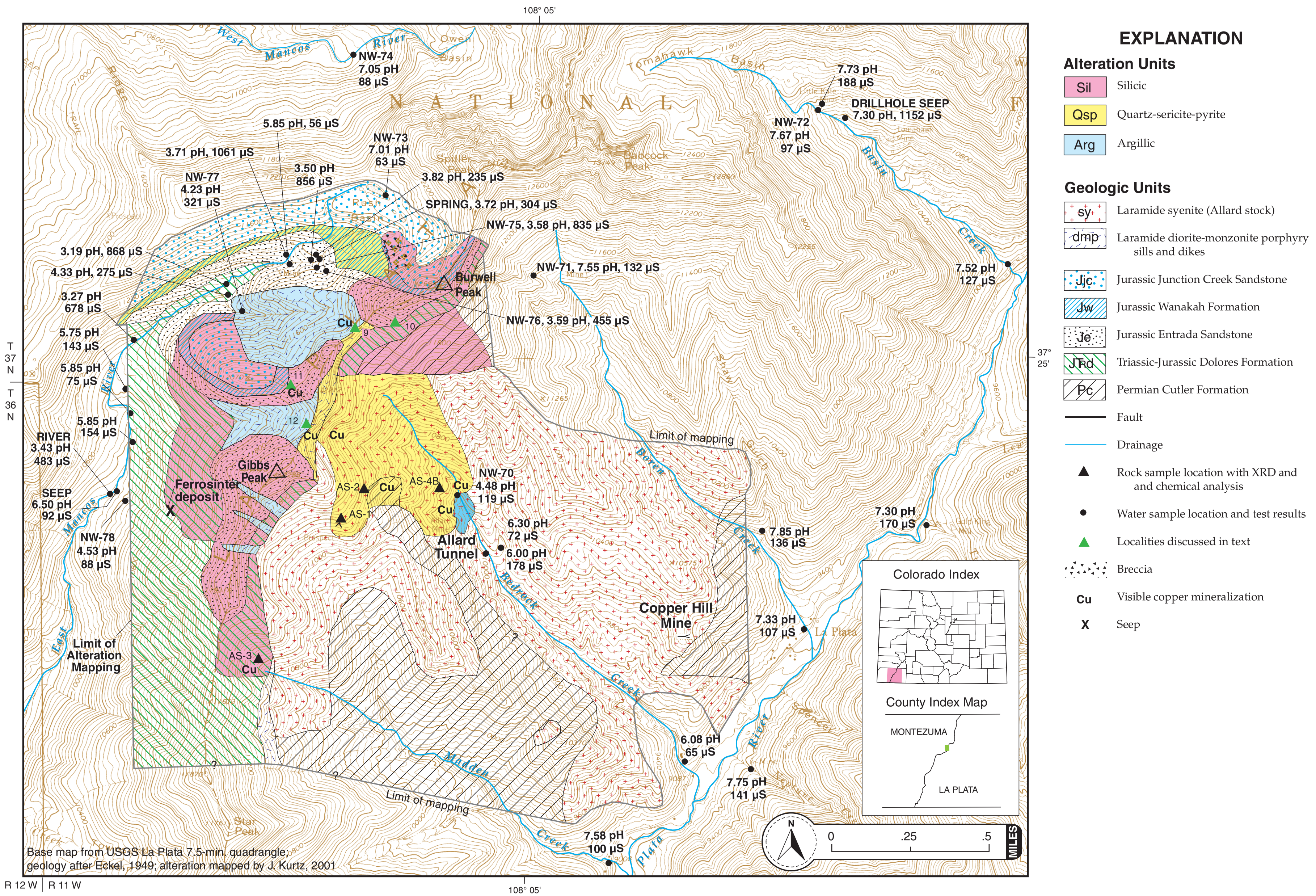


Figure 27. Map showing geology, hydrothermal alteration, rock and water sample sites NW-70 to NW-78, and water test sites in the La Plata Mountains.

Table 3. X-Ray diffraction results for rock samples from the Allard Stock area. (ND=not detected)

Sample	AS-1	AS-2	AS-4B
Assemblage	weak QSP	Weak Argillic	Weak Argillic
2nd Assemblage	Weak Argillic	Silicification	None
Quartz	major	major	Minor
Plagioclase	ND	ND	ND
Microcline	Major	ND	ND
Orthoclase	ND	minor	major
Dolomite	ND	ND	ND
Calcite	ND	ND	ND
Chlorite	ND	ND	ND
Kaolinite	minor	trace	Minor
Alunite	ND	ND	ND
Pyrophyllite	ND	ND	ND
Zunyite	ND	ND	ND
Sericite 1M	minor	ND	ND
Sericite 2M1	ND	ND	trace
Jarosite	ND	trace	ND
Pyrite	major	ND	ND
(Fe sulfate)	ND	ND	ND
Sphalerite	ND	ND	ND
Galena	ND	ND	ND
Hematite	ND	ND	ND
Anatase	trace	ND	ND

Table 4. ICP-AES Chemistry Results for Allard Stock rock samples.

Field No.	AS-1	AS-2	AS-4B
Sample Description	Wk QSP & weak ARG	Silicification & weak Argillic	weak Argillic
Al (%)	7.865	4.11	9.825
Ca (%)	0.025	0.05	0.035
Fe (%)	4.94	1.02	3.62
K (%)	6.81	4.71	7.7
Mg (%)	0.02	0.02	0.05
Na (%)	0.37	0.18	0.42
P (%)	0.115	0.035	0.07
Ti (%)	0.132	0.105	0.127
Ag (ppm)	10	<2	<2
As (ppm)	171	42	13
Ba (ppm)	265	656	1730
Bi (ppm)	<50	<50	<50
Cd (ppm)	<2	<2	<2
Co (ppm)	5	<2	<2
Cr (ppm)	3	2	4
Cu (ppm)	832	64	1180
Mn (ppm)	<4	28	6
Mo (ppm)	8	15	<2
Ni (ppm)	4	<3	<3
Pb (ppm)	138	120	17
Sr (ppm)	254	246	767
Zn (ppm)	16	4	27

sulfosalts, arsenopyrite, and fluorite in disseminated deposits and veins within the syenite and adjacent, altered sedimentary rocks. Werle and others (1984) reported the presence of chalcopyrite, arsenopyrite, bornite, enargite, chalcocite, and tennantite in veins in the area. Eckel (1938) also reported the presence of cuprite-bearing veins on the Copper Age claim near the Allard Tunnel. As an indication of the typical content of copper in rocks of the upper Bedrock Creek area, Eckel (1949) reported copper concentrations ranging from 0.15 to 0.55% along the length of the 740 ft long Allard Tunnel. Disseminated chalcopyrite-pyrite mineralization extends for at least 1,500 ft westward and at least 500 ft higher in elevation in the Bedrock Creek drainage from the Allard Tunnel. The three altered syenite rock samples that were chemically analyzed for this report contain enrichments in copper, arsenic, and possibly lead, with occasional molybdenum anomalies (Table 4).

Previous Water Quality Investigations

Acid rock drainage emerging in Rush Basin (south of NW-73) has formed an extensive bog-iron deposit along the East Mancos River. The deposit is up to 1,000 ft wide, 1.5 mi long, and up to 10 ft thick (Harrer and Tesch, 1959). Although this limonite deposit is downstream of a few small mines of the Doyle group, the deposit appears to predate mining activity. Water chemistry after the onset of mining may differ slightly from the pre-mining chemistry.

In the headwaters of the East Mancos River, on the north side of the Allard stock, Meyer and others (1996) collected five samples from the river, some seeps, and a small adit downstream from the other sample sites. All of the pH measurements were between 3.3 and 4. With the exception of one natural seep that contained high concentrations of dissolved metals, the natural waters and the adit effluent contained similar concentrations of most parameters. Metals with high concentrations included aluminum (>1,000 µg/L), copper (>200 µg/L), and zinc (>100 µg/L). Iron concentrations were above 5,000 µg/L in all but one of the in-stream samples.

Present Water Quality Investigations

Nine samples were collected in 1999 from the Allard stock area, from both the La Plata River drainage and the headwaters of the East Mancos River drainage (Figure 27). Sample NW-70 was collected upgradient from the Allard Tunnel, where a large subeconomic, disseminated copper occurrence is exposed at the surface. The sample site was at the base of a conspicuous cascade where Bedrock Creek flows across QSP-altered, mineralized intrusive rock with disseminated pyrite and chalcopyrite **(Figures 28 and 29)**. The intrusive rock at the cascade had a thin coating of hard, red precipitate and patches of copper carbonates. Stream gravel included mineralized intrusive rocks and fragments of ferricrete, and occasional weathered fluorite. The stream had a flow rate of 214 gpm, pH of 4.48, and

EC of 119 μS/cm. Copper, aluminum, manganese, iron, lead, zinc, and fluoride exceeded State water quality standards **(Appendix A-5)**. This was the only sample from the La Platas to show lead exceeding State standards. A water test in a tributary of Bedrock Creek, flowing from the northeast, indicated relatively clean water (pH of 6.3 and EC of 72 μS/cm). This water test result was similar to that from a water sample (NW-71) collected from the headwaters of Boren Creek (Table 9), just across the drainage divide (Figure 27).

Natural, iron-rich springs and seeps are present in several areas on the western side of the ridge. These typically form ferricrete deposits in small tributaries of the upper East Mancos River. The source for the metals in these seeps is probably the large masses of silicified and pyritized sedimentary rocks present at higher elevations (Figure 27).

Water sample NW-76 was from the headwaters of a small stream emerging from the heavily iron-stained, brecciated and silicified sandstone talus on the south side of Rush Basin (Figure 27). The channel was lined with old, partly eroded ferricrete **(Figure 30)**. Red precipitate was visible adjacent to seeps along the stream channel, and the stream bottom became completely coated with precipitate farther downstream. Flow in the stream was 18 gpm, pH was 3.59, and EC was 455 μS/cm. Aluminum, copper, manganese, zinc, cadmium, iron, and nickel exceeded State water quality standards (Appendix A-5). The sulfate concentration was just below standard.

Water sample NW-75 was collected a few hundred feet downstream from NW-76, but upstream from the stream's confluence with a larger stream that drains much of Rush Basin. The streambed was coated and

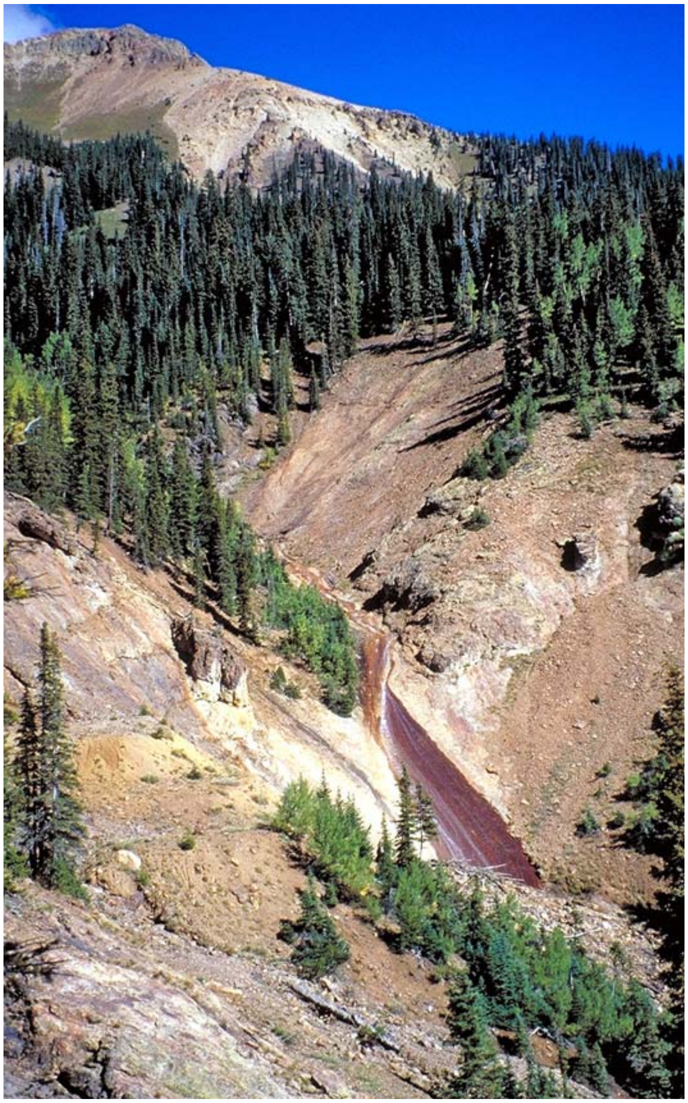


Figure 28. Bedrock Creek showing cascade flowing across precipitate-coated, QSP-altered and mineralized intrusive rock and altered slopes.

Figure 29. Water sample site NW-70 at base of cascade in Bedrock Creek.

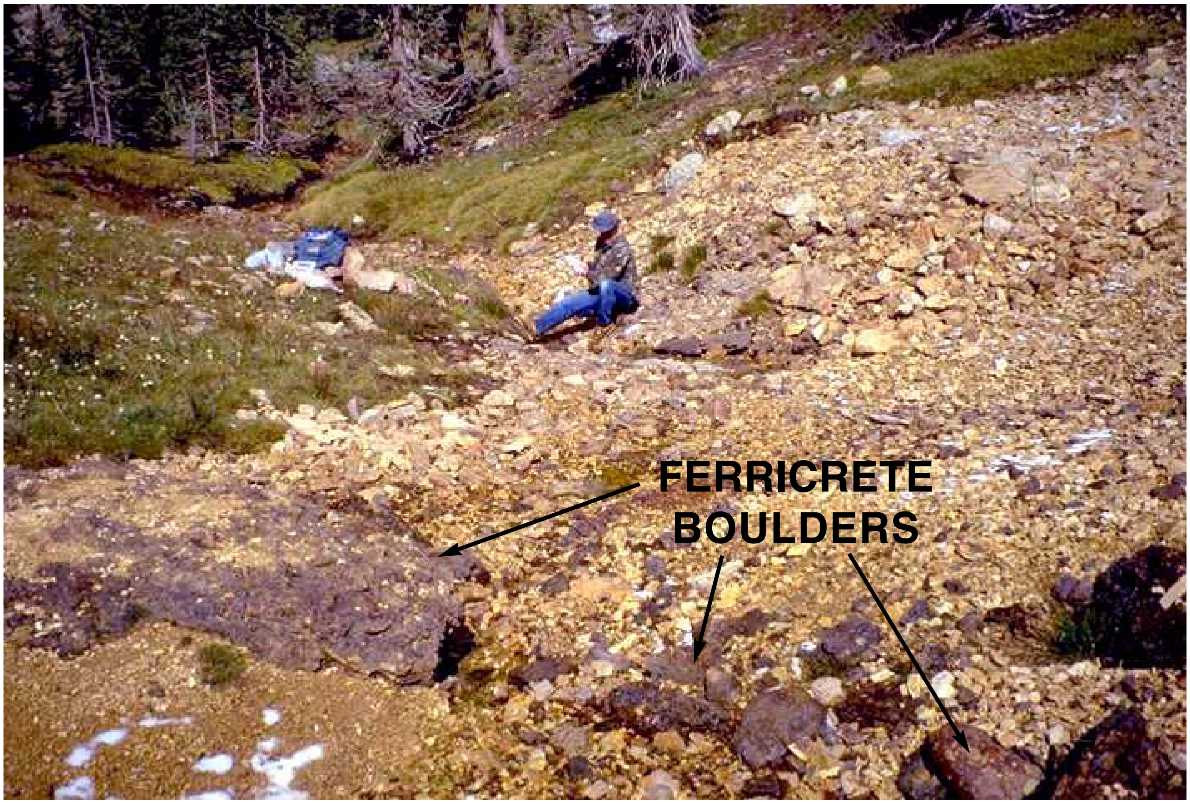


Figure 30. Weathered ferricrete west of Burwell Peak at water sample site NW-76.

terraced with actively forming red, brown, and yellow ferrosinter **(Figure 31)**. Flow was 42 gpm, pH was 3.58, and EC was 835 µS/cm. Concentrations of several metals were significantly greater than in the upstream sample; iron was about two orders of magnitude greater; copper, manganese, zinc, cadmium, aluminum, and nickel were significantly greater than in the upstream sample (Appendix A-5). In addition, arsenic, thallium, sulfate, and chromium exceeded State water quality standards. This sample had the lowest pH and highest concentrations of metals of all samples collected from the Allard stock area.

Sample NW-77 was collected from a stream draining the southwest side of Burwell Peak and the large area of argillic-altered diorite-monzonite porphyry (Figure 27). The stream channel and banks were composed almost exclusively of loose material derived from the steep overlying slopes. Almost no vegetation was present, and the channel had the appearance of an active and unstable debris flow. Stream gravel included pyritized and clay-altered diorite-monzonite porphyry, silicified-pyritized sandstone, relatively fresh diorite and hornfels, and broken pieces of ferricrete. Pyrite was common, whereas chrysocolla and chalcopyrite were sparse. Streamflow was measured at 65 gpm, pH was 4.23 and EC was 321 µS/cm. Aluminum, cadmium, copper, manganese, and zinc exceeded State water quality standards. The iron concentration of 11 µg/L (trec) is unusually low (Appendix A-5).

A small, dark red-brown ferrosinter deposit is visible on the west side of Gibbs Peak **(Figure 32)**. Sample NW-78 was collected from a small stream that drains the deposit. Alluvial material included silicified siltstone, contact-metamorphosed marl, and brown- and red-stained quartzite. The stream channel had abundant, unconsolidated, red precipitate. Flow was 28 gpm, pH was 4.83, and EC was 88 µS/cm. The copper concentration significantly exceeded the State water quality standard, but was low compared to samples collected farther north. This sample was collected near the outer limit of known copper mineralization. Manganese, zinc, and aluminum also exceeded standards (Appendix A-5).

Numerous water tests were conducted in the main branch of the East Mancos River and from side seeps and tributaries (Figure 27). The tests indicated that waters in most of the seeps and tributaries in this part of the East Mancos drainage basin are slightly acidic and may have high concentrations of metals. The main stem of the East Mancos River exhibits significant affects of ARD. At the lowest (downstream) test site, the East Mancos River had pH of 3.43 and EC of 483 µS/cm, similar to the natural ARD of sample NW-76. The streambed was coated with red precipitate. Past

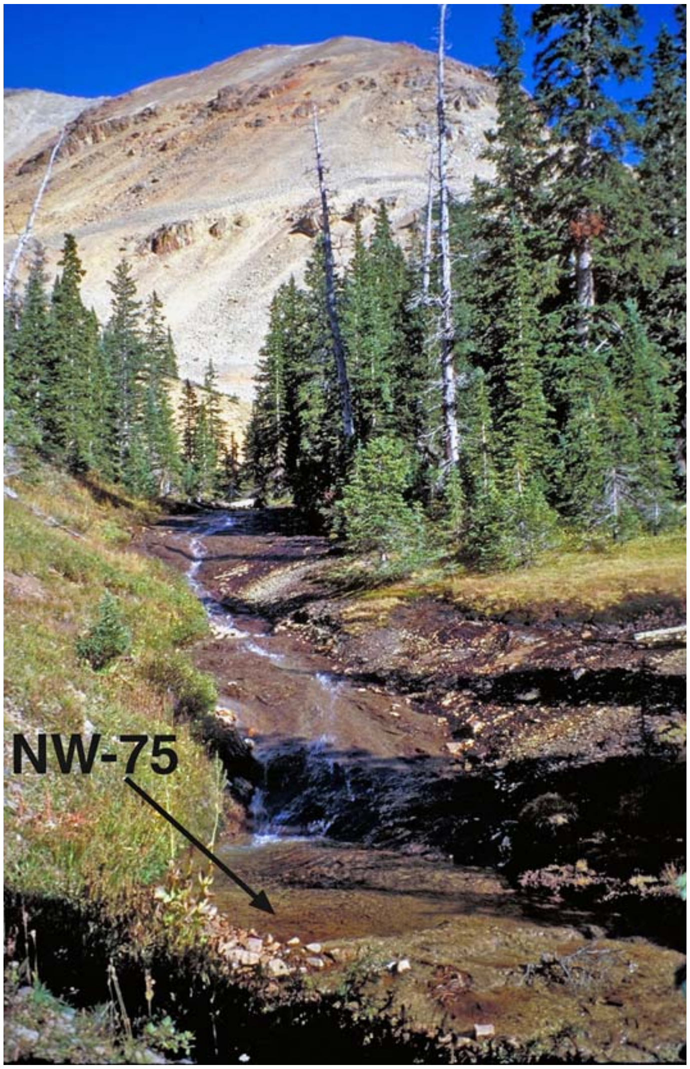


Figure 31. Water sample site NW-75 and terracettes of ferrosinter.

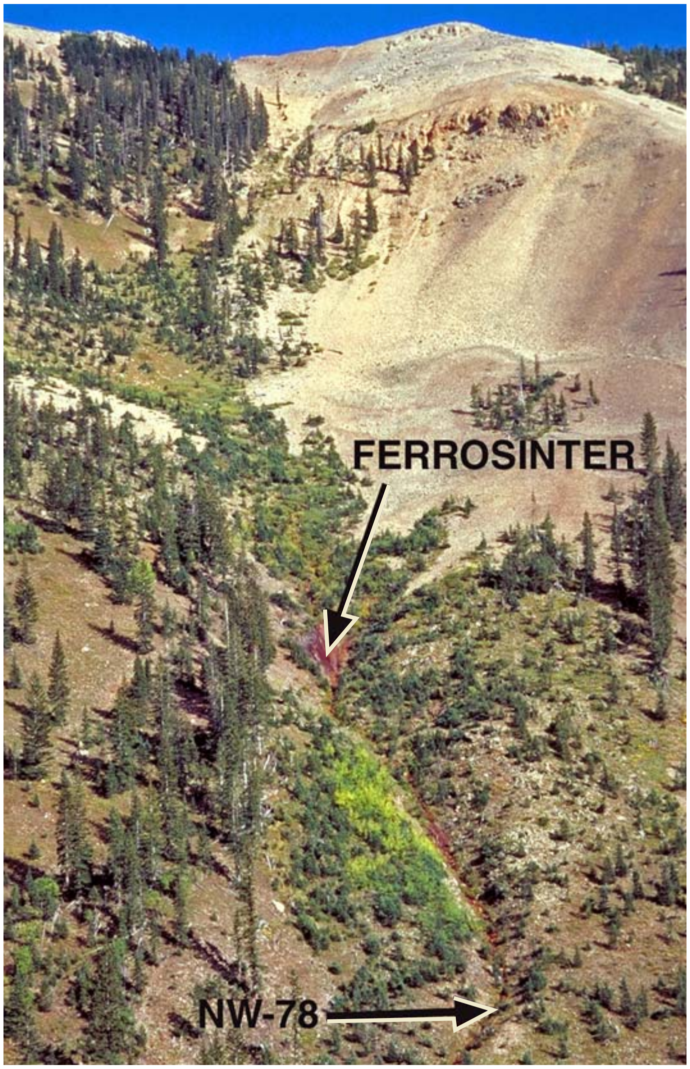


Figure 32. Ferrosinter deposit and water sample site NW-78 on west side of Gibbs Peak.

mining activities between this test site and the upper sample sites may affect water quality, but the effects are apparently dwarfed by the ARD runoff from the large exposures of altered bedrock and talus farther upstream.

Four of the water samples collected in the northern part of the La Plata Mountains study area (samples NW-71 to NW-74) were relatively clean and within State standards for all analyzed parameters (Appendix A-5), despite being collected from areas of hydrothermally altered sedimentary bedrock. An inactive, hard, and partly eroded ferricrete deposit is adjacent to the Boren Creek sample site (NW-71), and pyrite was visible in some of the alluvial material in Boren and Basin Creeks in the vicinity of sample site NW-72. However, both samples had similar metal concentrations and were relatively clean. Both of these sites were beyond the known area of disseminated copper mineralization and the outcrop of the Allard stock syenite. The absence of ARD in these areas may be related to the presence of large expanses of calcareous Cutler Formation forming the bedrock as opposed to the dominance of syenite in the Bedrock Creek drainage. Water tests of several other tributaries of the La Plata River indicated no serious ARD (Figure 27), and no additional samples were collected. Even though historic, small-scale gold mining occurred in upper Boren Gulch (Eckel, 1938; Eckel, 1949), no significant ARD was identified in the related water samples.

Sample NW-73, collected from a glacial lake at the headwaters of the East Mancos River above Rush Basin (Figure 27), was relatively clean, with pH of 7.01 and EC of only 63 µS/cm (Appendix A-5). Most of the sandstone bedrock above this sample lacked the prominent red, iron-staining prevalent near sites NW-75 to NW-78 and appears to show minimal alteration.

Sample NW-74 was from the West Mancos River downstream from Owen Basin (Figure 27). Although iron-stained and silicified sandstone is exposed above the sample site, and specularite and calcite were visible in the alluvium, the sample was relatively clean, with pH of 7.05 and EC of 88 µS/cm. Ferricrete and ferrosinter deposits with associated acidic, metal-rich springs reportedly exist downstream from site NW-74 (Benson and Nichols, 1998). Although some of these springs are associated with small mines, the mines likely were driven to explore fault zones where ARD emerged and formed precipitate deposits, an obvious mineral exploration target. These downstream sites were not visited during this study.

ARD in the Allard stock area is most clearly related to the areas with known, exposed copper mineralization and silicic to QSP alteration within and immediately adjacent to the syenite. Locally anomalous copper, arsenic, and fluoride concentrations in the waters are consistent with the presence of disseminated copper, arsenic, and fluorine-bearing minerals in the syenite and immediately adjacent rocks.

RICO MOUNTAINS

The Rico Mountains are in southwest Colorado, near the headwaters of the East and West Dolores Rivers (Figure 1). The town of Rico and the Rico and Dunton mining districts are within the mountain range. Waters affected by ARD that were sampled for this study originate in the Calico Peak-Eagle Peak area, and from Darling Ridge, which is between Rico and Dunton. Six water samples were collected during this reconnaissance-level investigation.

GENERAL GEOLOGY

Rocks exposed in the Rico area range in age from Precambrian to Tertiary. Within the area sampled for this report, the exposed sedimentary rocks include the Pennsylvanian Hermosa Formation, the Permian Cutler Formation, the Triassic Dolores Formation, the Jurassic Entrada and Wanakah Formations and the Jurassic Morrison Formation. The nearly 3,000-ft-thick Hermosa Formation is the most commonly exposed sedimentary sequence and consists of interbedded sandstones, arkoses, shales, conglomerates, limestones, dolomites, and gypsum (Pratt and others, 1969).

At least three magmatic intrusive episodes have affected the Rico area. Laramide-age latite porphyry sills and dikes are common throughout the district. In late Laramide time, a monzonite stock up to 2 mi wide intruded the rocks on the west side of the Dolores River. Intrusion of the monzonite stock and the associated hydrothermal fluids probably caused much of the replacement- and vein-type mineralization of the Rico mining district (Pratt and others, 1969). Much younger, Pliocene dikes and small stocks of alaskite are presumably related to deeply buried stockwork molybdenum occurrences (Anaconda Collection; Neubert and others, 1992).

Intrusion of the igneous rocks formed a structural dome about 6,000 ft high and 5 to 10 mi in diameter. Faulting, folding, and tilting of the sedimentary rocks in the Rico area accompanied the doming event. Some of the faults provided channels for injection of mineralizing fluids into adjacent sedimentary rocks and formation of vein deposits. Large quantities of silver, lead, zinc, and sulfuric acid (from pyrite) were produced from replacement and vein-type deposits in the Rico area. Gold and copper were byproducts of mining (Pratt and others, 1969). At least one deeply buried, sub-economic, stockwork molybdenum deposit exists (Anaconda Collection; Neubert and others, 1992).

At Calico Peak and Johnny Bull Mountain, about three miles west-northwest of Rico, Tertiary latite-porphyry dikes and plugs intruded Permian Cutler Formation. The igneous plug at Calico Peak and the surrounding sedimentary rocks, adjacent to faults and fractures, have been intensely altered. The alteration occurred in at least two stages – an earlier episode of adularia-sericite type hydrothermal alteration followed by a late stage consisting of acid-sulfate alteration. Many of the original minerals, especially the feldspars, have been altered to clay and disseminated or oxidized pyrite (limonite, goethite, hematite) is common. Alunite and jarosite are also present (Pratt and others, 1969; Miller and McHugh, 1999).

The Darling Ridge area is composed of arkoses, limestones and shales of the Permian Hermosa Formation cut by a monzonite porphyry stock.

Gases are often associated with springs in the Rico-Dunton area. Carbon dioxide and hydrogen sulfide gases are common in the mines. Small bubbles of gas were observed emerging from fractured bedrock exposed in some of the streambeds.

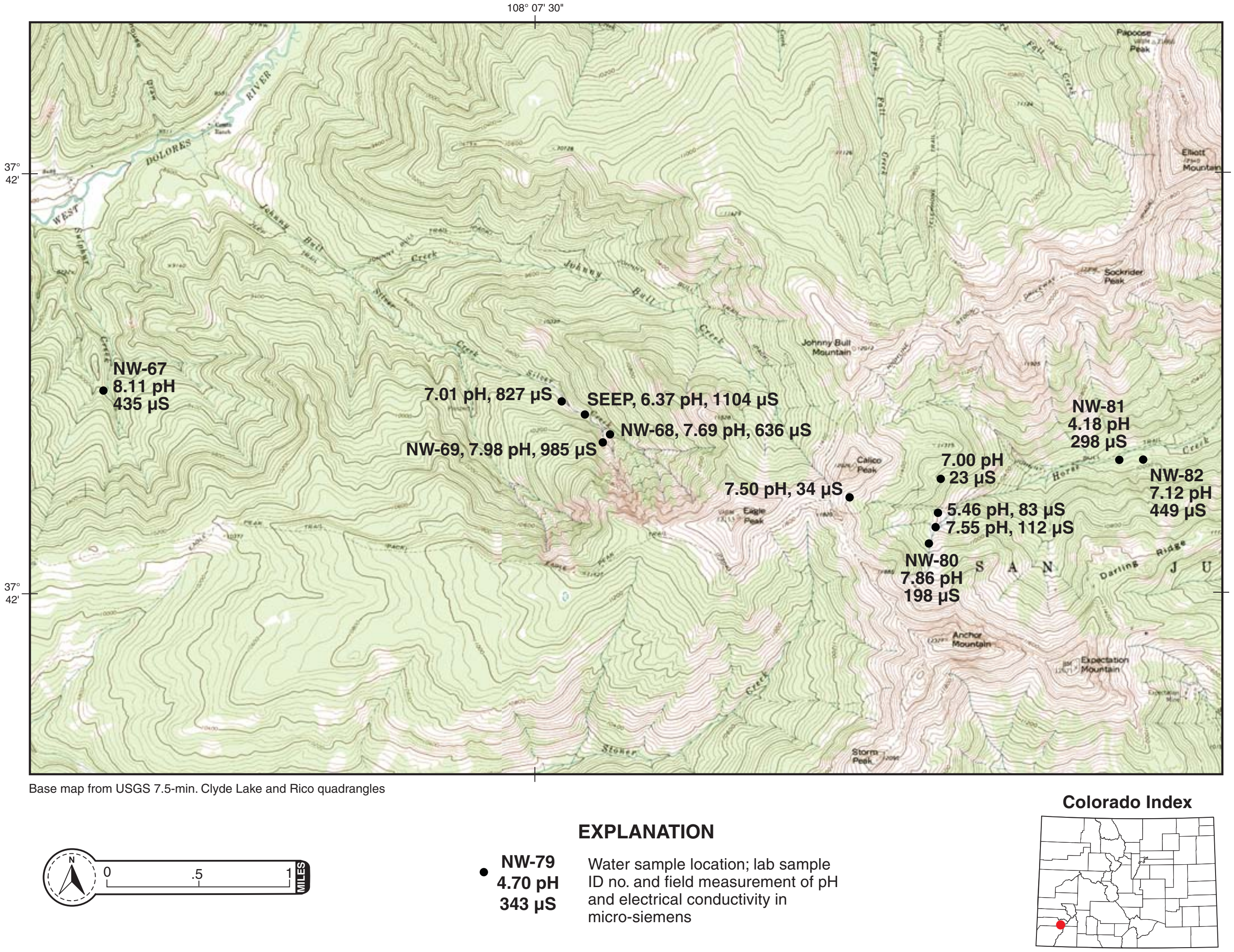
Previous Water Quality Investigations

Harrer and Tesch (1959) reported ferruginous springs in the area of Silver Creek, in the northern and western branches of upper Horse Creek, and in lower Horse Creek **(Figure 33)**. Horse Creek is northwest of Rico and drains the western side of the intensely altered terrane of Calico Peak and Johnny Bull Mountain. The springs have deposited limonite in swampy areas of the stream valley. The limonite deposits were recorded as early as 1900 (Harrer and Tesch, 1959), and probably predate the mining activity in these drainage basins. Upstream mining activity was small scale and not shown on maps of the area. The limonite deposits are probably not the result of the mining activity, although the chemistry of the springs could have been slightly altered after the onset of the activity.

Present Water Quality Investigations

Sample NW-67 was collected from Sulphur Creek, upstream from some small surface and underground sulfur mines (Figure 33). Streamflow was 90 gpm, pH was 8.11, and EC was 435 µS/cm. The water had relatively high hardness (224 mg/L as $CaCO_3$) and did not exceed State water quality standards in any of the analyzed parameters **(Appendix A-6)**. Zinc, iron, and manganese concentrations were slightly elevated (19, 28, and 13 µg/L respectively), but well within State standards. No sample was collected downstream from the sulfur occurrences because mining-derived versus natural discharges could not be distinguished.

Samples NW-68 and NW-69 were from the upper forks of Silver Creek, upstream from the Rosebud Mine and a few small sulfur occurrences (Figure 33). Bedrock adjacent to the sample sites included red beds of the Morrison and Dolores Formations cut by altered porphyry dikes **(Figure 34)** and sometimes overlain or flanked by secondary deposits of "claycrete", where pebbles and gravels of various compositions are cemented by light-colored clay. The "claycrete" is generally soft, but is locally indurated. Altered igneous rocks exposed upstream of the sample site at Calico Peak are known to contain alunite (Miller and McHugh, 1999). Alluvium in the stream channels includes medium- to coarse-grained red arkose, fine-grained gray and nearly white sandstone with some calcite in the matrix, and porphyritic igneous rocks. The porphyry shows various degrees of alteration, from completely argillized into clay, to fresher material with intense red stain and minor pyrite. A strong smell of sulfurous gas is present throughout this area.



Base map from USGS 7.5-min. Clyde Lake and Rico quadrangles

Figure 33. Map showing water sample sites NW-67 to NW-69, NW-80 to NW-82, and water test results in the Rico-Dunton area.

Sample NW-68 was collected from the main fork of Silver Creek (Figure 33). Streamflow was 150 gpm, pH was 7.69, and EC was 638 µS/cm. The stream water had elevated hardness (314 mg/L as $CaCO_3$) and alkalinity (125 mg/L as $CaCO_3$). Manganese was the only analyte to exceed its State water quality standard; sulfate was elevated (130 mg/L) but within standard (Appendix A-6). Because of the relatively high hardness of the sample (due to calcium), detection limits for copper and zinc were about 10 times higher than normal, and therefore the concentrations of these metals could not be accurately measured.

Sample NW-69 was from the west fork of Silver Creek, about 100 ft downstream from the outcrop of an argillic-altered, porphyry dike that crosses the stream channel (Figure 34). The water was slightly turbid, and red and yellow precipitate was visible in the stream channel. Streamflow was 18 gpm, pH was 7.98, and EC was 985 µS/cm. Hardness was relatively high at 620 mg/L. Manganese, and iron concentrations exceeded State water quality standards. Aluminum was very high at 1000 µg/L, but basic pH and water hardness caused the standard to exceed 3000 µg/L. Sulfate was relatively high at 210 mg/L (Appendix A-6). Similar to NW-68, detection limits for copper and zinc were about 10 times higher than normal and these elements were not detected. Large differences between total and dissolved concentrations of aluminum and iron indicate that compounds of these elements are present as suspended solids.

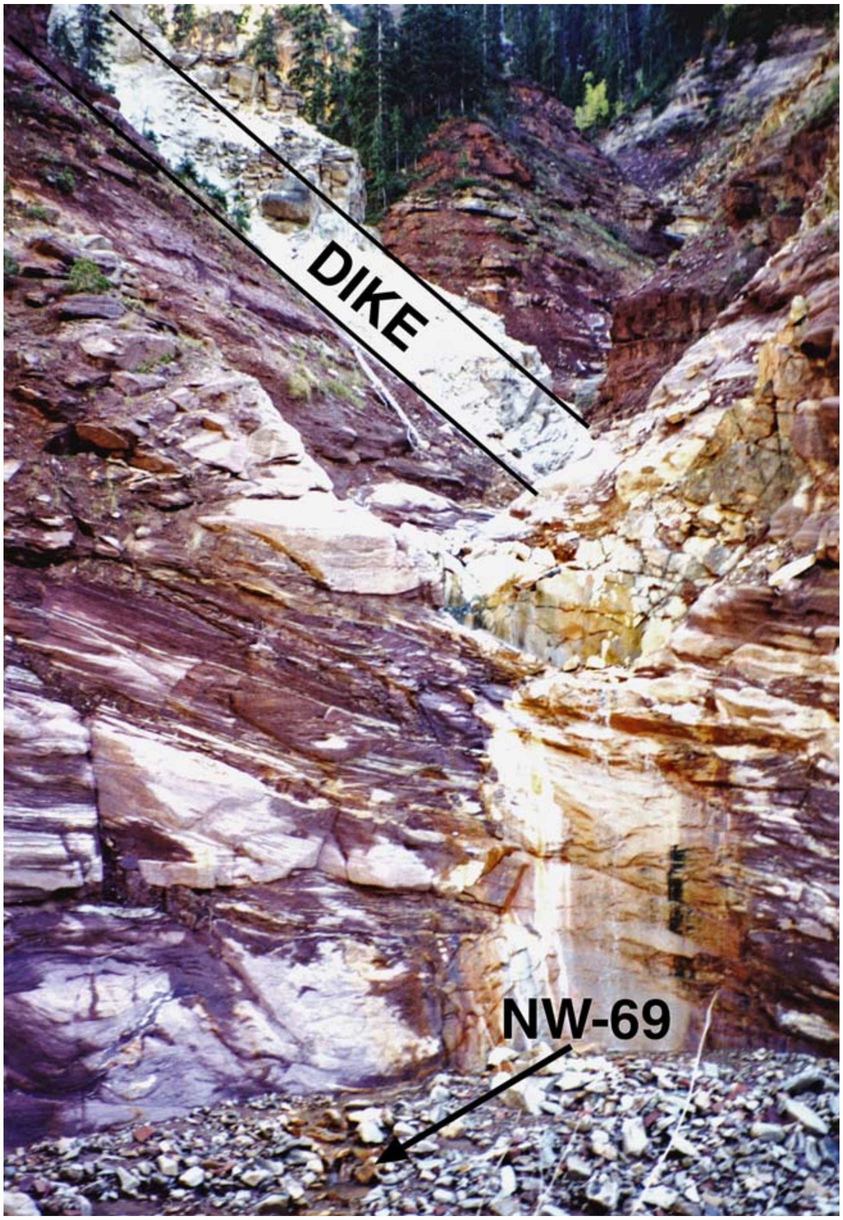


Figure 34. Water sample site NW-69 and porphyry dike in upper Silver Creek.

Sample NW-80 was from near the headwaters of Horse Creek which drains the Anchor Mountain area (Figure 33). Red staining appears on the bedrock and talus above the sample site. Flow was 150 gpm, pH was 7.86, and EC was 198 µS/cm. Despite the weakly altered rock above the sample site, this water displayed no significant effects of ARD and did not exceed standards in any of the tested analytes (Appendix A-6).

Sample NW-81 was collected from one of several springs emerging from and adjacent to an iron bog on the south side of Horse Creek **(Figures 33 and 35)**. Flow was estimated at 100 gpm for the series of springs. At the sample site, the pH was 4.18 and EC was 298 µS/cm. Manganese, aluminum, copper, zinc, cadmium, and iron exceeded State water quality standards (Table 10).

Sample NW-82 was from a steep gulch that borders the east side of the iron bog (Figure 33). Exposed bedrock higher in the gulch appeared altered and was stained dark brown to almost black **(Figure 36)**. This area was mapped as a landslide deposit by Pratt and others (1969). Alluvial material at the site included fresh diorite and altered porphyry. Some of the altered rocks were bleached, chalky, and friable; others were silicified with pyrite as veinlets or disseminated.

Flow was 23 gpm, pH was 7.12, and EC was 449 µS/cm. Hardness was 189 mg/L. Manganese concentration was 50 times higher than the State standard. Sulfate was elevated, but within standard (Appendix A-6). Yellow precipitate accumulated on the filter during the sampling, and large differences between the total and dissolved aluminum and iron concentrations indicate that these elements are present as suspended solids. This sample site was above a nearby caved adit that was draining ARD with pH of 6.03 and EC of 388 µS/cm. The effluent was forming a terraced ferrosinter deposit on the associated waste rock pile.

The carbonate-bearing sedimentary rocks in the Rico Mountains have apparently contributed to ARD neutralization, as evidenced by high concentrations of calcium and high hardness of most water samples. Sample NW-81, a spring, is the only water exhibiting a low pH. Carbonate neutralization of ARD does not completely remove the deleterious effects of ARD, because total dissolved solids are elevated and at least one metal (Mn) still exceeds standard in near-neutral pH water samples. Gypsum dissolution from the Hermosa Formation may also contribute to the high sulfate and calcium content of the waters.

Figure 35. Water sample site NW-81 at wetlands with acidic iron bog along Horse Creek.

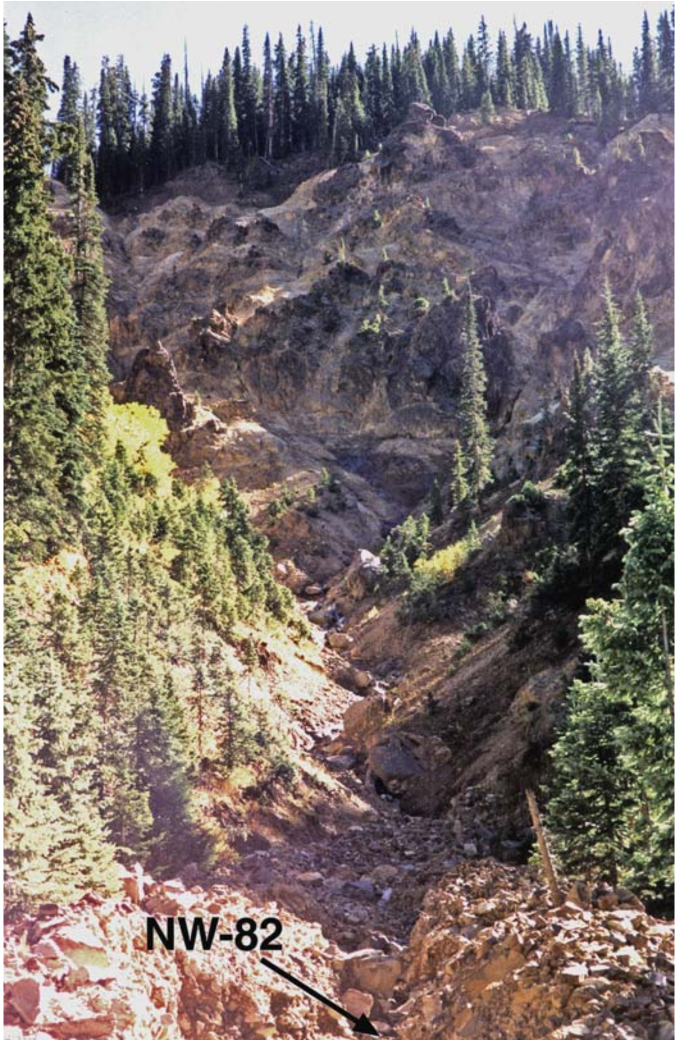


Figure 36. Water sample site NW-82 in an altered gulch draining into Horse Creek.

5

WEST-CENTRAL COLORADO

Areas investigated in west-central Colorado include altered areas associated with the Grizzly Peak caldera in the Sawatch Range, and parts of the Ruby Range near Crested Butte (Figure 1). Detailed mapping of hydrothermal alteration was conducted in the vicinity of Red Mountain to accompany the water sampling. In addition, rock samples were collected for geochemical characterization.

GRIZZLY PEAK CALDERA

The Grizzly Peak caldera is about 10 mi wide and straddles the Continental Divide (Figure 1), extending about 12 mi southward from Independence Pass, within and adjacent to the Collegiate Peaks Wilderness Area. The Red Mountain **(Figure 37)** and East Red Mountain (Figure 38) areas lie within the Grizzly Peak caldera. “East Red Mountain” is on the eastern boundary of the caldera (note: Cruson (1973) and Fridrich and others (1991) labeled this area “East Red Mountain,” although it has no name on the Independence Pass 7.5-minute topographic map). Red Mountain is in the central portion, and the headwaters of New York and Bowman Creeks are near the western boundary (Cruson, 1973; Fridrich and others, 1991; Tweto and others, 1978). ARD originates on both sides of the Continental Divide, affecting Lincoln Creek (Roaring Fork watershed on Figure 1) on the west side and South Fork of Lake Creek on the east side (Figure 37).

GENERAL GEOLOGY

About 39 Ma, prior to formation of the Grizzly Peak caldera, numerous rhyolitic stocks and dikes were emplaced in an arcuate zone of fractures that encircled and included the site of the future caldera. Circulation of hydrothermal fluids related to this pre-caldera magmatism caused widespread alteration and formed porphyry molybdenum/copper deposits and gold-bearing quartz-pyrite veins (Cruson, 1973; Fridrich and others, 1991).

The Grizzly Peak caldera is slightly older than the calderas of the San Juan Mountains, and resulted from eruption of the rhyolitic Grizzly Peak Tuff between 37 and 32 Ma. During subsidence, an inner ring-fracture zone formed because of substantial differences in depths of collapse within the caldera. Caldera resurgence caused by emplacement of a granodiorite laccolith resulted in a complexly faulted dome. Post-caldera, intermediate-composition dikes and small stocks later intruded the fault zones in the resurgent dome (Fridrich and others, 1991).

The caldera is an Oligocene (Fridrich and others, 1998) calc-alkaline construct that has formed largely above and within rocks of Precambrian age. The dominant rock unit within the caldera is the Grizzly Peak tuff, a phenocryst-rich, lithic, lapilli ash-flow tuff that varies in composition from high- to low-silica rhyolite. Caldera collapse breccias (megabreccias), composed largely of Precambrian wall-rock clasts, are prominent in the East Red Mountain area. Numerous intermediate to felsic composition dikes and plutons related to the caldera appear within and on the margins of the caldera.

Hydrothermal alteration is prominent in several areas within the caldera, most notably the Red Mountain and East Red Mountain areas. While historic prospecting has occurred in the two map areas, no significant mining activity occurred on the eastern side of the Continental Divide in the Red Mountain area, or in the East Red Mountain area. One exploration tunnel 1,275 ft long was driven in the southwestern part of the East Red Mountain area (the Burge Tunnel) at an elevation of about 12,600 ft (Figure 37).

RED MOUNTAIN

Geology

Both Fridrich and others (1998) and Holtzclaw (1973) mapped a small, north-south trending, Tertiary quartz-latite porphyry stock (Tqlp) on the western side of the Continental Divide on the southwestern flank of Red Mountain (Figure 37). The stock is strongly hydrothermally altered and weathered, making its distinction difficult, therefore, contacts on the geologic map are only approximate. The stock contains quartz-molybdenite-pyrite stockwork veins in a quartz-sericite-pyrite (QSP) matrix. This intrusive is the likely cause of the extensive alteration of the Red Mountain area. Within the mapped area (Figure 37), Tertiary igneous rocks and rocks related to caldera collapse are common. These include dikes of quartz-latite and dacite porphyry;

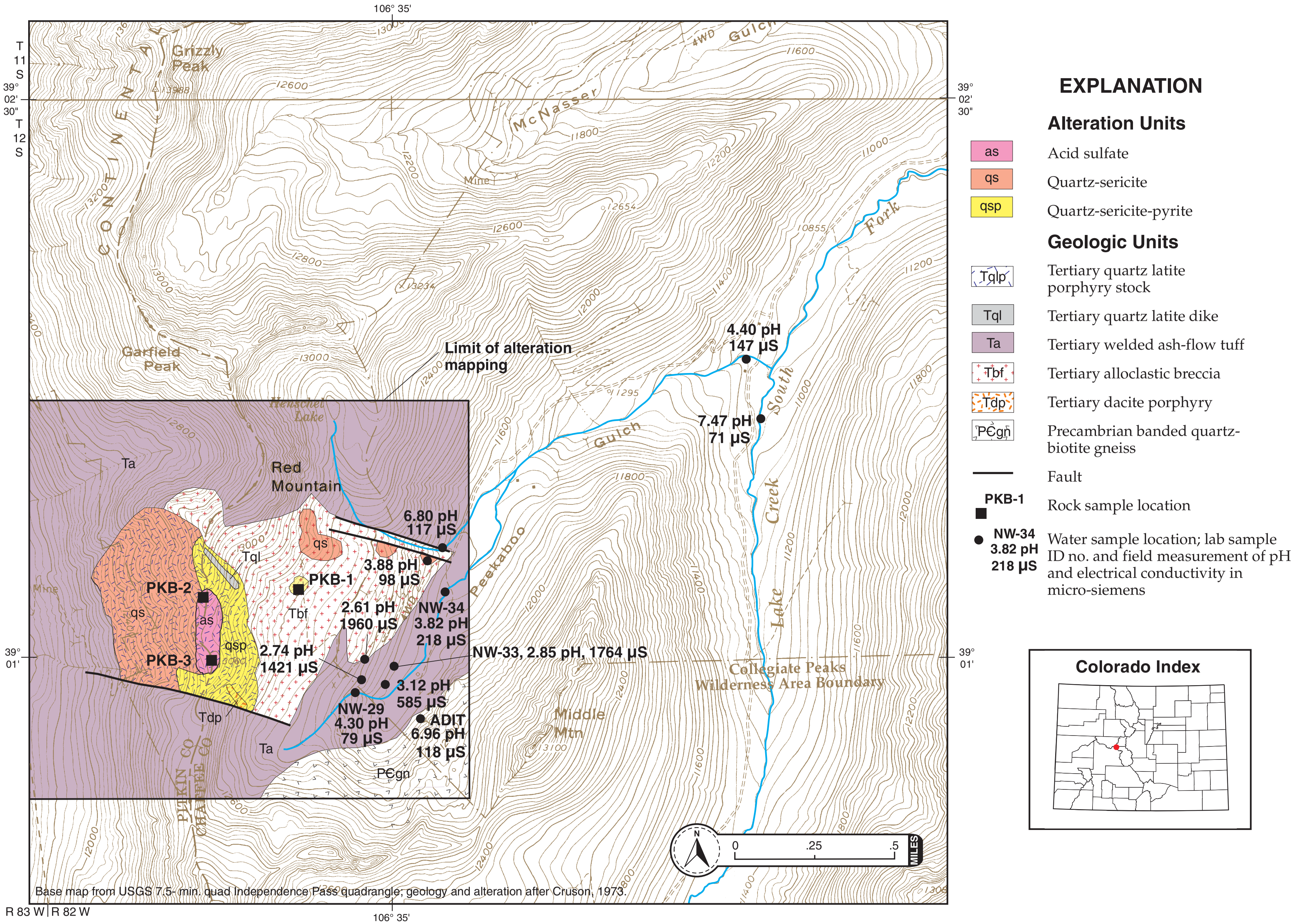


Figure 37. Map showing geology, hydrothermal alteration, sample sites, and water test results in the Grizzly Peak caldera, Red Mountain area.

quartz-latite porphyry stocks; the Grizzly Peak quartz-latite to rhyolite welded ash-flow lithic tuff; and a megabreccia composed of large, well-indurated Precambrian rock fragments with weak chloritic alteration. Exposures are limited due to the extensive alteration and steep slopes covered with talus.

Structure

Several structural features are important in the area (Figure 37). Two prominent dikes with N60W trend were mapped. These may be aligned with the southwestern ring-fracture zone of the central caldera block. A N60W biotite-latite dike (Tql - granodiorite of Cruson, 1973), 30 ft wide at the ridgetop, marks the main northern edge of the QSP-altered zone, discussed below. The tuff on the northern side of the dike is slightly argillized. Blocks of fresh biotite-latite are locally present on the south side of the dike.

A N60W dacite porphyry dike (Tdp - granodiorite of Cruson, 1973), extends across the ridge near the southern end of the altered zone. Holtzclaw (1973) indicates that this dike contains a high percentage of deuteric magnetite. Minor sericite was also identified. A N80W fault, marked by numerous seeps, bounds the southern end of the alteration zone.

Alteration

Acid-sulfate alteration, composed of the assemblage quartz-sericite-alunite-pyrophyllite was identified by X-ray diffraction analyses of sample PKB-2 **(Table 5)**, taken from an elevation of 13,100 ft on the ridgeline north of the point at 13,060 ft (Figure 37). Some pyrophyllite was also present in sample PKB-3 on the peak at 13,060 ft and a trace was present in PKB-1 collected from a prospect along a drill road at about 12,400 ft. The full extent of this acid-sulfate alteration is unknown, but it appears to extend over a significant vertical range on Red Mountain. Quartz-sericite alteration (QS) is prominent along the ridgeline (sample PKB-3), on the west side of the divide and in local areas near northwest-trending faults.

QSP is the dominant alteration type present on the upper east slopes of Red Mountain. Similar alteration was seen in a sample taken at a small open cut along the drill road at an elevation of 12,400 ft (sample PKB-1). Argillic alteration is most prominent on the western side of the Continental Divide, but was not mapped during this project.

Mine Workings

Mine workings are limited in the area. They include several small prospect pits about 5 ft across located in the lower ferricrete zone of alloclastic breccia. An open cut (25 by 25 ft), with inclined drill hole, is located along the drill road at 12,400 ft elevation (sample PKB-1). At the upper end of the drill road there is a prospect pit measuring 20 by 30 ft, with a few timbers lying on the ground nearby.

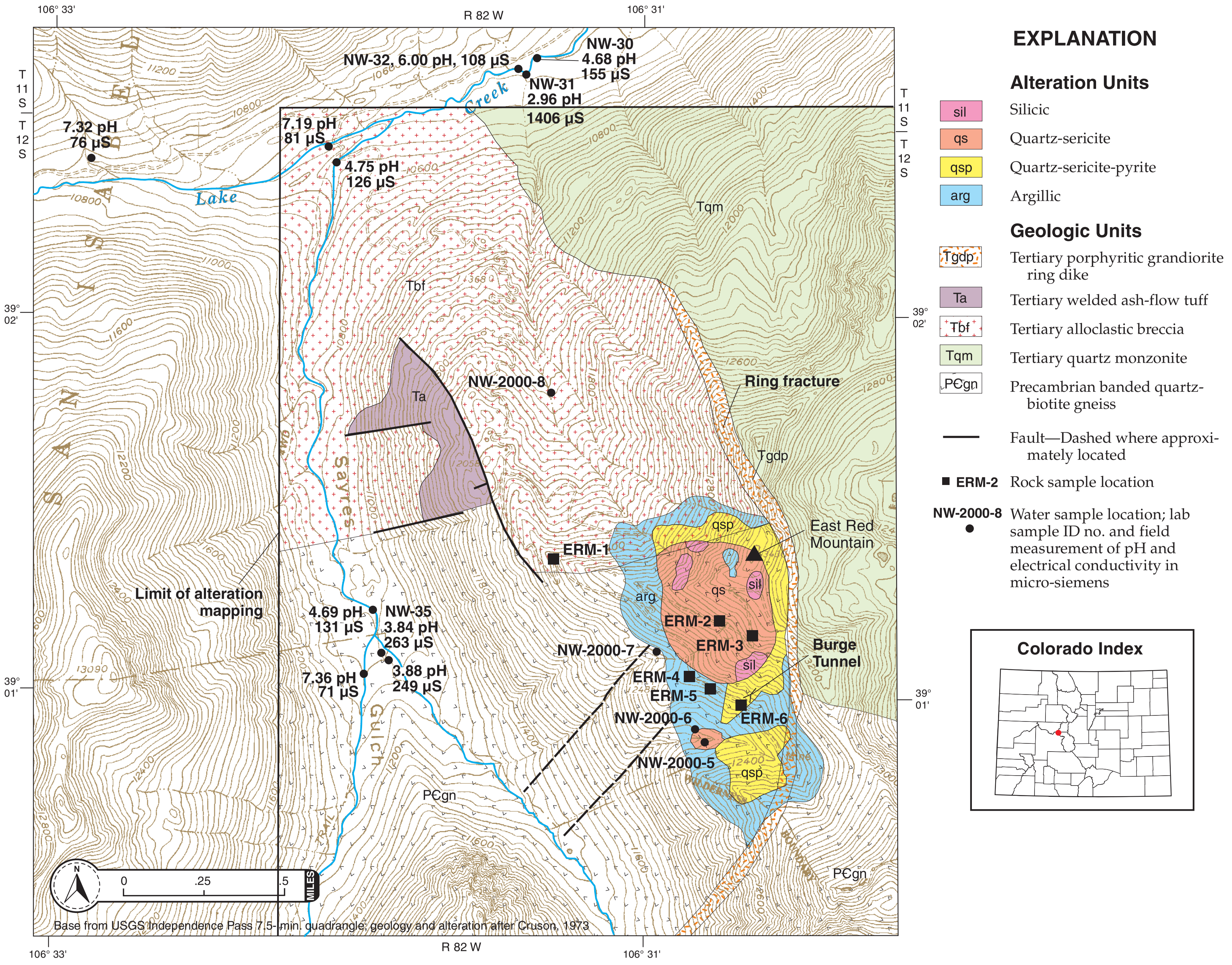
Table 5. X-Ray diffraction results for rock samples from the Red Mountain (PKB) and East Red Mountain (ERM) areas. (ND=not detected)

Sample No.	PKB-1	PKB-2	PKB-3	ERM-1	ERM-2	ERM-3	ERM-4	ERM-5	ERM-6
Primary Assemblage	QSP	Acid sulfate	QSP	QSP	Quartz Sericite	Quartz Sericite	QSP	Acid Sericitic Argillic	QSP (dump)
Secondary Assemblage	None	QSP	Acid sulfate	Argillic	None	None	Argillic	None	None
Quartz	Major	Major	Major	major	Major	Major	Major	Major	Major
Plagioclase	ND	ND	ND	ND	ND	ND	ND	ND	ND
Microcline	ND	ND	ND	ND	ND	ND	ND	ND	ND
Orthoclase	Trace	ND	ND	ND	ND	Trace	ND	Trace	ND
Dolomite	ND	ND	ND	ND	ND	ND	ND	ND	ND
Calcite	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chlorite	ND	ND	ND	Major	ND	ND	Major	ND	ND
Kaolinite	Trace	ND	Trace	Major	Trace	Trace	Major	Trace	Trace
Alunite	ND	Minor	ND	ND	ND	ND	ND	ND	ND
Pyrophyllite	Trace	Minor	Trace	ND	ND	ND	ND	ND	ND
Zunyite	ND	Trace	ND	ND	ND	ND	ND	ND	ND
Sericite 1M	ND	ND	ND	Minor	ND	ND	ND	ND	ND
Sericite 2M1	Minor	Trace	Minor	Major	Major	Major	Major	Minor	Major
Jarosite	ND	ND	Trace	ND	Minor	Minor	ND	ND	ND
Pyrite	Minor	ND	Trace	ND	ND	ND	ND	ND	Minor
(Fe sulfate)	ND	ND	ND	Minor	ND	ND	ND	ND	ND
Sphalerite	ND	ND	ND	ND	ND	ND	ND	ND	ND
Galena	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hematite	ND	ND	ND	ND	ND	ND	ND	ND	ND
Anatase	ND	ND	ND	ND	ND	ND	ND	ND	ND

EAST RED MOUNTAIN

Geology

Bedrock in the lower southwestern slope of East Red Mountain, along the two southern tributaries to East Sayres Gulch, is composed of essentially unaltered, Precambrian, banded quartz-biotite gneiss (P€gn **Figure 38**). Foliation in the Precambrian gneiss strikes N20-50W and dips 70E. The gneiss locally contains quartz veins and pegmatites. The principal altered rocks at East Red Mountain also appear to be composed of Precambrian gneiss, but the intense alteration makes distinction of rock types difficult. A porphyritic grandiorite



Base from USGS Independence Pass 7.5-min. quadrangle; geology and alteration after Cruson, 1973

Figure 38. Map showing geology, hydrothermal alteration, sample sites, and water test results in the Grizzly Peak caldera, East Red Mountain area.

ring-dike (Tgdp) marks the southeastern rim of the Grizzly Peak caldera on the southeastern margin of East Red Mountain (Figure 38).

The Grizzly Peak welded ash-flow tuff (Ta) is a quartz-latite to rhyolite lithic tuff that forms the main caldera fill. This unit forms a fault-bounded block on the lower northwestern slope of East Red Mountain.

An alloclastic breccia (Tbf), composed of a well-indurated mixture of large Precambrian rock fragments and rock flour with ubiquitous low-grade chloritic alteration, is widespread in the East and West Red Mountain areas. The breccia contains rare Tertiary volcanic rock fragments. This megabreccia marks the margin of the caldera in the East Red Mountain area and is one of the main host rocks for hydrothermal alteration on the eastern side of the Continental Divide in the West Red Mountain area. The weakly altered megabreccia zone (Tbf) forms the majority of the lower northwestern slopes of East Red Mountain (Figure 38).

Quartz monzonite (Tqm) forms the major rock type on the eastern side of the ring fracture zone. This is a portion of the pre-caldera Twin Lakes batholith. This intrusive forms the northeastern slope of East Red Mountain, which drops into an east-flowing drainage.

Structure

Major structural features in the East Red Mountain area include: a caldera ring fracture, a N20-30W fault block, and N40-60E faults paralleling the southeastern ring fracture.

A N20W trending fault forms a prominent ridge along the western side of the drill road accessing the East Red Mountain area from the north (Figure 38). The ridge is composed of a limonitic breccia of Precambrian gneiss forming small pinnacles. The breccia zone mainly follows the eastern side of the pinnacles. The main normal fault shown on the map is poorly exposed just to the west of this ridge.

Alteration Assemblages

A large area of hydrothermally altered rock is exposed to the east of Sayres Gulch on East Red Mountain **(Figures 38 and 39)**, which lies along the eastern ring fracture of the Grizzly Peak caldera. The ring fracture is well marked by megabreccias and a ring dike. Based upon the localization of the hydrothermal alteration and its associated copper and molybdenum anomalies, Cruson (1973) suggests that the altered area probably overlies a shallow, felsic, post-caldera collapse, porphyry intrusion, which was injected along the ring fracture.

Quartz-sericite altered rock (QS) forms the core of the East Red Mountain area (samples ERM-2 and ERM-3 in **Tables 5 and 6,** and on Figure 38). Local areas of quartz stockwork (SIL) exist within the main quartz-sericite zone. These appear to be composed of nearly pure quartz forming a mass of intersecting veinlets.

A semicircular zone of QSP-altered rock is present around the north, east, and south sides of the principal quartz-sericite zone, and is also present in a separate zone on the southern end of the altered area (Figure 38). Sample ERM-6, from the waste rock dump of the Burge Tunnel, provides a good example of this type of alteration.

Argillically altered (ARG) rocks are exposed along the ridge top of East Red Mountain (sample ERM-1 in Tables 5 and 6), and form the outermost alteration zone in much of the map area (Figure 38). Due to the high kaolinite content, rocks of this alteration assemblage are characteristically soft and generally poorly exposed. Samples ERM-4 and ERM-5 (Tables 5 and 6) were collected from the argillic zone near the transitional boundary with the quartz-sericite zone.

Propylitic alteration assemblages are the typical type of alteration assemblage present in the megabreccia unit on the northwest side of East Red Mountain. Chlorite is the dominant mineral in the zone of propylitic alteration

Mine Workings

Cruson (1973), mapped the northeast trending Burge Tunnel, now caved, on the southwestern slope of East Red Mountain. At present, the location of the tunnel is marked by a large waste rock dump consisting of altered QSP material along the drill road at an elevation of about 12,600 ft (site of sample ERM-6 on Figure 38). Old rails and wood debris from the adit are present at the waste rock dump. A small dry gulch south of the dump has no active drainage and appears to experience only rare surface wash events. The waste rock and talus in the gulch is quartz-sericite altered with no iron staining.

Cruson (1973) identified N70W trending pebble-dikes and a N70E trending fault within the gneissic wall rocks of the Burge Tunnel. The majority of the rock was moderately to strongly silicified and pyritized within the first 500 ft past the entrance. Argillic alteration was prominent for the remainder of the adit's length. Rare molybdenite and copper carbonates were noted within the deeper section of the adit.

Two adit symbols and a prospect symbol are erroneously plotted on the Independence Pass 7.5-minute topographic map, in the East Red Mountain area. These are not mining features; the symbols represent drill pad and drill roads from past mineral exploration.

No actual mines exist in the East Red Mountain area. The Burge tunnel is the only working of any size known in the area.

ROCK GEOCHEMISTRY DATA

Cruson (1973) compiled maps showing copper (>100 ppm) and molybdenum (>10 ppm) anomalies, one of which was centered on the East Red Mountain area,

Table 6. ICP-AES Chemistry Results for rock samples from the Red Mountain-Peekaboo Gulch (PKB) and East Red Mountain (ERM) areas.

Field No.	PKB-1	PKB-2	PKB-3	ERM-1	ERM-2	ERM-3	ERM-4	ERM-5	ERM-6
Sample Description	QSP	Acid Sulfate & QSP	QSP & Acid Sulfate	Argillic & QSP	Quartz Sericite	Quartz Sericite	Argillic & Quartz Sericite	Quartz Sericite & Argillic	dump (Burge Tunnel)
Al (%)	5.2	4.325	4.94	7.44	6.785	6.63	8.635	7.16	6.15
Ca (%)	0.155	0.075	0.04	0.035	0.09	0.03	0.02	0.02	0.01
Fe (%)	3.35	0.4	1.82	3.91	0.33	1.76	4.29	0.76	2.41
K (%)	1.35	1.11	1.92	2.34	3.05	3.19	3.19	3.34	2.77
Mg (%)	0.065	0.02	0.075	0.535	0.285	0.405	0.925	0.335	0.16
Na (%)	0.035	0.215	0.09	0.75	0.065	0.09	0.15	0.065	0.08
P (%)	0.23	0.11	0.06	0.015	0.075	0.1	0.01	0.02	0.01
Ti (%)	0.083	0.039	0.072	0.138	0.094	0.121	0.341	0.116	0.099
Ag (ppm)	<2	4	<2	<2	<2	<2	<2	<2	<2
As (ppm)	<10	10	<10	<10	<10	<10	<10	<10	<10
Ba (ppm)	166	448	699	280	1210	1030	1320	754	447
Bi (ppm)	<50	<50	<50	<50	<50	<50	<50	<50	<50
Cd (ppm)	<2	<2	<2	<2	<2	<2	<2	<2	<2
Co (ppm)	14	<2	<2	11	<2	<2	6	<2	7
Cr (ppm)	6	<2	3	19	<2	3	21	4	9
Cu (ppm)	14	19	49	26	49	64	29	13	7
Mn (ppm)	<4	<4	<4	133	<4	<4	152	<4	<4
Mo (ppm)	7	<2	819	<2	7	119	<2	8	2
Ni (ppm)	6	<3	<3	24	<3	3	28	<3	10
Pb (ppm)	21	736	24	11	76	14	53	25	5
Sr (ppm)	227	510	208	41	106	52	54	31	28
Zn (ppm)	11	4	9	36	11	22	36	23	5

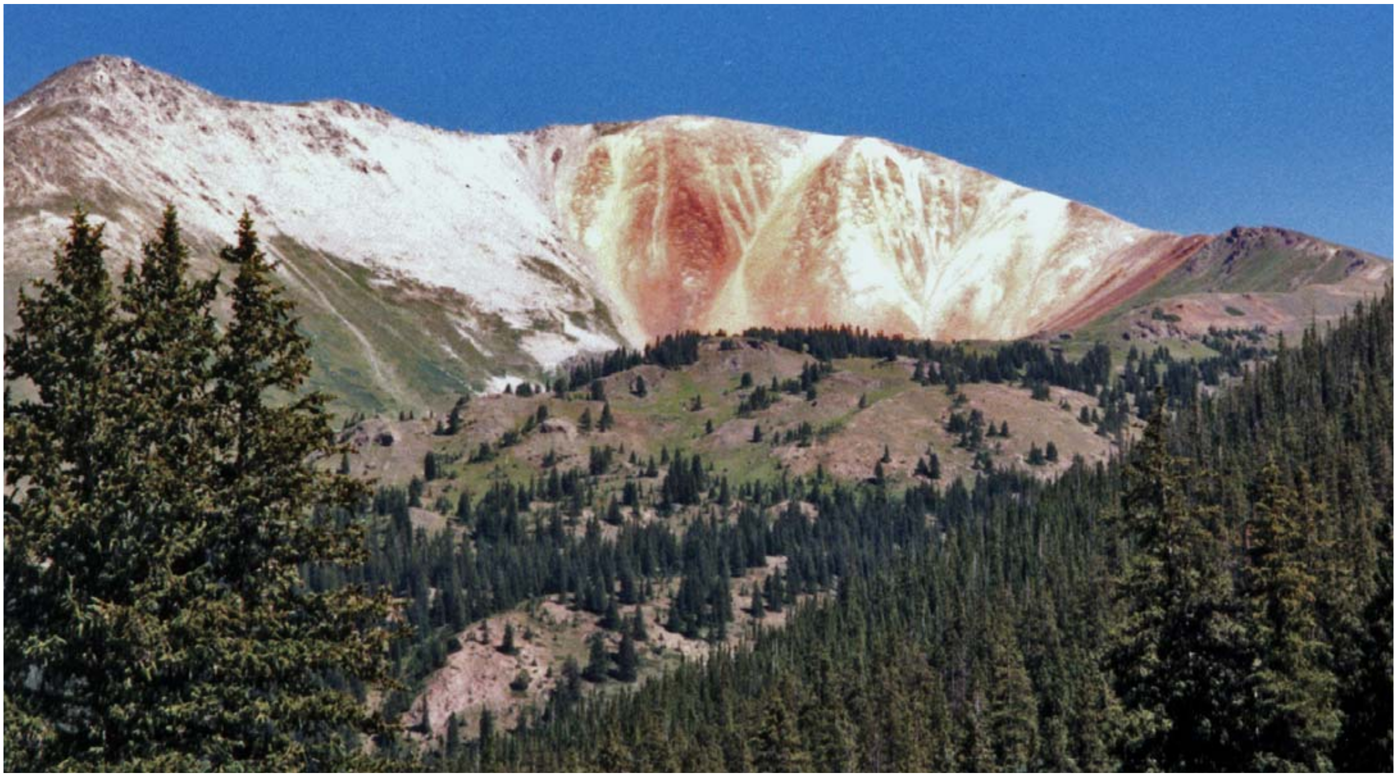


Figure 39. East Red Mountain.

and the other was just to the south and west of the Red Mountain area. The results of the present investigation are generally consistent with those of Cruson. The present investigation identified only molybdenum enrichment in the few rock samples from the area without any copper anomalies, possibly due to extensive leaching of copper from surficial rocks in the strongly altered areas that were sampled (Table 6). Two samples from East Red Mountain (ERM-2 and ERM-4) indicated the presence of anomalous lead in abundances of 76 ppm and 53 ppm, respectively. The sample containing the strongest acid-sulfate alteration above Peekaboo Gulch (PKB-2), at Red Mountain, was enriched in silver (4 ppm), arsenic (10 ppm), lead (736 ppm), and strontium (510 ppm) (Table 6). However, the sample from the waste rock dump near the Burge Tunnel (ERM-6) indicated no metal enrichments, other than trace molybdenum, in comparison to the other samples.

PREVIOUS WATER QUALITY INVESTIGATIONS

In 1994, CGS personnel collected a water sample from one of a series of springs on the northwest side of Peekaboo Gulch, about 0.5 mi below its headwaters **(Figure 40)**. The springs emerge near a ring fracture that separates older, intracaldera collapse-breccias and lavas on the northwestern side of the fault from younger Grizzly Peak Tuff on the southeastern side of the fault. The ring fracture is a reverse fault with 3,000 to 4,000 ft of displacement that formed during resurgent doming within the caldera (Fridrich and others, 1991). Emplacement of intrusions during the resurgent doming episode caused extensive and pervasive hydrothermal alteration and metal-sulfide mineralization in the overlying rocks (Sares, 1996; Fridrich and others, 1991).

Although a few small prospects exist upslope from this spring, they drain no water and probably do not significantly affect the springs at Peekaboo Gulch. Water sampled in 1994 from a spring in Peekaboo Gulch contained concentrations of aluminum (150 mg/L), cadmium (16 µg/L), copper (6 mg/L), iron (100 mg/L), zinc (710 µg/L), silver (0.2 µg/L), and sulfate (1,500 mg/L) that exceeded State water quality standards (Sares, 1996). This spring water had pH of 2.17, EC of 2,470 µS/cm, and an estimated flow of 25 gpm. Water from a series of springs in this area had an obvious impact on Peekaboo Gulch. Above the springs the water in the stream was clear and pH was nearly neutral. Below the springs the stream water had pH of about 3.5 and was red from apparent iron hydroxide precipitate (Sares, 1996). Where dilution of the acidic spring water initially begins, white precipitate forms, presumably aluminum hydroxide (Figure 40).

Acid-sulfate and QSP assemblages, similar to that observed in rocks of Red Mountain and the ridge to the south are also present in Lincoln Creek, a tributary of the Roaring Fork River (Figure 1) on the west side of the Continental Divide near the ghost town of Ruby.

Figure 40. Red Mountain, west side of Peekaboo Gulch.

In 1997, CGS sampled an unmapped and unnamed tributary of Lincoln Creek, originating from the altered rocks in the ridge extending south from Red Mountain. Water samples were collected from the stream above all known mines. The active channel was lined with well-indurated ferricrete and ferrosinter, and a weathered ferrosinter deposit comprising brown powdery material was adjacent to and north of this stream. Water at the sample site had EC exceeding 2,000 µS/cm and pH of about 3. Aluminum and iron concentrations both exceeded 150,000 µg/L and exceeded State water quality standards. Copper, manganese, sulfate, zinc, cadmium, chromium, and nickel also exceeded standards. Lincoln Creek contained red precipitate, which began at the confluence with the unnamed stream. Water test results from an unnamed stream draining the west side of Red Mountain, only about 800 ft north of the acidic, metal-rich stream, did not indicate significant ARD (Neubert and others, 1998).

No draining mines of significant size are known to exist in the east fork of the Sayres Gulch drainage basin. However, at least two tributaries of the east fork, draining the altered upper southwestern slopes of East Red Mountain, were lined with precipitate. Water tests from the tributaries during the CGS abandoned mine inventory in 1994 indicated pH values less than 3.6 and ECs of about 250 to 1,150 µS/cm. Upstream from the influence of these acidic, metal-rich tributaries, the east fork of Sayres Gulch contained no precipitate, pH of the water was neutral, and EC was less than 100 µS/cm (See USFS-AMLIP inventory forms #12-01-368/4319-1 and #12-01-367/4319-1, available at CGS, Denver, Colorado).

Bird and others (2005) characterized water quality draining from the hydrothermally altered terrane of Red and East Red Mountains and downstream hydrogeochemistry in the Lake Creek watershed. This work was part of a study that employed hyperspectral remote sensing to map the hydrothermally altered rocks of Red and East Red Mountains. The hyperspectral imagery also mapped downstream changes in surface water chemistry in the watershed based on the type of iron and aluminum precipitates coating stream gravels (Sares and others, 2004).

PRESENT WATER QUALITY INVESTIGATION

Seven samples were collected in the vicinity of Red Mountain in 1999, all in the South Fork Lake Creek drainage basin (Figures 37 and 38). Water sample and test results are discussed beginning with the upstream sites. In 2000, four additional water samples were collected in the East Red Mountain area.

Red Mountain Area — Peekaboo Gulch

Water tests were performed on some of the numerous springs that emerge on the west side of Peekaboo Gulch, near the break in slope between the steep walls of the lower part of the gulch and a relatively flat bench (Figure 40). The slopes above the springs include QSP- and acid-sulfate-altered and fractured volcanic rocks with red, brown, and yellow staining and some bleaching (Figure 37). Disseminated pyrite is common in the volcanic rocks. Although a few small prospects have been developed on the slope above the bench, these prospect pits were dry and probably have little affect on groundwater in the area. The pH of the springs ranged from 2.61 to 3.12, and EC ranged from 585 µS/cm to 1,960 µS/cm. Abundant fresh ferrosinter and older, hard, red-brown ferrosinter deposits appear throughout the areas containing springs, and indicate a history of ARD.

Sample NW-29 was collected from the upper reaches of the stream in Peekaboo Gulch, where light gray-green precipitate has formed as a result of the ARD discharging from the springs (Figure 40). Flow was estimated at 800 gpm, pH was 4.30, and EC was 79 µS/cm. The water exceeded State water quality standards in aluminum, copper, and zinc **(Appendix A-7)**. The total aluminum concentration was more than twice the dissolved concentration, indicating that much of the precipitate consists of aluminum phases.

Sample NW-33 was collected from the lower portion of a large ferrosinter/ferricrete deposit, below the convergence of several small springs **(Figures 37 and 41)**. This is the same general area where the 1994 sample was collected (Sares, 1996). Some of the ferricrete is stained yellow-green, possibly from copiapite ($[Fe,Mg][Fe3+]4[SO_4]6[OH]_2{\cdot}20H_2O$). Flow was measured at 30 gpm, pH was 2.85, and EC was 1,764 µS/cm. This water exceeded State water quality standards by more than two orders of magnitude in concentrations of aluminum, iron, and copper. Manganese, zinc, cadmium, and sulfate also exceeded State standards (Appendix A-7).

Several similar springs join Peekaboo Gulch from the west side in the area extending from a few hundred feet south of water sample site NW-33 to the stream that serves as the outlet of Herschel Lake (Figure 37). This zone of acidic, metal-rich seeps corresponds with the contact between the alloclastic breccia (Tbf) and the welded ash-flow tuff (Ta), with the QSP-altered, red-stained bedrock and talus that forms the southeastern slopes of Red Mountain. The stream draining Herschel Lake acquires most of its water from weakly altered bedrock on the northeastern side of Red Mountain. The pH of the stream was 6.8 and EC was 117 µS/cm (Figure 37). Water tested in a ravine about 100 ft south of the Herschel Lake outlet stream had pH of 3.88 and EC of 98 µS/cm. This ravine originates in the hydrothermally altered slopes on the southeast side of Red Mountain and follows a fault with strong quartz-sericite alteration (Figure 37). A small prospect was visible adjacent to the stream and above the test site.

On the east side of Peekaboo Gulch, bedrock of the Precambrian and Grizzly Peak tuff is not strongly altered, and a water test indicated no ARD. Water draining from a small adit, across the gulch from sample site NW-33, had pH of 6.96 and EC of 118 µS/cm (Figure 37).

Sample NW-34 was collected from Peekaboo Gulch, downstream from most of the acidic, metal-rich springs described earlier, and above the diluting influence of the stream draining Herschel Lake (Figure 37). Stream water was slightly turbid, and abundant light red, red-brown, and orange precipitate coated the streambed. The precipitate extended onto the banks of the stream and included ferrosinter and ferricrete. Most of the precipitate was weakly indurated. However, within the flowing water a thin layer of soft, fresh orange precipitate lies on the older, hardened material. Above the banks of the stream, some of the older precipitate was weathering into dark brown soil. At the sample site, flow was measured at 500 gpm, pH was 3.82, and EC was 218 µS/cm. This water exceeded State standards in aluminum, copper, iron, manganese, and zinc. Concentrations and loadings of aluminum, iron, copper, and manganese were substantially greater than those of sample NW-29 about 0.5 mile upstream (Appendix A-7).

A water test from Peekaboo Gulch, a few hundred feet upstream of its confluence with South Fork of Lake Creek, revealed pH of 4.4 and EC of 147 µS/cm. Minor amounts of white precipitate coated the rocks of the streambed. South Fork of Lake Creek, tested about 1,000 ft upstream of its confluence with Peekaboo Gulch, exhibited no obvious evidence of ARD, with pH of 7.47 and EC of 71 µS/cm. Immediately below the confluence of South Fork and Peekaboo Gulch, minor amounts of red precipitate were present in the stream. A small amount of red precipitate was visible in South Fork continuously from McNasser Gulch (which tested at 7.32 pH, 76 µS/cm EC) to Sayres Gulch. About 1,000 ft upstream from the confluence with Sayres Gulch (below the confluence with McNasser Gulch), South Fork of Lake Creek had pH of 7.19 and EC of 81 µS/cm (Figure 38).

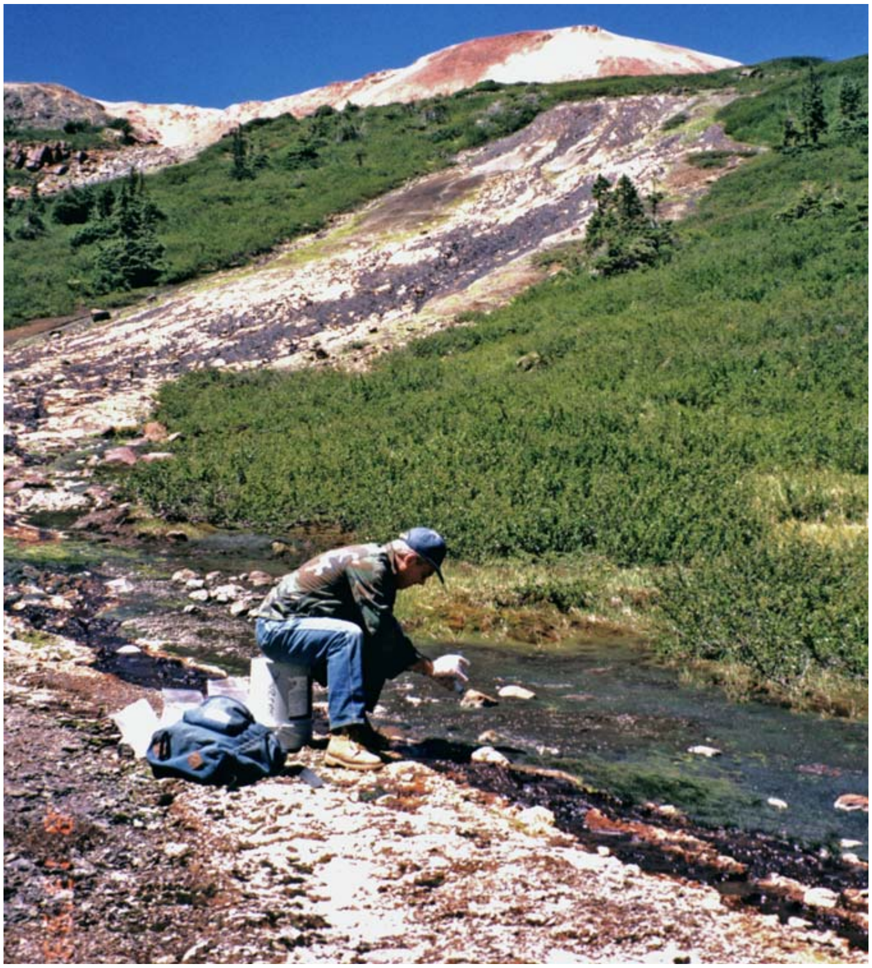


Figure 41. Water sample site NW-33 and ferrosinter/ferricrete deposit.

East Red Mountain Area — Sayres Gulch

In 1999, several water tests were conducted and a water sample was collected in Sayres Gulch, in the vicinity of East Red Mountain. Sample NW-35 was collected from the east fork of Sayres Gulch, which drains the west side of East Red Mountain, the site of subeconomic porphyry Mo-Cu mineralization and associated alteration (Cruson, 1973). This site is upstream from the diluting influence of the west fork of Sayres Gulch (Figure 38). Where sampled, the channel was coated with abundant, light yellow-red precipitate that weakly cemented some of the stream gravel and cobbles. Partially weathered ferricrete/ferrosinter was exposed on the stream banks, suggesting a history of poor-quality water.

The east fork of Sayres Gulch (site NW-35) was slightly turbid and flowing at about 1,200 gpm with pH of 3.84 and EC of 263 µS/cm. Aluminum, copper, iron, manganese, and zinc exceeded State water quality standards (Appendix A-7). The difference between concentrations of total and dissolved iron suggests that precipitates of iron minerals are responsible for the turbid water.

During the 2000 field program, three water samples were collected from the two upper tributaries of the east fork of Sayres Gulch (NW-2000-5 to 7 on Figure 38) that had been tested in 1994 during the CGS abandoned mine inventory and found to have significant ARD. Ferricretes are common in the more southerly of these two tributaries, from the junction with east fork of Sayres Gulch up to an elevation of 11,650 ft (below NW-2000-5). All ferricretes are found within fresh Precambrian gneiss. Ferricrete is also common from an elevation of 12,500 ft down to about 12,000 ft along the more northerly of these two tributaries of the east fork of Sayres Gulch (below NW-2000-7). The iron that cemented these ferricretes clearly originates from numerous iron-rich seeps at the contact of QSP-altered rock with argillic-altered rock near the contact with underlying fresh Precambrian rock at an elevation ranging from 12,200 to 12,500 ft (i.e. sites NW-2000-5 to NW-2000-7 on Figure 38).

The southernmost of the two tributaries to the east fork was sampled at two locations at an elevation of 12,200 ft, where a prominent break in slope and change in rock alteration appears (sample NW-2000-5 and NW-2000-6 on Figure 38. At both water sample sites, the channel was lined with abundant iron precipitate and ferricrete and appeared to be actively forming a bog-iron deposit. The adjacent rocks were affected by strong argillic and QSP alteration (Figure 38). The tributary originates as numerous seeps from the base of the prominent QSP-altered zone immediately adjacent to the tributary. Below the sample location, the tributary crosses unaltered Precambrian gneiss for the remainder of its reach down to its confluence with the east fork of Sayres Gulch. Ferricretes are common along most of this reach. Sample NW-2000-5 was collected from a clear spring on the south side of the tributary drainage basin. Additional springs emerging from the altered rocks were present immediately downstream. The pH of the water was 2.36 and EC was 1,152 µS/cm. The sample exceeded State water quality standards for aluminum, copper, iron, manganese, nickel, sulfate, and zinc (Appendix A-7). Sample NW-2000-6 was collected from a clear spring on the northern side of this tributary basin, just above the confluence with the spring sampled at location NW-2000-5 (Figure 38). The water had pH of 2.69 and EC of 1,448 µS/cm. Similar to water from sample site NW-2000-5, the sample exceeds State standards for aluminum, copper, iron, manganese, nickel, and zinc (Appendix A-7). Sulfate is present slightly below standards.

The northern acidic, metal-rich tributary to the east fork of Sayres Gulch was sampled (NW-2000-7) at an elevation of 12,500 ft on East Red Mountain (Figure 38), where the stream first forms a prominent series of seeps along the contact of the main argillic alteration zone with underlying unaltered Precambrian gneiss. Where sampled, the channel was coated with abundant red precipitate that cemented some of the stream gravel and cobbles. Partially weathered ferricrete and ferrosinter deposits are exposed on the stream banks, suggesting a history of ARD. The pH was 2.81 and the EC was 926 µS/cm. The sample exceeded State water quality standards for aluminum, iron, manganese, cadmium, copper, nickel, zinc, and sulfate (Appendix A-7). All three water samples (NW-2000-5 to NW-2000-7) from the upper slopes of East Red Mountain show highly elevated copper concentrations (520–1,700 ug/L), with fairly high Cu:Zn ratios (1 to 12). These data are consistent with rock geochemical data from the East Red Mountain area (Table 6, this report; Cruson, 1973), which also show similar Cu:Zn ratios, and are fairly characteristic of other subeconomic porphyry Mo-Cu systems in western Colorado (Bove and others, USGS, unpublished data).

Water from the west fork of Sayres Gulch was tested about 400 ft upstream of its confluence with the east fork. The water appeared clean and had pH of 7.36 and EC of 71 µS/cm. At the confluence of the apparently clean water of the west fork, and the obviously poor-quality water of the east fork, white precipitate appeared and the stream water became considerably more turbid **(Figure 42)**. A water test conducted about 500 ft downstream of the confluence indicated pH of 4.69 and EC of 131 µS/cm. The rapid change in pH caused by mixing of the two forks appears to be causing aluminum phases to precipitate, which both coat the stream channel and remain in suspension. About 1.5 mi farther downstream and about 1,000 ft upstream from its confluence with South Fork of Lake Creek, white and light red precipitate were present in Sayres Gulch, and the turbid water had pH of 4.75 and EC of 126 µS/cm (Figure 38). A water test indicates minimal chemical change in Sayres Gulch from the mixing zone of the east and west forks downstream to South Fork of Lake Creek.

ARD with an estimated flow of 500 gpm enters South Fork of Lake Creek from an unnamed gulch east of Sayres Gulch (sites NW-31 and NW-2000-8 on Figures 38 and 39). This stream drains the highly altered northwest slopes of East Red Mountain. The few drill pads in this sub-basin are not believed to

Figure 42. Mixing zone of east and west forks of Sayres Gulch.

affect the runoff significantly, especially in comparison to the large exposures of altered rocks. In 1994, a water test conducted from a precipitate-laden stream near the headwaters of this sub-basin indicated a pH of less than 3.0 and EC of 923 µS/cm (See USFS-AMLIP inventory forms #12-01-367/4320-1 and #12-01-368/4319-1). In 1999, sample NW-31 was collected from this unnamed gulch about 100 ft upstream from its confluence with South Fork (Figure 38). The creek flowed across terraces of red precipitate that are soft on the top and harder at depth. Although this water was less cloudy than the water of South Fork, it had much poorer quality, with pH of 2.96 and EC of 1,406 µS/cm. Concentrations of aluminum and iron were more than two orders of magnitude above State water quality standards; copper and manganese exceeded State standards by more than an order of magnitude; and sulfate, zinc, nickel, and cadmium also exceeded State standards (Appendix A-7). High concentrations of metals, combined with the relatively high flow rate, indicate that this tributary contributes a large proportion of the metal load in the South Fork drainage basin.

A water sample (NW-2000-8) was collected from the upper reaches of this same unnamed creek that drains the northwest slopes of East Red Mountain, at an elevation of approximately 12,300 ft (Figure 38). The head of the tributary drains a prominent, brightly colored QSP and argillic alteration zone (Figures 38 and 39). The sample was collected from a clear spring with a flow of 30 gpm emerging just to the east of the main, red-stained streambed. The pH was 2.44 and EC was 2,850 µS/cm. The water sample exceeded State water quality standards for aluminum, iron, copper, cadmium, manganese, nickel, sulfate, and zinc. These analytical results are quite similar to those for water sample NW-31 (Appendix A-7), which was collected closer to the junction of this tributary with the South Fork of Lake Creek. Similar to the scenario for sites NW-2000-5 to -2000-7 (discussed above), the elevated copper (150 ug/L) and fluoride (2 mg/L) concentrations at sites NW-31 and NW-2000-8 likely reflect the subeconomic Mo-Cu porphyry alteration and mineralization focused at East Red Mountain, as discussed in Cruson, 1973 (Bove and others, 2002). High Cu:Zn ratios (approximately 3), typical of the water sampled at this site, may also be a characteristic of these types of mineralized systems; whereas, waters reflecting interaction with polymetallic veins in western Colorado typically have low Cu:Zn ratios (<1). Sample NW-32 was collected from South Fork of Lake Creek, above the influence of the unnamed tributary and downstream from Sayres Gulch (Figure 38). The stream was turbid with minor amounts of light red precipitate. The creek had an estimated flow of 7,000 gpm, pH of 6.0, and EC of 108 µS/cm. Although the addition of acidic, metal-rich water from Sayres Gulch had a noticeable effect on South Fork, the sample exceeded State water quality standards only in concentrations of iron and copper (Appendix A-7). Large differences between the concentrations of total and dissolved aluminum and iron indicate that the precipitate and the suspended solids in South Fork are composed primarily of aluminum and iron phases.

Sample NW-30 was collected from the South Fork of Lake Creek, downstream from the confluence with the acidic, metal-rich tributary sampled at site NW-31 (Figure 38). The stream at site NW-30 was turbid with more light red precipitates than were present at site NW-32, which was just upstream of the metal-rich tributary. Streamflow at site NW-30 was estimated to be 7,000 gpm; after mixing with the tributary (NW-31), pH had dropped from 6.0 to 4.68, and EC had increased from 108 to 155 µS/cm. Concentrations of aluminum, copper, iron, and manganese at site NW-30 exceeded State water quality standards (Appendix A-7). Concentrations of dissolved and total iron and aluminum indicate that the precipitate lining the channel and the suspended solids are probably phases of iron and aluminum. No additional inflows of ARD were observed downstream from sample site NW-30 during this reconnaissance study.

RUBY RANGE

The Ruby Range is northwest of Crested Butte and south of Marble, in west-central Colorado (Figure 1). The West Elk Mountains are adjacent to the Ruby Range on the south, and the Elk Mountains are to the north and east. Five water samples were collected from four separate areas (Paradise Basin, Redwell Basin, Red Lady Basin, Gold Creek) in the Ruby Range during this reconnaissance level investigation. These areas lie in the Crystal River, Oh-Be-Joyful, and Gold Creek drainage basins.

GEOLOGY

The crest of the Ruby Range consists of a series of Oligocene igneous stocks of intermediate-composition with related sills, dikes, and laccoliths. The igneous rocks intruded a sequence of Cretaceous and Tertiary carbonaceous shales, siltstones, and sandstones. Younger, felsic igneous rocks were emplaced in the late Tertiary. Hydrothermal alteration and mineralization of the rocks in the range are related to the intrusive events, especially to the younger, felsic intrusions. Disseminated pyrite is abundant in many of the altered areas. Vein deposits of copper, lead, zinc and precious metals have been mined in the past from the Ruby and Irwin districts, and exploration and possible development of a stockwork molybdenum deposit at Mt. Emmons continues (Thomas and Galey, 1982). Another known stockwork molybdenum occurrence, with associated veining and alteration, underlies Redwell Basin, and others are postulated to exist farther north in the range (Mutschler and others, 1981a; Ludington and Ellis, 1983).

Numerous ferruginous springs emerge in the Ruby Range. Although past mining has probably affected many of the drainage basins, most of the springs and associated limonite deposits apparently existed prior to mining. Deposition of ferrihydrites continues at present in springs of this area.

The Daisy mine, in upper Redwell Basin, was active from 1950–1969. The 41-ft-wide ore vein was composed of sphalerite, galena, chalcopyrite, pyrite, rhodonite, and rhodochrosite. Veins with similar mineralogy were also mined historically at the Keystone Mine and at the Standard Mine in Elk Basin. A major NE-trending structure that passes through upper Redwell Basin hosts the veins at the Standard mine and Daisy mine (Ludington and Ellis, 1983).

PREVIOUS WATER QUALITY INVESTIGATIONS

Keystone Spring

Limonite and other ferrihydrites have been deposited on a swampy hillside below the Keystone Spring, about 3 mi west of Crested Butte (Figure 1). The deposit is 3,000 ft long, 800 to 2,200 ft wide, up to 15 ft thick, and extends to Coal Creek (Harrer and Tesch, 1959). The spring emerges below the nearby Keystone lead-zinc-copper mine. A large volume of water flows from the Keystone Mine and is diverted to a water treatment plant between the mine and Coal Creek. Although the limonite deposit predates the mining activity, and deposition of limonite presumably continues at present, water from the mine has probably affected local hydrology and possibly water chemistry. The Keystone bog-iron deposit, or fen, has recently drawn attention because it holds the southernmost documented occurrence of the Roundleaf Sundew carnivorous plant.

Redwell Basin

Redwell Basin is about 10 mi northwest of Crested Butte. The Red Well is a spring emerging from feldspathic sandstones and carbonaceous shales of the Cretaceous Mesa Verde Formation near the head of Redwell Basin **(Figure 43)**. Water discharging from the spring is depositing hydrous iron oxides. Lower in the basin, another iron-rich spring discharges from a shallow shaft. The spring predates the shaft, which was sunk during exploration of the bog-iron deposit. Ferrihydrite is actively being deposited in the swampy portions of Redwell Basin. Iron precipitates form a deposit about 600 ft long, 75 ft wide, and up to 5 ft thick (Harrer and Tesch, 1959).

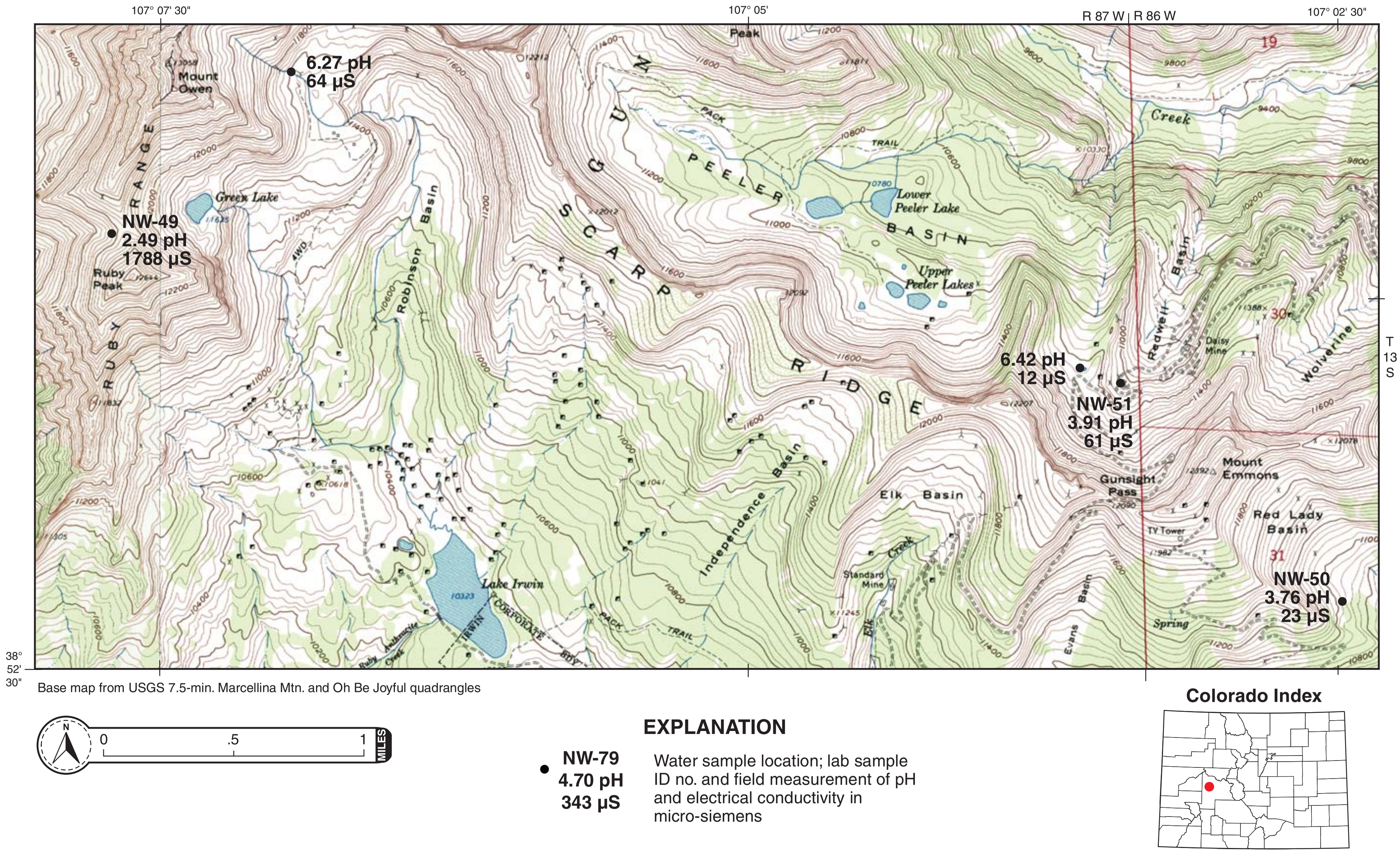


Figure 43. Map showing water sample sites NW-49 to NW-51 and water test results in the southern part of the Ruby Range.

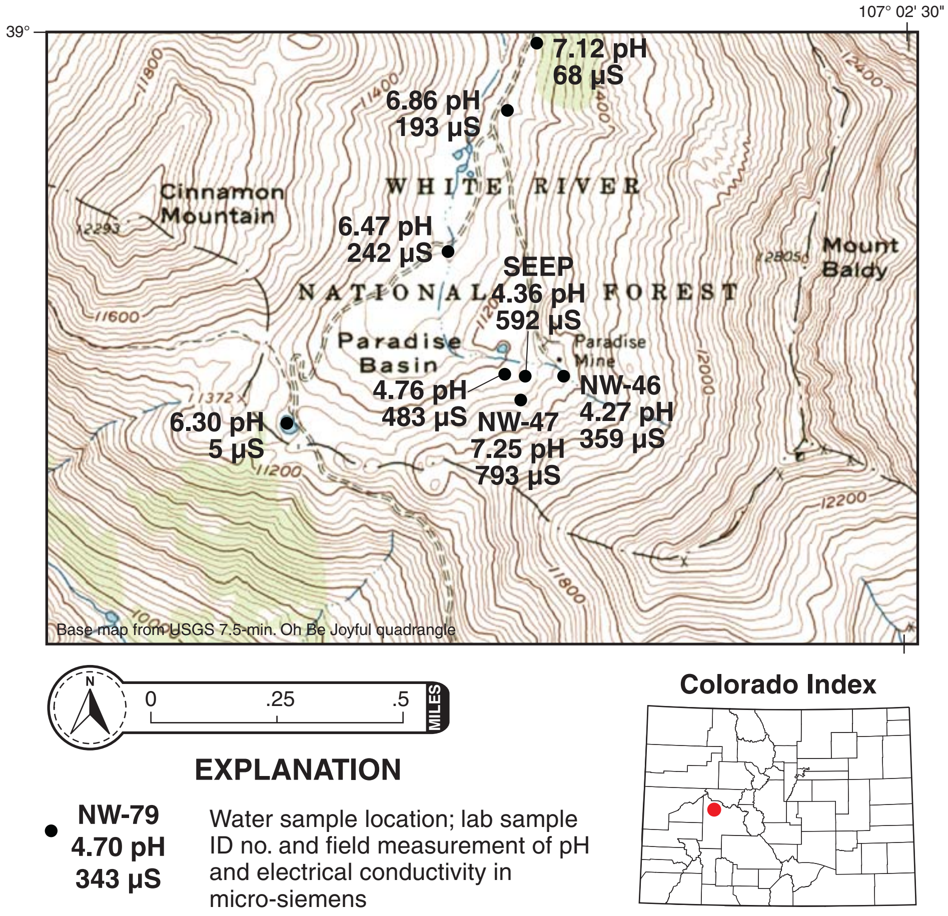


Figure 44. Map showing water sample sites NW-46 and NW-47 in Paradise Basin.

In October 1996, CGS personnel collected a sample from the pool of water filling the depression in the ferrosinter deposit at the Red Well. The water had pH of 3.51, EC of 304 µS/cm, and exceeded State water quality standards in aluminum (3,900 µg/L), cadmium (61 µg/L), copper (14 µg/L), iron (23,000 µg/L), lead (1,600 µg/L), manganese (1,900 µg/L), and zinc (6,900 µg/L) (Fehlmann and others, 1998). Although the spring predates mining activity in the basin, its position topographically below several large copper-lead-zinc mines (principally the Daisy Mine), and the occurrence of high concentrations of trace metals, indicate that groundwater may be affected by subsurface mine drainage.

PRESENT WATER QUALITY INVESTIGATION

Water samples were collected in 1999 from some of the acidic, metal-rich springs that are topographically above all known significant mines in the Ruby Range.

Paradise Basin **(Figure 44)** is in the headwaters of the Crystal River watershed and drains to Rock Creek. The Tertiary Paradise stock intruded this area, and much of the exposed bedrock and talus have been altered and stained red **(Figure 45)**. Hydrothermal fluids related to the intrusion have mineralized and altered the stock and surrounding rocks. The basin has been an exploration target for a stockwork molybdenum deposit and hosts a few small mines (Thomas and Galey, 1982; Ludington and Ellis, 1983). During this study, two samples were collected from Paradise Basin, above all known mines.

Sample NW-46 was collected from the eastern part of Paradise Basin, above the Paradise Mine (Figures 44 and 45). The stream infiltrated into and disappeared beneath iron-stained alluvium and colluvium about 200 ft downstream from the sample site. The flow rate was slightly higher upstream than at the sample site. Alluvium and colluvium in this area comprise baked (contact metamorphosed) dark shale and light-colored, fine-grained intrusive rock. Disseminated pyrite and pyrite veinlets were common in both rock types. Where sampled, flow was 25 gpm, pH was 4.27, and EC was 359 µS/cm. Aluminum, cadmium, copper, lead, and manganese exceeded State water quality standards **(Appendix A-8)**. Sulfate was elevated but within standard.

Sample NW-47 was collected a few hundred feet upstream from wetlands where intermingling waters cause abundant white precipitate to form **(Figures 44 and 46)**. Moderate amounts of gray precipitate coated the stream channel at the sample site. Colluvium and alluvium consisted of baked (contact metamorphosed) shale and intrusive rock containing only minor pyrite and iron staining. Flow was 25 gpm, pH was 7.25, and EC was 793 µS/cm. This exceptionally hard water slightly exceeded State water quality standards in sulfate and aluminum (Appendix A-8), but had lower concentrations of trace metals than NW-46.

Figure 45. Water sample site NW-46 and the altered bedrock and talus of Paradise Basin.

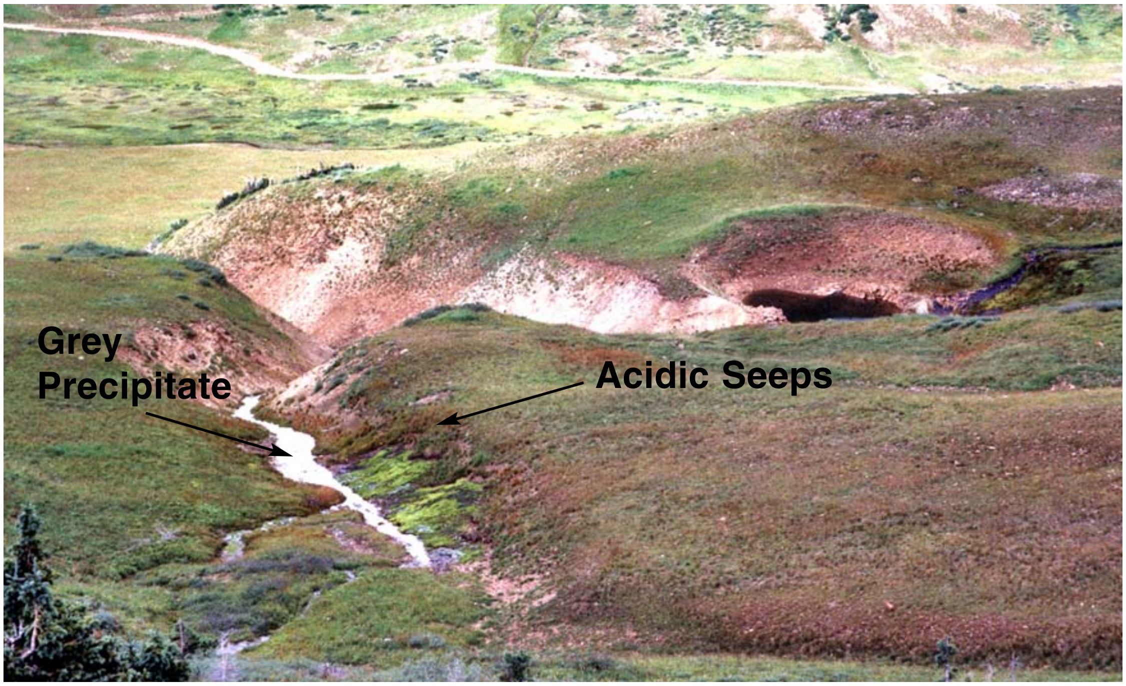


Figure 46. Mixing of waters in Paradise Basin.

The wetlands consist of a series of acidic seeps, probably representing the re-emergence of some of the flow of the stream near water sample site NW-46. The abundant white precipitate that appeared downstream from sample site NW-47 probably consists primarily of aluminum and sulfate that form as the aluminum-rich, acidic waters of the seeps are partly neutralized by the slightly alkaline, calcium- and sulfate-rich waters of the stream from which water sample NW-47 was collected. A PHREEQC simulation of water sample NW-47 indicates that many mineral phases are near or over saturation including alunite, basaluminite, various forms of aluminum hydroxide such as boehmite, diaspore, gibbsite, and an amorphous phase,

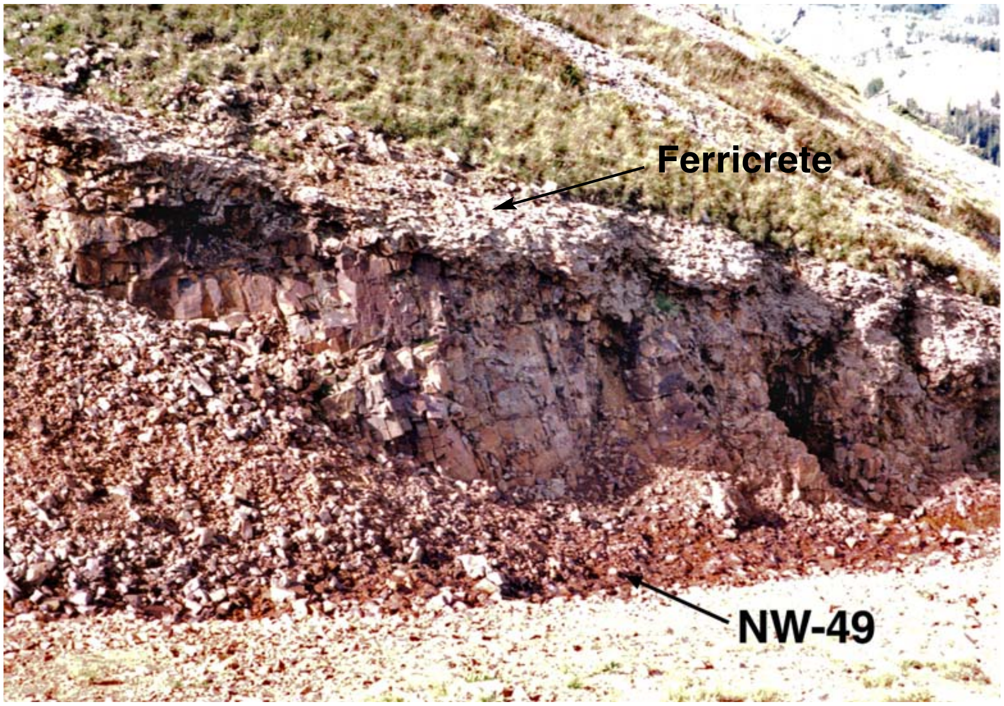


Figure 47. Water sample site NW-49 and ferricrete cap rock about eight feet above the present stream channel in upper Gold Creek.

chalcedony, amorphous ferric hydroxide, K-jarosite, and various clays.

Sample NW-49 was collected from the uppermost headwaters of the south fork of Gold Creek (Figure 43), on the northwest flank of Ruby Peak and about 100 ft downstream from where the water emerges from talus. Bedrock and talus in this area consist of pyritized intrusive rocks. A layer of ferricrete overlies the bedrock about eight feet above the active stream channel, and blocks of broken ferricrete are within and alongside the streambed **(Figure 47)**. Minor amounts of red precipitate coated the channel. Flow was 18 gpm, pH was 2.49, and EC was 1,788 µS/cm. Although the water had an acidic pH, the hardness exceeded 266 mg/L (Appendix A-8), indicating weathering of calcium- or magnesium-bearing minerals. This water exhibited significant effects of ARD, with concentrations of aluminum, arsenic, cadmium, chloride, copper, iron, lead, manganese, silver, sulfate, and zinc exceeding State water quality standards.

Sample NW-50 was collected from Red Lady Basin (Figure 43), above the Keystone Mine and the bog-iron deposit at Keystone Spring described previously. In this vicinity, no major mines are known above this elevation. The walls of Red Lady Basin are altered feldspathic sandstones and carbonaceous shales of the Mesa Verde Formation that have been stained red and brown **(Figure 48)**. A ferrosinter deposit is present within the basin **(Figure 49)**, but when examined for this study, no water was flowing through the deposit. Most of the deposit appeared to be inactive and was weathering into dark brown soil. Sample NW-50 was collected from an unmapped stream on the west side of the basin, peripheral to the ferrosinter deposit. Minor amounts of red precipitate were evident, flow was 6 gpm, pH was 3.76, and EC was only 23 µS/cm. Aluminum, copper,

Figure 48. Altered bedrock and talus in Red Lady Basin.

Figure 49. Partly weathered ferrosinter deposit in Red Lady Basin.

cadmium, manganese, lead, and zinc exceeded standards (Appendix A-8). State water quality standards for lead, zinc, copper, and cadmium were low because of the low hardness of the sample. Metal loads at this sample locale are not substantial because of the low flow rate and low trace-metal concentrations.

Sample NW-51 was collected from a site (originally thought to be a spring) near the middle of the upper part of Redwell Basin, above the Red Well and the Daisy Mine **(Figures 43 and 50)**. This location is on strike with a major NE-trending structure that hosts the base-metal veins in the Daisy and Standard mines. The water emerges from grass and talus within the Mesa Verde Formation near the access road that traverses the basin. Flow was 10 gpm, pH was 3.91, and EC was 61 µS/cm. Lead (410 µS/L) was three orders of magnitude above the State water quality standard. Silver (0.6 µS/L), zinc (670 µg/L), cadmium (5.2 µS/L), copper (43 µS/L), manganese (560 µS/L), and aluminum (830 µS/L) exceeded State standards by over an order of magnitude (Appendix A-8). Recent USGS studies indicate that the source of this water is actually a well-concealed collapsed adit, which discharges water with nearly identical composition to sample NW-51 (R. Wanty, oral commun., USGS, 2002). These unusually high lead concentrations in combination with high zinc but relatively low sulfate, iron, and aluminum concentrations are typical of discharge from the Daisy and other mines in this area (Bove and Knepper, 2000; R. Wanty, oral commun., USGS, 2002).

Reactive solute-transport simulation of pre-mining metal concentrations was performed in the Redwell basin by Kimball and others (2009). The results indicate that although instream pH and metal concentrations were significantly lower prior to mining, aquatic life standards were still exceeded.

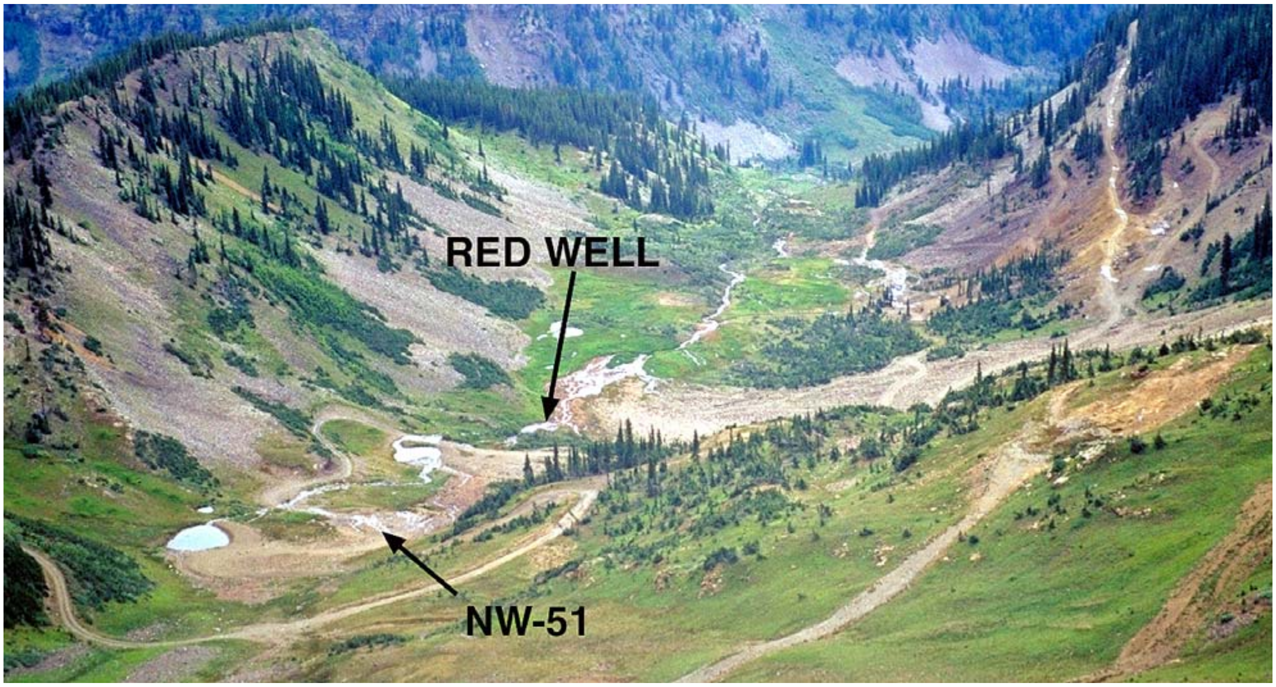
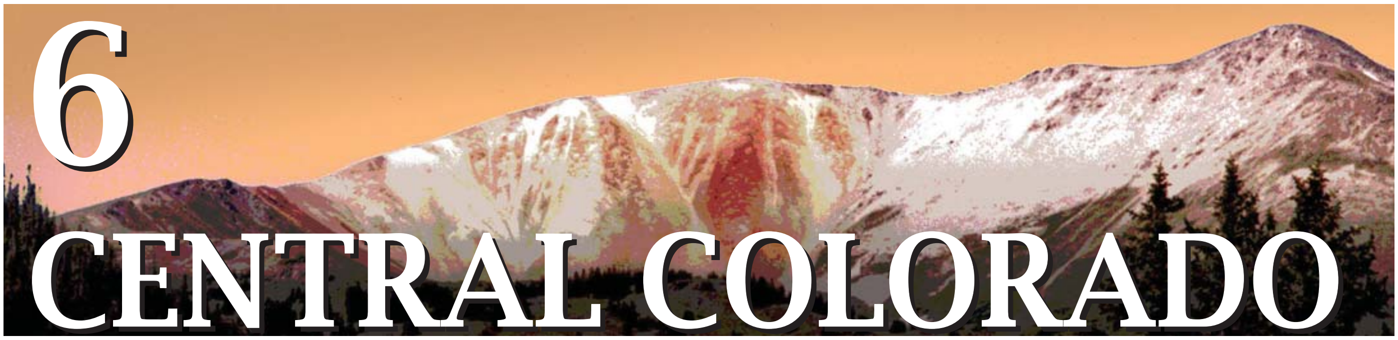


Figure 50. Water sample site NW-51 and Redwell Basin.

6

CENTRAL COLORADO



Three areas in central Colorado that have natural ARD associated with areas of hydrothermally altered rock and related mineralization were investigated during this study. The first of these investigations focused in the area around the Montezuma stock (Figure 1) and associated hydrothermally altered terrane between Breckenridge and Georgetown, where ARD affects several headwater stream basins. The second central Colorado study was conducted at the Red Amphitheatre, a localized area of intense alteration affecting a tributary to Buckskin Creek, northwest of Fairplay. The Twelvemile Creek area (Figure 1) in the southern part of the Mosquito Range, west of South Park, was the third area investigated. As is the case in most of the other areas studied for this report, natural ARD in these three areas is related to shallow, high-level intrusions and associated hydrothermal alteration. However, no Tertiary calderas are currently recognized in these three areas of central Colorado. Detailed mapping of hydrothermal alteration was conducted in the Montezuma and Red Amphitheatre area, while studies in the Twelvemile area were reconnaissance-level only.

MONTEZUMA STOCK

The Montezuma stock and its associated alteration straddle the Continental Divide in Park, Clear Creek, and Summit Counties (Figure 1). Breckenridge is about 10 mi to the west-southwest, Georgetown is about 10 mi to the northeast, and Grant is about 12 mi east-southeast of the central part of the stock.

Natural ARD associated with the altered rocks affects stream basins on both sides of the Continental Divide, as shown on Plate 2 (from unpublished mapping, courtesy of Cyprus-Amax Inc.). Handcart Gulch, a tributary of the North Fork of the South Platte River, and the headwaters of the Snake River were the focus of work in this area. Water samples were also collected from Bruno Gulch and tributaries of Peru Creek.

GENERAL GEOLOGY

Emplacement of the 40 Ma (Oligocene) Montezuma stock and associated dikes and small intrusive plugs was one of the primary factors causing extensive fracturing and mineralization in the Montezuma mining district. The heated, metal-rich fluids that formed economic mineral deposits also created widespread hydrothermal alteration and abundant disseminated pyrite. The Montezuma stock intruded Precambrian hornblende gneiss and schist, and consists primarily of quartz monzonite porphyry. Faults, fractures, and pyrite-rich alteration products associated with the stock extend into the surrounding gneiss (Meyer and others, 1996).

At the surface, the stock only extends southward to about the town of Montezuma, except for a sliver exposed in the headwaters of the North Fork of the South Platte River, on the southwestern side of Hall Valley (Plate 2). The stock broadens at depth, as determined from maps of the Roberts Tunnel (Neuerburg, 1971). The Montezuma Shear Zone, a broad northeast-trending ductile deformation zone, is generally superimposed by a band of argillized, sericitized, and pyritized rocks about one to two miles wide (Plate 2). The shear zone and related trend of altered rocks is present along the southeastern part of the Montezuma stock, and can be traced southward and westward within the Precambrian rock units (Neuerburg, 1971).

Pyrite, galena, and sphalerite are the major sulfide minerals in veins associated with the Montezuma stock. Chalcopyrite and copper sulfosalts are also common. Quartz, manganiferous carbonates, and barite are present as gangue minerals (Neuerburg, 1971). Local molybdenite-rich veins are also common. Ferricrete and ferrosinter deposits are common in the areas underlain and flanked by altered rocks.

INTRUSIVE HISTORY

The Montezuma stock and its associated intrusions are part of a voluminous suite of quartz monzonite porphyries that were emplaced 45–35 Ma along the north-central Colorado Mineral Belt from Empire to Climax (Bookstrom and others, 1987). The copper, zinc, lead, silver, gold and molybdenum-bearing hydrothermal systems of the Montezuma and surrounding area are related to intrusions of this suite of late Eocene-early Oligocene granitic intrusions.

High-silica rhyolite porphyries of the Alma district and Geneva area, near Montezuma, were emplaced about 35–33 Ma. These are compositionally similar to the 33–20 Ma, high-silica, bimodal rhyolite-granite porphyries at Climax and Red Mountain (Bookstrom and others, 1987), sites of two giant porphyry molybdenum deposits.

The Montezuma quartz-monzonite porphyry stock is the largest outcropping pluton in a northeast-trending swarm of smaller stocks, plugs, cupolas, and dikes. This swarm extends from near Breckenridge, northeastward to near Empire. Several cupolas and dikes of sericitic-altered and argillized biotite rhyolite porphyry (of lower silica content) (39–37 Ma) are exposed along the northeast-trending Montezuma Shear Zone and along a broad south to southeast fracture zone between Montezuma and Webster Pass (Bookstrom and others, 1987). These intrusions are spatially and temporally associated with hydrothermal breccias, zones of hydrothermally altered pyritized rock, and swarms of veins and veinlets. It is postulated that these intrusions are connected to a much larger, hidden pluton of quartz monzonite porphyry south of the Montezuma stock (Neuerburg and others, 1974). Relatively sparse 35 Ma dikes and plugs of dacite porphyry locally cross-cut the more abundant 39-37 Ma dikes and plugs of sericitized and argillized, biotite rhyolite (Bookstsrom and others, 1987). A thick sill of 33 Ma, high-silica rhyolite porphyry crops out in the cirque of Geneva Gulch, southeast of the Montezuma stock (Bookstrom and others, 1987). This intrusion may belong to the same family of intrusions as the 33–20 Ma, high-silica rhyolites associated with the Henderson and Climax porphyry molybdenum deposits.

HYDROTHERMAL ALTERATION AND MINERALIZATION

Hydrothermally altered rock and sulfide veins are common throughout the Montezuma district, as shown on Plate 2. Zones of the most intensely altered rock show a strong spatial correlation with the Montezuma Shear Zone, and especially to the less than 40 Ma granite-rhyolite porphyry intrusions (A. Bookstrom, oral commun., 2001). An innermost zone of potassic altered rock is only recognized locally, in the Snake River cirque. This assemblage is characterized by the recrystallization of the intrusive groundmass to quartz and K-feldspar as well as a stockwork of quartz-magnetite-pyrite-molybdenite veinlets (Neuerburg, 1974). Sericitic alteration is concentrated mostly within and adjacent to the post 40 Ma granite-rhyolite porphyry intrusions, although it is also present within the Precambrian rocks localized by faults and other planar structures. The sericitic alteration assemblage produced a pyritic quartz-sericite rock, the original texture of which was commonly obliterated. Quartz and quartz-pyrite veinlets, which occasionally grade transitionally into zones of silicified rock, are common locally. Pyrite within these rocks is typically fine-grained and abundant. Other sulfides including chalcopyrite, bismuthinite, molybdenite, and sphalerite, are rare. In some localities, the sericite-altered rock is vuggy and quite permeable. The vugs are located preferentially in and around the sites of former phenocrysts, which are lined with euhedral muscovite with overgrowths of pyrite and rare sphalerite. Quartz-pyrite veins commonly accompany these vuggy sericitic zones. Neuerburg and others (1974) postulated these zones to be major conduits of the complex hydrothermal system.

Propylitically altered rock is volumetrically abundant throughout the area (Plate 2) and consists of chloritized biotite and partially sericitized plagioclase, with fine pyrite, carbonate, and locally minor sphalerite. These rocks are typically enriched in zinc as well as other ore elements (e.g., copper, molybdenum, and lead), largely due to the abundance of fracture-filling veins. Bleached and argillic-altered zones are also present (Plate 2), but are unimportant volumetrically. Zones of propylitically altered rock grade outward into a regional, weak chloritic zone, in which biotite is altered to chlorite, and hematite is present along fractures (A. Bookstrom, oral commun, USGS, 2000).

The ore deposits within the Montezuma district are dominantly silver-lead-zinc veins, which are localized in and around the margins of hydrothermally altered rock and extend into regions of unaltered rock. Sulfides are mainly pyrite, galena, and sphalerite, generally with tetrahedrite and chalcopyrite and less commonly with sulfosalts of silver and bismuth (Neuerburg, 1971). Other metallic minerals are rarely present, and gold is mostly insignificant. Sericitic and propylitically altered zones on vein margins grade rapidly into unaltered or regional chloritic alteration. Alteration zones range in thickness from nil to several times the vein width (Neuerburg, 1971). The character of propylitic vein margins is generally indistinguishable from the more pervasive regional propylitic alteration.

Molybdenite is disseminated in trace abundance in many of the rocks in the Montezuma area, and is also present locally within vein and fracture fillings (Neuerburg and others, 1974). The disseminated molybdenite spatially corresponds to zones of more intensely altered rock and increases slightly in quantity toward the inner alteration zones. Two groups of molybdenite veins are associated with sericitic and potassic-altered rock, and have been targets of exploratory drilling (Neuerburg and others, 1974).

One group is locally present as a stockwork of quartz-magnetite-pyrite-molybdenite veinlets within potassic altered rock in the area of the Snake River cirque. Several hundred feet to the west, the veinlets are flanked by molybdenite-filled fractures within a sericitically-altered intrusion. Molybdenite veins also are distributed over a relatively large area on the north side of Independence Mountain (west central portion of Plate 2) and are reportedly related to contact metamorphism (Neuerburg and others, 1974).

Geochemical studies by Climax Exploration, Inc. (unpublished data, courtesy of Cyprus-Amax Inc.), suggest the presence of two main centers of intrusion, hydrothermal activity, and mineralization near Santa Fe Peak and Red Cone. These areas, which lie along the Montezuma Shear Zone, are delineated by adjacent stream and spring waters with low pH, anomalous potassium and fluoride, and elevated trace metals such as copper and zinc (Caine and others, 2006).

PREVIOUS WATER QUALITY INVESTIGATIONS

Water samples were collected in 1992 and 1995 from streams on the south and east sides of the Continental Divide in the area of Red Cone (Streufert, 1993; Meyer and others, 1996). In 1992, a water sample was collected from Handcart Gulch, in the upper part of some ferricrete and bog-iron deposits. A small exploration adit had been driven in the higher reaches of the western tributary of this drainage basin. This adit had a shallow pool of standing water, but no water was discharging, and the adit appeared to have negligible impact on local water quality. Water in upper Handcart Gulch exceeded State water quality standards in concentrations of iron and manganese; copper, zinc, and cadmium concentrations were also relatively high. The stream had pH of 3.8 and flow rate of about 1,350 gpm (Sares, 1996).

Field measurements from 1992 indicated low pH and high metal concentrations, which implies the existence of ARD downstream in Handcart Gulch. Natural interaction of the acidic stream water with the extensive bog-iron deposits that line Handcart Gulch may cause the ARD, but disturbance of the deposits made during historic placer mining and small-scale iron mining possibly exacerbates the problem (Sares, 1996).

In 1995, water samples were collected from Handcart Gulch by Meyer and others (1996) as part of a study comparing naturally acidic stream and spring waters to mine discharges in three mining districts in Colorado. Sample results indicate that water in Handcart Gulch contains lower concentrations of trace metals than the other drainage basins in the study area (Iron Creek near the Alamosa River and the East Mancos River). Major cation (calcium, magnesium, potassium, and sodium) concentrations correlated well with sulfate, suggesting that as pH decreases, minerals such as calcite, dolomite, feldspars, pyroxenes, and amphiboles dissolve and neutralize some of the acid. Water from the Whale Mine in Hall Valley, about one mile west of Handcart Gulch (Plate 2), was of considerably different character than that from the natural waters of Handcart Gulch. Although the pH was higher in the mine water, concentrations of cadmium, manganese, lead, and zinc were also greater. Concentrations of aluminum, copper, iron, and sulfate were within the ranges found in the natural waters (Meyer and others, 1996).

In 1999, water samples were collected from Handcart Gulch by Perse (Perse, 2000) as part of his master's thesis studying the relationships between water chemistry and ferricretes in the Gulch. His principal finding was that there was a good correlation between trace metal concentrations (Ag, Cu, Mo, Pb and Zn) in waters and those in corresponding ferricretes. In addition he found limited change in stream pH (2.9 to 3.7) along the 5,000 meter course of the sampled portion of Handcart Gulch.

The U.S. Geological Survey recently conducted a study of the Snake River watershed in order to assess the impact of past mining activities on trout survivability and water quality in Dillon Reservoir (Fey and others, 2002). They collected 36 surface water samples and 38 streambed samples with discharge measurements at each site. Sampling covered the complete watershed with the heaviest emphasis on the upper Snake River and Peru Creek where historic mining was centered. In general, their findings were that the most contaminated waters were located in the upper Snake River area, and the reach of Peru Creek between Cinnamon Gulch and its confluence with the Snake River. Iron, aluminum, manganese, lead, zinc and copper were all highest in the same reaches. Metal loading calculations indicated that Cinnamon Gulch contributes a very minimal portion of the total load to the Snake River, even though the metal concentrations were very high. CGS performed a watershed characterization of Cinnamon Gulch (Wood and others, 2005; Bird, 2003). The study measured and sampled mine effluent, natural springs, and stream discharge in Cinnamon Gulch. Results indicate that directly measureable mining-related effluent accounts for only 4 percent of the metal load in Cinnamon Gulch during low(base) flow and 5 to 8 percent of the load during high flow. Subsurface drainage from the Pennsylvania mine area near Cinnamon Gulch appeared to be a significant contributor to the total metal loading. In addition, a groundwater source of high copper and zinc loading was noted in the Peru Creek reach between Chihuahua Gulch and the confluence with the Snake River (Fey and others, 2002).

In 1992, two samples were collected from Bruno Gulch (Note: on the newest U.S. Geological Survey topographic map of the Montezuma quadrangle, this feature is labeled as “Buno”, and that is how it is reported in Sares (1996) and Streufert (1993). Older U.S. Geological Survey publications use “Bruno”, as does the newest version of the Mount Evans quadrangle immediately to the east). Bruno Gulch is a tributary of Geneva Creek and drains the eastern side of Red Cone (Plate 2). No known mines are within this drainage basin. Water in upper Bruno Gulch exceeded State water quality standards in concentrations of aluminum, copper, and zinc. Inflows of relatively pure water from unaltered areas diluted the poor quality water so that a sample from lower Bruno Gulch only slightly exceeded standards in cadmium. The upstream water had pH of 5.5, and an estimated flow of 900 gpm. The downstream water was flowing at an estimated rate of 2,250 gpm and had pH of 8.2 (Sares, 1996).

Extensive bog-iron deposits occur north of Webster Pass in the upper reaches of the Snake River drainage basin (Plate 2). This swampy, iron-rich feature is called the Snake River fen by recent researchers. Numerous acidic, metal-rich springs and seeps draining to the northwest from the northwest slope of Red Cone have deposited ferrihydrites on the mountain slope and along the bottom of the Snake River. The precipitates have formed deposits that extend about 1,000 ft along the slopes of Red Cone and are about 100 ft wide along the marshy drainage bottoms. Discontinuous deposits occur for about one mile along the Snake River. Thicknesses of up to 10 ft were observed (Harrer and Tesch, 1959; Perse, 2000).

Limonite deposits that have formed from ferruginous spring water are present in Upper Geneva Creek (referred to as West Geneva Creek in Harrer and Tesch, 1959) northwest of Grant (Plate 2). The source of the iron is probably oxidized pyrite associated with the altered Montezuma stock and surrounding country rock. Although old mines have been driven in veins above these iron-rich springs, the limonite deposits predate the mining operations, and they are still forming today. The limonite occurs in at least five distinct deposits, the dimensions of which vary from 700 to 4,200 ft long, 200 to 500 ft wide, and up to 15 ft or more thick (Harrer and Tesch, 1959). Natural ARD has probably emerged from the associated springs for thousands of years in order to form the thick limonite deposits. However, mining in the upstream reaches also may have introduced anthropogenic ARD to the stream.

PRESENT WATER QUALITY INVESTIGATION

Most of the samples collected during this investigation were from the Handcart Gulch drainage basin and tributaries of the Snake River (Plate 2), although a few samples were collected from tributaries of Peru Creek and from Bruno Gulch.

Red Cone Area — Handcart And Bruno Gulches

Bedrock at Red Cone **(Figure 51)** consists of Precambrian schist and gneiss that was intensely

Figure 51. Headwaters of Handcart Gulch and Red Cone.

altered to an assemblage of QSP during the emplacement of dacitic to granitic intrusions related to the Montezuma stock. Disseminated pyrite is abundant in the bedrock and in rocks of the talus slopes (Caine and others, 2006).

Below the talus slopes, extensive bog-iron and ferricrete deposits exist in Handcart Gulch and Hall Valley, near the headwaters of the North Fork South Platte River. In Handcart Gulch, the deposits extend from near Red Cone and Webster Pass downstream to its confluence with Hall Valley, then a short distance farther downstream in Hall Valley. The deposit is about 100 ft wide and 6 or more feet thick. Composition of the deposit varies considerably, from older and well indurated, hard material to soft, freshly precipitated ferrihydrites (Harrer and Tesch, 1959; Streufert, 1993).

In August 1999, samples were collected from the two uppermost tributaries of Handcart Gulch (NW-36 and NW-37, Plate 2). The eastern tributary drains the south side of Webster Pass and the area of strong QSP alteration on the southwest slope of Red Cone. Minor ferricrete exists in the basin above sample site NW-36, and the exposed bedrock is stained bright red. Alluvium in the channel comprises iron-stained, propylitized and argillized granitic and metamorphic rocks, some with disseminated pyrite. Stream water flowing at 48 gpm had 3.59 pH and 201 µS/cm EC. Aluminum, cadmium, copper, zinc, and manganese concentrations exceeded State water quality standards **(Appendix A-9)**.

The western tributary drains the eastern side of Handcart Peak (Plate 2) and is coated with brown and orange-red ferrosinter and ferricrete. Fresh and older, partly decomposed ferricrete and ferrosinter deposits cover much of this valley floor, which is in a wetland environment. QSP altered bedrock exposed on the walls of this drainage basin has been stained red, yellow, and brown. At sample site NW-37, the creek was flowing at about 165 gpm and had pH of 3.47, EC of 296 µS/cm, and contained much higher metal concentrations than the eastern tributary. Aluminum, iron, manganese, nickel, zinc, and cadmium values exceeded State standards (Appendix A-9).

Discharges from numerous surface seeps and subsurface interflow in talus probably contribute to ARD downstream in Handcart Gulch. Samples NW-38 and NW-40 were collected from springs or seeps on the east side of Handcart Gulch (Plate 2). Sample NW-38 was collected from one of several seeps that emerge near the toe of a large rock glacier that consists of yellow QSP altered rocks from the southwestern side of Red Cone. This water had pH of 2.63 and EC of 2,980 µS/cm. Analytes exceeding State water quality standards included iron, aluminum, copper, manganese, chromium, sulfate, nickel, zinc, cadmium, and sulfate (Appendix A-9). Handcart Gulch contained some ferricrete and precipitate above this area of numerous seeps. Below the confluence with the seeps, water in Handcart Gulch had pH of 3.17 and EC of 688 µS/cm. Orange-red precipitate coating the streambed was more abundant than above the confluence.

Sample NW-39 was collected from Handcart Gulch downstream from the group of seeps near NW-38 and upstream from the springs at NW-40 (Plate 2). The stream channel was coated with ferricrete and abundant orange-red precipitate, and lesser amounts of gray-yellow precipitate **(Figure 52)**. Streamflow was 500 gpm, pH was 3.15, and EC was 843 µS/cm. Concentrations of aluminum, iron, copper, manganese, zinc, cadmium, and nickel values exceeded State water quality standards (Appendix A-9). A few hundred feet downstream from this sample site, the quantity of

Figure 52. Water sample site NW-39 and Handcart Gulch.

orange-red precipitate increased and formed terraces in the stream. Rocks on the ridge that forms the drainage divide between Handcart Gulch and Hall Valley are fractured, altered, and stained brownish-yellow. Rocks on the ridge northeast of Handcart Gulch also contain strong QSP alteration (Plate 2).

Sample NW-40 was collected from a spring that emerges from a 10-ft-long prospect adit in a large ferrosinter deposit on the east side of Handcart Gulch (Plate 2). This small adit is entirely within the ferrosinter. Although it is possible that the quality of water emerging from the adit is no different than premining water that might have discharged, it is likely that the presence of the adit has allowed an increased availability of oxygen, which in turn is increasing the oxidation of rocks within the adit and adversely affecting water quality. Several smaller springs emerged from this brown and yellow-green ferrosinter deposit, but the spring from which sample NW-40 was collected was the largest, with a flow rate of about 25 gpm. EC of the water was 1,004 µS/cm and the pH was 3.61. The sample was slightly cleaner (less total dissolved solids) than NW-38, but greatly exceeded State water quality standards in aluminum and iron concentrations. Manganese, cadmium, copper, sulfate, and zinc also exceeded State water quality standards (Appendix A-9). Near the mouth of Handcart Gulch, precipitate was abundant, and the stream water had pH of 3.19 with EC of 673 µS/cm (just off the southern boundary of Plate 2), indicating that the water quality was similar to that of sample NW-39 and influence from natural ARD extended the length of the drainage. No sample was collected at the mouth of Handcart Gulch, because some small draining mines about 0.25 mi downstream of sample site NW-40, and upstream of the mouth, may affect water quality.

Water samples were collected from the main branch and the north fork of Bruno Gulch in the fall of 1999. Water sample NW-58 was collected from the north fork that drains the southeastern side of Landslide Peak (Plate 2). Rocks in the headwater area of this stream appear propylitically altered and are stained dark brown, but most of the stream reach is outside of the altered area mapped by Neuerburg (1971) and by Climax (Plate 2). This water had no significant concentrations of metals (Appendix A-9). Water sample NW-59 was collected from Bruno Gulch, upstream from its confluence with the north fork (Plate 2), at approximately the same location as the 1992 sample discussed under Previous Water Quality Investigations. The QSP alteration of the eastern slope of Red Cone forms part of the headwater area for this stream segment. The streambed and algae were coated with minor amounts of light-brown precipitate, and the pH was moderately acidic at 4.85. Although the flow was considerably different in 1999 (80 gpm) than in 1992 (900 gpm), the two water samples had similar concentrations of metals. The 1999 sample (NW-59) exceeded State water quality standards in concentrations of aluminum, iron, copper, zinc and manganese (Appendix A-9).

A water test of the south fork of Bruno Gulch indicated good quality water, with neutral pH and EC of 29 µS/cm (Plate 2). Most of the gently sloping terrain above this site was covered with alpine vegetation, alteration of the bedrock was not obvious. The area has not been mapped as altered by Climax Exploration (Plate 2). A water test in Sawmill Gulch, near its mouth, revealed pH of 6.40 and EC of 47 µS/cm, indicating no significant ARD in the surface waters in this area, which is consistent with the lack of alteration in the headwater area.

Snake River

Extensive iron bogs are present within and adjacent to the alteration zone associated with the Montezuma stock (Neuerburg, 1971), and are consistent with metal-rich drainage near the headwaters of the Snake River. Numerous water tests and samples were collected from the stream and springs in this area (Samples NW-14 to NW-24, NW-41, NW-42, and nearby test sites shown on Plate 2), the upper reaches of which are essentially devoid of mines or prospects. Water samples collected farther north (NW-25 to NW-28 and NW-45) are downgradient from some small mine workings, but the mines and associated waste rock piles are not draining and are believed to have no significant effect on water quality.

Water samples and tests confirmed the presence of natural ARD in stream and spring water in the southern portion of the Snake River drainage basin, primarily from springs and streams originating on the east side of the river. From the southern slopes of Santa Fe Peak to Webster Pass, the pH of the surface water was between 3.3 and 5.31, and EC ranged from 18 to 289 µS/cm.

Water sample NW-14 was collected from a 7-gpm seep about 2,000 ft north of Webster Pass (Plate 2). Water sample NW-15 was collected above the seep in an adjacent stream that was flowing at 150 gpm. Both sites originate from the area of strong QSP alteration near the top of Webster Pass and on the northwestern slope of Red Cone. Water from the seep was slightly more acidic than that in the stream, and had higher EC, but most metal concentrations were similar (Appendix A-9). Both samples exceeded State water quality standards in concentrations of aluminum, copper, and zinc. Water from the seep also exceeded State water quality standards in cadmium and lead.

Downstream in the same tributary, samples NW-42 and NW-43 were replicate samples collected from a site adjacent to a 4WD trail (Plate 2). Flow increased from 150 to 400 gpm between the two sites, pH decreased to 3.68, and EC increased to 113 µS/cm. The stream channel was steep and had red precipitate, some of which was relatively indurated and some quite soft and muddy. Terracettes of ferrosinter/ferricrete were present in the lower reach, but were not as well developed as those in tributaries to the north (described in the following paragraphs). Concentrations of aluminum, iron, and zinc increased substantially compared with those in the upstream sample, and the stream water exceeded State water quality standards in aluminum, iron, zinc, manganese, and cadmium (Appendix A-9). Copper was quantified at the detection limit (4 µg/L) in NW-42 exceeding standard, but was not detected in the replicate sample. Hardness was low in all of the samples (<20 mg/L), therefore hardness-related standards for copper, zinc, and cadmium were low as well.

Water samples NW-16 and NW-41 were taken from the adjacent tributary to the north of sample NW-42 (Plate 2). This tributary drains a large area of altered granitic rock and amphibolite with dark brown, light brown and yellow stains. A large area of QSP alteration is immediately above sample site NW-16, and propylitic alteration is present near the top of the ridge. At sample site NW-16, streamflow was 80 gpm, pH was 3.91, and EC was 74 µS/cm. Aluminum, copper, zinc, and manganese concentrations exceeded State water quality standards (Appendix A-9). At water sample site NW-41, the stream flows over terracettes of red precipitate; the flow was 500 gpm, pH had decreased to 3.32, and EC had increased to 274 µS/cm. Aluminum, iron, manganese, copper, nickel, zinc, and cadmium concentrations exceeded State water quality standards (Appendix A-9). The conditions were similar to those of the previously described tributary in that pH decreased and metal concentrations and EC increased in the downstream direction. Water tests from upstream to downstream verified the decrease in pH and increase in EC (Plate 2). At the water test site that had pH of 3.63 and EC of 161 µS/cm (Plate 2), a large, partly weathered ferrosinter deposit is exposed. From this limited, reconnaissance-level sampling and testing, it is not clear whether the ferrosinter deposit affects the surface water chemistry, or if the deposit indicates an area of poor-quality groundwater that discharges to the surface.

Water samples NW-17 to NW-20 are from the drainage basin on the southwest side of Landslide Peak (Plate 2). The upper slopes of the drainage basin have exposures of propylitic and QSP alteration and have been stained brown and yellow. A large, actively-forming ferrosinter deposit is exposed on the slope **(Figure 53)**. Numerous springs emerge in and near the ferrosinter deposit. Shallow prospect pits excavated within the bog-iron deposit do not appear to discharge any water that could affect water quality in the drainage.

Two samples were collected at this ferrosinter deposit. Sample NW-20 was taken from a pool of clear water near the upper part of the deposit (Figure 53). Hardened, red-brown precipitate formed the walls of the pool, which was about two feet deep **(Figure 54)**. Flow from the pool was dispersed and unmeasurable, but was estimated at about 10 gpm. The pH of the water was 3.84 and EC was 163 µS/cm. Concentrations of aluminum, copper, iron, manganese, zinc, and cadmium exceeded State water quality standards (Appendix A-9).

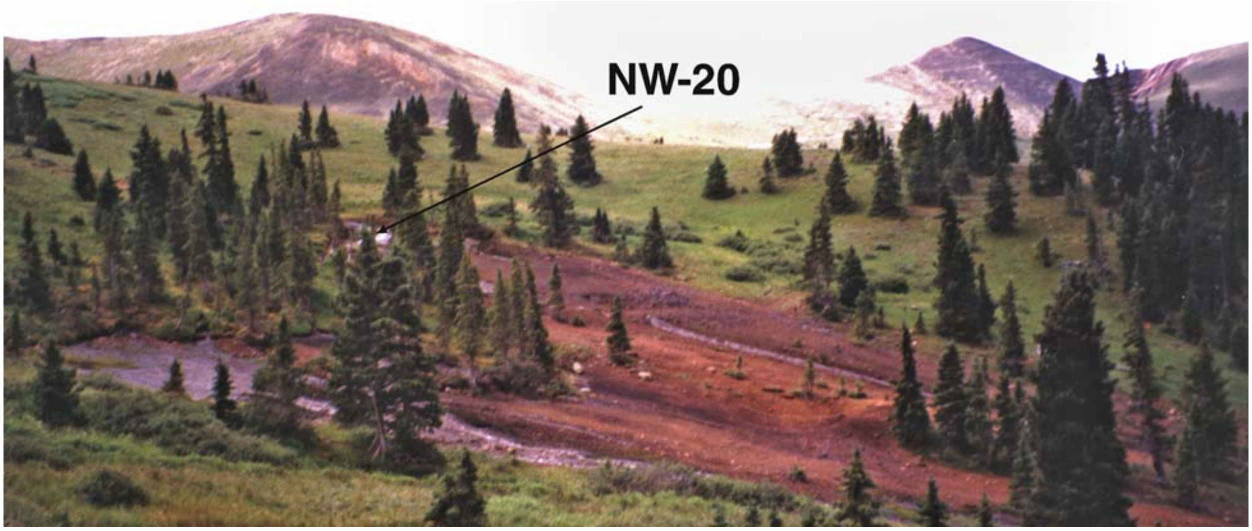


Figure 53. Water sample site NW-20 at ferrosinter deposit on the southwest side of Landslide Peak.

Figure 54. Pool of water in ferrosinter deposit at water sample site NW-20.

Water sample NW-18 was collected near the lowest part of the exposed portion of the ferrosinter deposit, just upstream from the confluence of the ferrosinter drainage with the mapped stream flowing from the southwest side of Landslide Peak (Plate 2). Several of the springs and seeps associated with the ferrosinter deposit had coalesced into larger streams. Sample NW-18 was from the largest of these streams, which flowed at 30 gpm. The pH was 3.3 and the EC was 233 µS/cm. Although pH and EC indicate that water near the base of the ferrosinter deposit was more acidic and metal-rich than water in the spring near the top of the deposit, laboratory analyses show that concentrations of most trace-metals were lower in the water at the base of the deposit. Although still above standards, aluminum and iron concentrations were significantly lower in sample NW-18 than in NW-20, and copper was somewhat lower (Appendix A-9). Zinc and cadmium concentrations exhibited minor change, and the manganese concentration increased slightly in the lower area. The higher EC of water at the base of the deposit (NW-18) probably resulted from additional sulfate in the water, although sulfate concentrations still met the State water quality standard. The decrease in pH may be attributable to hydrolysis. Water sample results indicate that the ferrosinter deposit contains abundant iron and aluminum with anomalous concentrations of copper.

Water sample NW-19 was from the mapped tributary draining the area of dominant propylitic alteration on the southwest side of Landslide Peak, upstream of any obvious influence from the springs at the ferrosinter deposit (Plate 2). Flow rate was 300 gpm, pH was 4.81, and EC was 18 µS/cm. The stream channel had no apparent precipitate. Aluminum and zinc concentrations slightly exceeded State water quality standards. Iron, copper, and cadmium levels were below detection limits, but the copper and cadmium detection limits exceeded State water quality standards due to the water’s low hardness of 5 mg/L (Appendix A-9).

A water test downstream of the confluence of the relatively clean water of NW-19, with the poor-quality water associated with the ferrosinter deposit, had pH of 3.9 and EC of 89 µS/cm (Plate 2). Below the confluence, the main stream channel is coated with smooth, hard, red, precipitate that creates a flume-like appearance.

Sample NW-17 was collected from this same mapped stream about 2,000 ft downstream from the ferrosinter deposit (Plate 2). Streamflow was 800 gpm, pH was 3.79, and EC was 89 µS/cm. Abundant red precipitate, some well indurated, coated the stream channel, occasionally forming terracettes. Aluminum, copper, manganese, iron, zinc, and cadmium exceeded State water quality standards (Appendix A-9).

Numerous seeps with associated red precipitate emerge on the eastern side of the Snake River between sample sites NW-42 and NW-17 (Plate 2). Water tests from some of these seeps revealed similar pH and EC as the samples collected in streams nearby, indicating that large volumes of water with similar chemistry flow beneath and at the surface, eventually draining into the Snake River. These acidic, metal-rich tributaries and numerous seeps and springs contribute substantially to metal loads in the upper Snake River, and are above all known significant mining activity.

Water sample NW-21 was collected in the headwaters of the Snake River, upstream from water sample NW-42 (Plate 2). This sample site is above all of the large bog-iron deposits, near the western boundary of the hydrothermally altered area (Neuerburg, 1971), and within a zone of potassic-altered rock cut by molybdenite veins. Although rocks on the northwest side of Handcart Peak were stained brown, this 62-gpm stream appeared to have minimal influence from ARD, with pH of 5.79 and EC of 82 µS/cm. Much of the stream gravel had a red, iron-oxide coating. Most metals were not detected in water sample analyses, and none exceeded State water quality standards (Appendix A-9).

The alteration zone shown by Neuerburg (1971) (Plate 2) extends northward along the Montezuma Shear Zone. Historic mining features are common in the area. Numerous water tests and samples (NW-22 to NW-24) were collected from the Snake River and its tributaries, which drain the Continental Divide from Geneva Peak northward to the southwest side of Santa Fe Peak (Plate 2). Efforts were made to select samples from locations that drain unmined areas, or areas where previous mining activity was absent or limited. A few small, dry mines lie above some of the sample sites, however the effect of these mines on water quality is probably minimal. Some of the water tests shown on Plate 2 are from streams that may be influenced by past mining activities.

Water sample NW-24 was from an unnamed stream between Geneva Peak and Sullivan Mountain (Plate 2). The sample was collected near the lower end of a contiguous deposit of ferricrete and ferrosinter, immediately below the confluence of the mapped stream and an unmapped stream flowing from the east. Flow was 200 gpm, pH was 3.77 and EC was 197 µS/cm. Concentrations of aluminum, copper, manganese, iron, zinc, and cadmium exceeded State water quality standards (Appendix A-9). Two water tests upstream of the ferruginous deposit had pH greater than 5 and EC less than 40 µS/cm (Plate 2).

Water sample NW-23 was taken from a stream draining southwest from Sullivan Mountain (Plate 2). Iron-stained rocks and distinct veins compose the slopes of this drainage basin, and the stream channel is coated with ferricrete. Yellow filtrate, which clogged the water filter, indicated that the stream was carrying suspended solids. Streamflow was 300 gpm, pH was 3.84, and EC was 289 µS/cm. Concentrations of aluminum, manganese, zinc, iron, nickel, cadmium, and copper exceeded State water quality standards (Appendix A-9). Water tested near the upper part of the ferricrete channel had pH of 4.41 and EC of 258 µS/cm (Plate 2).

Downstream from its confluence with the streams from which samples NW-23 and NW-24 were collected, the Snake River water had pH of 3.82 and EC of 117 µS/cm, and the channel contained abundant red precipitate (Plate 2).

Water sample NW-22 was collected from an unmapped stream draining the southwest side of Santa Fe Peak (Plate 2). The sample was collected upstream from any obvious influence from the Climax Mine, however the first discharge of water along this stream is directly downgradient from a talus and colluvial slope below the Climax mine. While the mine wasn't draining, the water was about 4 degrees C, and the very high base-metals content of this sample suggests possible influence from the subsurface workings of the Climax mine as well as mixing with groundwater. Several other small mines are situated on the south side of Santa Fe Peak above this sample site. Most of the alluvium consisted of gneissic rocks with coatings of red iron-oxide and black manganese-oxide. Flow was 80 gpm, pH was 4.41, and EC was 258 µS/cm. Concentrations of aluminum, manganese, zinc, copper, cadmium, and lead exceeded State water quality standards (Appendix A-9). A south-flowing tributary upstream of this sample site had pH of 5.14 and EC of 200 µS/cm (Plate 2).

Peru Creek

The north-facing slopes of the Continental Divide drain toward Peru Creek and are within the area of hydrothermal alteration mapped by Neuerburg (1971) and Climax Exploration (Plate 2). The Montezuma stock is exposed at lower elevations on these slopes. Samples NW-25 to NW-28, and NW-45 were collected from some of these north-flowing tributaries (Plate 2). Numerous small mines have been driven into the slopes in this area containing red and yellow staining, QSP alteration and silicification, but most of the large mines are at lower elevations. During this study, efforts were made to collect samples from streams that were above all known mines discharging water and mines with significant workings.

Water sample NW-25 was taken from an eastern tributary of Warden Gulch that drains the area of QSP alteration on the northwest side of Brittle Silver Mountain (Plate 2). Rocks in the streambed had a red stain, but no precipitate was evident. Water was flowing at 50 gpm with pH of 4.29 and EC of 117 µS/cm. Concentrations of aluminum, manganese, copper, zinc, and cadmium exceeded State water quality standards (Appendix A-9).

Sample NW-26 was taken from a tributary of Peru Creek that drains the northwest side of Brittle Silver Mountain (Plate 2). The streambed contains granitic rocks of the Montezuma stock, altered to a QSP assemblage and stained yellow and red. Streamflow was 15 gpm, pH was 3.89, and EC was 179 µS/cm. Concentrations of metals in this water exceeded State water quality standards for the same parameters as those of sample NW-25, but the concentrations of most trace metals were three to five times higher than in NW-25 (Appendix A-9). The aluminum concentration was comparable to that of NW-25

Water sample NW-27 was collected from a 5-gpm spring that drains into an unmapped, northeast-flowing tributary of Cinnamon Gulch (Plate 2). This spring was one of several on the north-facing slope of a grassy, swampy basin. About 20 ft to the west of the spring, another spring emerged from an 8-ft-deep prospect pit. Many of the springs, including the one at the prospect pit, emerged from a sub-horizontal fracture in the bedrock. Bedrock and talus on the slopes above the spring had brown iron staining, and alteration appears to be weak propylitic (Plate 2). The springs had no visible indications of ARD, but pH was 3.65 and EC was 143 µS/cm. This water exceeded State water quality standards for copper, lead, silver, aluminum, zinc, manganese, cadmium, and thallium (Appendix A-9). It is reasonable to assume that the other springs emerging from this fracture have similar water quality. If so, this series of springs may be a significant source of metal loading to water in upper Cinnamon Gulch.

Water sample NW-28 was collected from a large spring emerging near the base of a steep slope on the eastern side of Cinnamon Gulch (Plate 2). Moderate amounts of light yellow precipitate coat the rocks in the stream channel. The yellow precipitate continues downstream for about 500 ft to where the spring water merges with the main stream of Cinnamon Gulch. Bedrock and talus exposed on the slopes above this 300-gpm spring are locally intensely altered along veins and are stained brown, red-brown, and yellow. EC was 142 µS/cm and pH was 4.54. Concentrations of manganese, aluminum, copper, zinc, and cadmium exceeded State water quality standards (Appendix A-9). The water was moderately hard, so standards for zinc, copper, and cadmium were higher than those for most of the samples collected near the Montezuma stock.

Sample NW-45 was collected from the upper basin of Cinnamon Gulch, just above the Silver Spoon Mine (Plate 2), where the drainage follows a large vein. Bedrock and talus on the slopes have been strongly altered and are stained brown, red-brown, and yellow. The stream was flowing at 220 gpm with slight turbidity. EC was only 29 µS/cm and pH was 4.37. No precipitate was observed in the channel. Although the water did not have significantly high metal concentrations, the low hardness of the sample resulted in concentrations of zinc, lead, aluminum, copper, cadmium, and manganese exceeding State water quality standards (Appendix A-9).

Beginning a few hundred feet downstream from NW-45 in the upper basin of Cinnamon Gulch, at the approximate elevation of the Silver Spoon Mine, Cinnamon Gulch has moderate to abundant red precipitate coating the streambed. Water was not sampled in the precipitate-coated portion of Cinnamon Gulch because multiple abandoned mines in and along the flanks of this upper basin probably contribute ARD downstream from the Silver Spoon Mine. The abundant red precipitate in upper Cinnamon Gulch appears to be caused by a combination of natural springs that emerge in this basin (such as the spring of NW-28), and the effluent from some of the abandoned mines that intersected water-bearing, mineralized fractures.

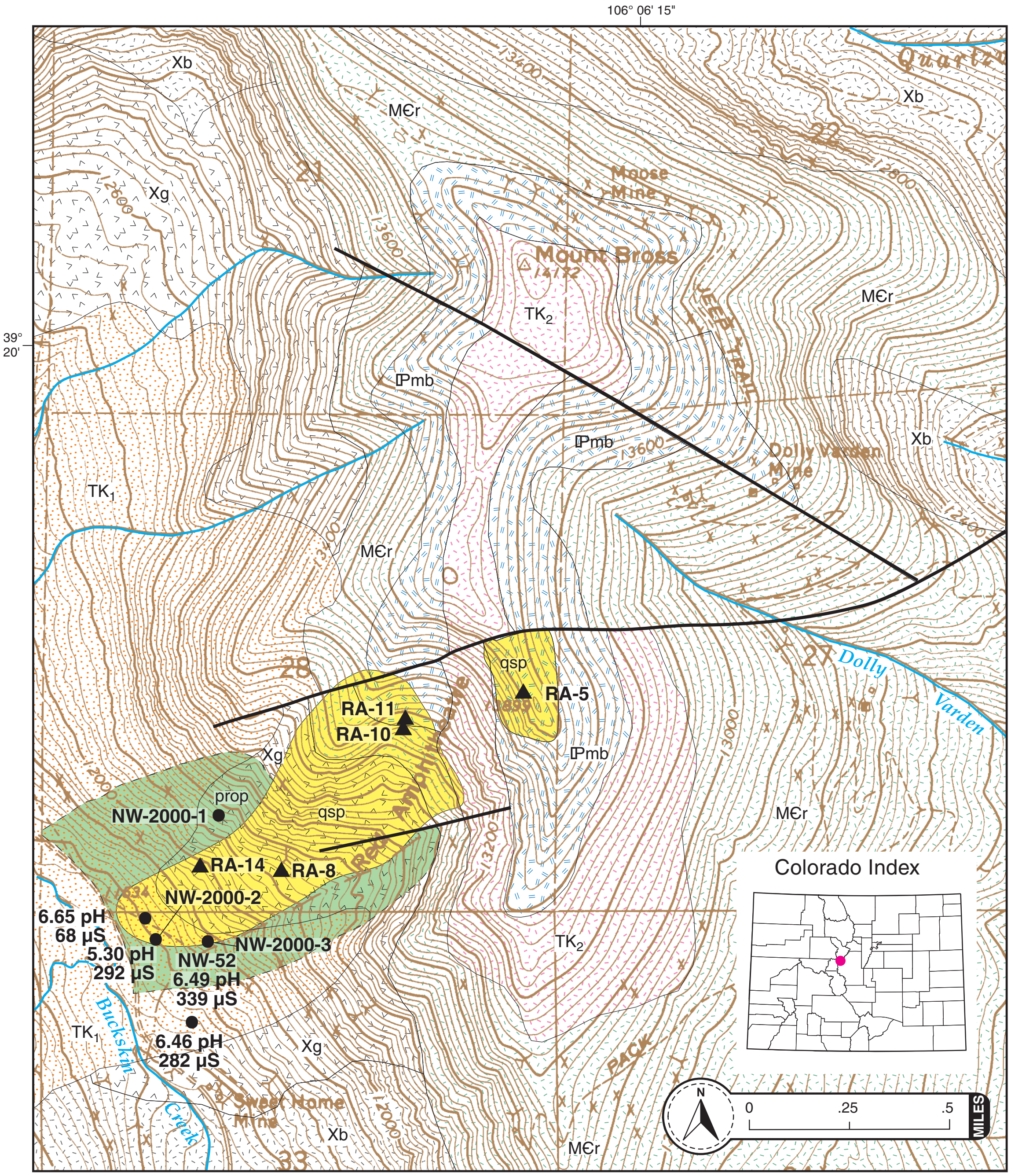
In summary, essentially all surface waters and springs along the Montezuma Shear Zone have been significantly influenced by ARD. The most prominent ARD is seen in drainage basins having prominent QSP alteration. The only waters in the area that are relatively unaffected are those of the north branch and the south fork of Bruno Gulch, which are outside of the Montezuma Shear Zone.

RED AMPHITHEATRE

An area of natural ARD is present in Red Amphitheatre (Figure 1), upgradient from the Sweet Home Mine and about five miles northwest of Alma in Park County. Red Amphitheatre is about one-half mile long and one-quarter mile wide **(Figure 55)**. The unnamed stream that drains this basin merges with Buckskin Creek, eventually flowing into the Middle Fork of the South Platte River near Alma. Hydrothermal alteration was mapped in detail with five rock and four water samples collected for this investigation.

GEOLOGY

The area is a marginal zone of hydrothermally altered Paleozoic sediments and Precambrian rocks that are beneath and adjacent to an unaltered, Laramide-age, quartz-monzonite porphyry sill that caps Mount Bross and extends southward along the ridgeline. The Laramide-age Buckskin Stock forms a large, poorly exposed intrusive body at the lower elevations of the area (Tweto, 1974; Tweto and others, 1978). Three zones of fracture-controlled QSP alteration trend northeast across the Precambrian and Paleozoic rocks



Base map from USGS 7.5-min. Alma quadrangle; geology after Widmann, 2004; Alma quad, CGS OFR 04-03; alteration mapped by J. Kurtz, 2000

EXPLANATION

▲ Rock sample with XRD and chemical analysis

● Water sample location and test results

— Fault

ALTERATION

qsp Quartz-sericite-pyrite

prop Propylitic

GEOLOGY

TK$_1$ Tertiary-Cretaceous intrusive stock

TK$_2$ Tertiary-Cretaceous intrusive sill

ℙmb Pennsylvanian Minturn and Belden Formations

MЄr Missisipian Leadville Dolomite, Devonian Chaffee Formation, Ordovician Manitou Dolomite, Cambrian Peerless Formation and Cambrian Sawatch Quartzite

Xg Precambrian granite

Xb Precambrian biotite gneiss

Figure 55. Map showing geology, hydrothermal alteration, rock and water sample sites, and water test results for the Red Amphitheatre area.

in Red Amphitheatre and are most prominent on the north wall of the drainage (Figure 55). These zones are characterized by fine-grained pyrite in veinlets and disseminations, with sericitic alteration of feldspar. Much of the pyrite has oxidized to jarosite and various iron oxides to produce a distinctive coloration of the rocks. Quartz veinlets and silicified carbonate rocks are associated with this alteration type. Fracture zones, trending N70E to east-west and dipping 80N, appear to host the major QSP alteration in the Red Amphitheatre area. Another major structural feature of the area is a set of N60W trending fracture planes and dikes of Laramide quartz monzonite porphyry.

The prominent weathered outcrops are coated with brown goethite, yellow jarosite, red hematite and black manganese oxides. Chlorite (after biotite and hornblende) is the dominant alteration mineral in the propylitic alteration zone outside the zone of sericitic alteration. Veinlets of chlorite, pyrite-chlorite, quartz-chlorite, and quartz-chlorite-hematite are common. Staining by black manganese oxide is ubiquitous on weathered exposures of chloritized rocks.

Several small workings or prospects are present on the south side of Red Amphitheatre at high elevations within the altered Paleozoic sediments. These all are at relatively inaccessible locations on the cliffs, at elevations above 12,900 ft. Associated very small waste rock dumps indicate minimal workings. No active drainage from any of the workings was visible.

One small mine was developed on the lower, northwestern side of Red Amphitheatre at the lowest rock exposure (shown as an adit at 12,290 ft on Figure 55 at rock sample location RA-8). The rocks here are pyritic and sericitic Precambrian gneiss, which are cut by veinlets of pyrite, blackjack sphalerite, and rare chalcopyrite. A high-grade sample (biased toward ore-bearing rock) was collected from the waste rock dump (sample RA-8). Purple, green, and white fluorite is locally present in vugs. The north-trending adit follows no obvious structure and has completely collapsed.

Much of the drainage basin of Red Amphitheatre consists of iron-stained talus and colluvium that flank steep ridges **(Figure 56)**. A small tributary of Buckskin Creek flows along the western side of the bold colored outcrops in Red Amphitheatre. The upper drainage basin of the western tributary is within colluvium from an unaltered quartz monzonite porphyry, and includes Paleozoic sediments, and propylitically-altered Precambrian gneiss.

The late Cretaceous-early Tertiary (Bookstrom, 1989) porphyry sill forming Mt. Bross and the ridgeline extending southward across the head of Red Amphitheatre is a quartz monzonite composed of coarse potas-

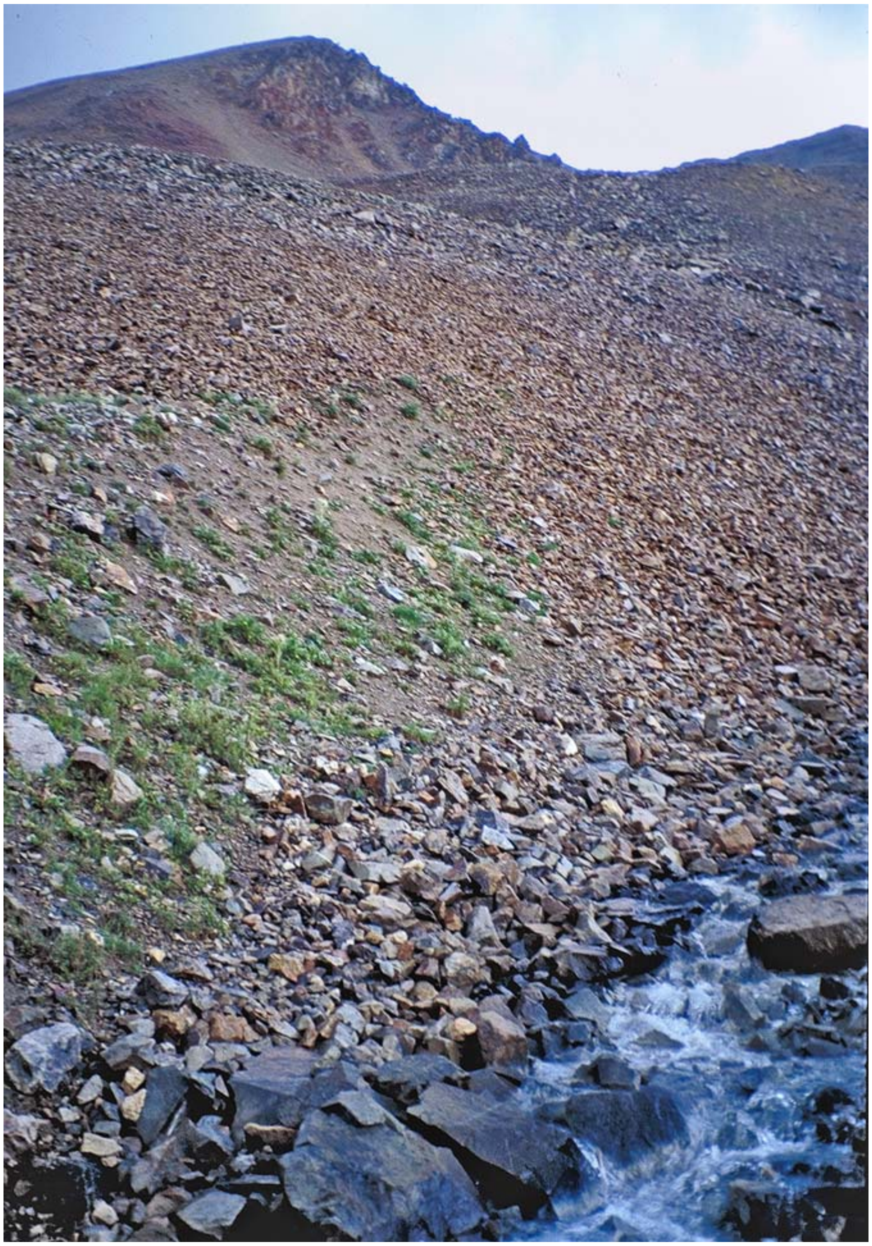


Figure 56. Stream about 20 ft upstream of water sample sites NW-52 and NW-2000-3, and the western flank of Red Amphitheatre.

sium-feldspar phenocrysts, quartz, plagioclase, and hornblende. The porphyry intrusion appears to be unaltered up to the contact with altered sediments (Figure 55). The intrusive sill appears to form a cap to the alteration in the underlying Paleozoic sedimentary section.

The sediments closest to the contact are quartzites, with prominent coarse sericite grains. Jarosite (or goethite) is visible along fractures near the contact with the sill. Tweto (1974) mapped these sediments as the Pennsylvanian Minturn Formation. South of the quartzite is black, carbonaceous shale with sericite and possibly some fine sulfide, which Tweto (1974) mapped as the Pennsylvanian Belden Formation.

On the south, adjacent to the shale and quartzite, is a series of finer grained intrusive dikes and sills, some of which are propylitic to weakly sericitic altered (sample RA-5 in **Tables 7 and 8**). To the southeast, along the ridgeline, a series of alternating porphyritic sills and quartzite occurs every five to 20 ft. The knob at an elevation of 13,899 ft (site of sample RA-5 on Figure 55) is composed of weakly propylitic to weakly sericitic, equigranular intrusive rocks interfingered with sericitized quartzite and calcareous sediments.

The south side of Red Amphitheatre (Figure 55) at lower elevations (11,800 ft) is composed of Precambrian granite and Laramide granodiorite of the Buckskin Stock. The rocks form bold, blocky outcrops with minor iron-oxide staining. These rocks are weakly propylitic (chloritic), and are cut by fine fractures coated with fine-grained pyrite. The Laramide Buckskin Gulch stock apparently crosscuts this area in an irregular manner.

On the north side of Red Amphitheatre, local dikes 6 to 8 ft wide, composed of finely porphyritic hornblende monzonite, cut Precambrian banded felsic gneiss along a trend of N60W. The gneiss is locally propylitically altered and contains pyrite on fine fractures. Locally, strongly QSP-altered and jarositic zones trending N70E and 6 to 10 ft wide occur within the banded felsic gneiss. These zones alternate with the more abundant weakly propylitic zones. At an elevation of 13,020 ft on the north wall, massive white quartzite, dipping approximately 10 degrees east, overlies the Precambrian felsic gneiss. The quartzite unit is about 70 ft thick and is overlain by a poorly exposed, dirty sandstone about 30 ft thick (Cambrian Sawatch Quartzite).

Above the quartzite and sandstone is a 40-ft-thick zone of strongly chloritic, silicic, very-fine-grained dolomitic sandstone interbedded with strongly chloritic, foliated metashale (Cambrian Peerless Shale). The sandstone contains calcite on abundant fractures and is cut by an east-west trending, 80N dipping, one

Table 7. X-Ray diffraction results for rock samples from Red Amphitheatre. (ND=not detected)

Sample No.	**RA-5**	**RA-8**	**RA-10**	**RA-11**	**RA-14**
Primary Assemblage	Weak Sericitic	Ore/ Dump	Silicic	Silicic	Weak QSP
Secondary Assemblage	Weak Propylitic	QSP	Propylitic	None	None
Quartz	Major	Major	Major	major	Major
Plagioclase	ND	ND	Minor	ND	ND
Microcline	ND	ND	ND	ND	ND
Orthoclase	Trace	Trace	Major	ND	Minor
Dolomite	ND	ND	Major	Major	ND
Calcite	ND	ND	Trace	Trace	ND
Chlorite	Minor	ND	Minor	ND	ND
Kaolinite	ND	ND	ND	Minor	ND
Alunite	ND	ND	ND	ND	ND
Pyrophyllite	ND	ND	ND	ND	ND
Zunyite	ND	ND	ND	ND	ND
Sericite 1M	ND	ND	ND	ND	ND
Sericite 2M1	Minor	Minor	ND	ND	Minor
Jarosite	ND	ND	ND	ND	Trace
Pyrite	ND	Minor	ND	ND	Trace
(Fe sulfate)	ND	ND	ND	ND	ND
Sphalerite	ND	Minor	ND	ND	ND
Galena	ND	Trace	ND	ND	ND
Hematite	Trace	ND	ND	ND	ND
Anatase	ND	ND	ND	ND	ND

Table 8. ICP-AES Chemistry Results for Red Amphitheatre rock samples.

Sample No.	**RA-5**	**RA-8**	**RA-10**	**RA-11**	**RA-14**
Sample Description	Weak Propylitic	Hi-grade dump sample	SIL Dolomitic SS	SIL Dolomite	QSP vein
Al (%)	8.235	3.565	3.745	1.155	5.425
Ca (%)	2.065	0.925	9.485	12.7	0.03
Fe (%)	2.11	8.73	3.72	3.45	2.74
K (%)	2.55	2.48	3.89	0.09	3.92
Mg (%)	0.465	0.16	6.64	6.775	0.15
Na (%)	2.35	0.02	0.415	<0.005	0.19
P (%)	0.065	0.065	0.025	0.03	0.01
Ti (%)	0.121	0.028	0.237	0.05	0.061
Ag (ppm)	<2	325	<2	<2	4
As (ppm)	<10	12	<10	<10	<10
Ba (ppm)	1,110	208	489	25	1420
Bi (ppm)	<50	416	<50	<50	<50
Cd (ppm)	<2	62	<2	<2	<2
Co (ppm)	4	<2	6	4	<2
Cr (ppm)	<2	6	5	4	<2
Cu (ppm)	2	890	4	15	88
Mn (ppm)	686	1,790	1,140	1,900	455
Mo (ppm)	<2	10	<2	4	3
Ni (ppm)	<3	4	7	<3	<3
Pb (ppm)	11	8,650	6	9	259
Sr (ppm)	666	24	94	122	33
Zn (ppm)	61	11,610	55	66	90

to two-inch wide quartz-chlorite veins (sample RA-10 in Tables 7 and 8). Trace metal concentrations of the altered Peerless Shale are low.

The last exposure on the north wall is a 40-ft-thick, silicified, orange-brown dolomitic limestone with local chert horizons (Ordovician Manitou Limestone). This is cut by one-quarter- to one-half-inch wide, banded, white quartz veinlets. Chemical analyses reveal that iron, manganese, molybdenum, and copper appear to be enriched in this silicified dolomite (sample RA-11 in Table 8). Very large blocks of strongly altered, orange-stained, silicified dolomite occupy the head of the Red Amphitheatre drainage.

The gully northwest of Red Amphitheatre appears to mark the western contact of the main zone of QSP alteration (Figure 55). Other than on the ridgetop, there are no exposures above 12,540 ft, but all of the talus and colluvium on the north side of the gully is composed of fresh, coarsely-porphyritic quartz monzonite down to an elevation of 12,670 ft. The uppermost exposure in this gully is composed of chloritic, manganese-stained Precambrian gneiss on the north side of the gully and alternating layers of chloritic and sericitic-jarositic gneiss on the south side.

The gneiss is unaltered at an elevation of 12,360 ft on the north side of the gully, and chloritic on the south side. Rare one- to three-foot-wide jarositic zones cut the gneiss striking east-west and dipping 80N. Water sample NW-2000-1 was taken at this location just above the jarositic QSP zones (Figure 55). Very limited exposures or occurrences of gneiss with QSP alteration are present above this sample location on the south side of the gully.

A small caved prospect adit is present at an elevation of 12,110 ft on the north side of the gully. The adit is only four feet wide and apparently not much deeper. The adit was developed along a small pyritic-sericitic zone in the gneiss.

The lowest outcrops on the north side of the gully are composed of weakly chloritic, manganese-stained gneiss. Talus and alluvium below this elevation (11,990 ft) is dominantly composed of jarositic-sericitic alteration products and appears to have been shed from the south side of the gully (the main QSP alteration zone of Red Amphitheatre). A sample of float containing a sericitic quartz-pyrite vein in gneiss was enriched in silver, barium, copper, lead, and zinc (sample RA-14 in Table 8).

ROCK GEOCHEMISTRY

Bookstrom (1989) identified an extensive molybdenum geochemical anomaly in soil overlying the west slope of Mt. Bross and the Buckskin Gulch stock. Corresponding anomalies in copper, lead, and zinc are present as well.

The mineralized samples collected for the present study (RA-8 and RA-14) contain anomalously high concentrations of copper, lead, zinc, molybdenum and silver with respect to the other samples (Table 8). The high-grade grab sample from the waste rock dump at the old mine (RA-8) also has high arsenic, bismuth, and cadmium concentrations consistent with the highly mineralized nature of the rock. Fluorite was also identified in this sample.

PREVIOUS WATER QUALITY INVESTIGATION

This area was included in an abandoned mine inventory conducted for the USFS by CGS in 1992 (White and Sares, 1995). A caved and dry adit was inventoried at an elevation of 12,290 ft on the north side of the Red Amphitheatre drainage basin. The volume of the associated waste rock pile was less than 1,500 cubic yards, suggesting that the underground workings are not extensive (USFS-AMLIP inventory form #12-10-403/4352-1, available at CGS). The surface area of the strongly altered and iron-stained rock and talus exposed in Red Amphitheatre dwarfs the surface area of rocks exposed by this caved underground mine. Water tested near the mouth of Red Amphitheatre in October 1992 had a pH of 6.3 and EC of 100 µS/cm, with an estimated flow of 450 gpm (USFS-AMLIP inventory form #12-10-403/4352-1). No sample was collected.

PRESENT WATER QUALITY INVESTIGATION

Water sample NW-52 was collected in 1999 near the mouth of Red Amphitheatre, from a steep, rocky section of the main drainage, at an elevation of 11,680 ft, just above the access road and below the old mine (Figure 55). Above the sample site, the stream flowed beneath loose, iron-stained talus in a snowbank and could not be sampled. Alluvium and colluvium at and near the sample site included limestone or dolomite, quartzite, and propylitically-altered intrusive igneous rocks, all with varying amounts of iron staining. One fragment contained molybdenite. Stream flow was 70 gpm, pH was 6.49, and EC was 339 µS/cm. White and light-brown precipitate coated the stream channel. Although the stream water appeared to be fairly clear, the water filter caught white suspended solids. The sample exceeded Statewide water quality standards for concentrations of dissolved aluminum, cadmium, manganese, and zinc. Fluoride was just below standard. Because of the high hardness, the standards for zinc and cadmium were higher than those for most alpine environments. Dissolved aluminum was about 20 percent of the concentration of total aluminum, which suggests that the precipitate and the suspended solids are dominantly aluminum phases (**Appendix A-10**). Other 1999 water test results from near Red Amphitheatre were inconclusive. Two water tests showed evidence of ARD, with similar or lower pH to that of NW-52, and similar ECs (Figure 55).

Water at the most northwestern site, on a separate tributary of Buckskin Creek (Figure 55), had low EC (68 µS/cm) and did not appear to be affected by ARD. This tributary flows primarily through unaltered talus eroded from the porphyritic sill capping Mt. Bross and from the propylitically altered Precambrian gneiss and intrusive of the Buckskin stock. Manganese staining of the propylitic rocks is prominent.

The northwestern site was resampled in early August of 2000, and three new samples (NW-2000-1 to 2000-3) were collected from the Red Amphitheatre area (Figure 55). Sample NW-2000-1 was taken at an elevation of 12,360 ft, from a small creek immediately west of the drainage through Red Amphitheatre (Figure 55). In this area the surrounding rocks were unaltered porphyry talus from the ridge top and propylitically altered, manganese-stained, Precambrian granite gneiss. The stream could be heard flowing beneath the talus from an elevation of 12,770 ft down to the sampling point where it was first accessible for sampling. The streamflow was 8 gpm, the pH was 7.21, and EC was 86 µS/cm. The water was clear and had no visible evidence of ARD. No metal concentrations exceeded State water quality standards (Appendix A-10). Iron, manganese, and aluminum concentrations were all below detection.

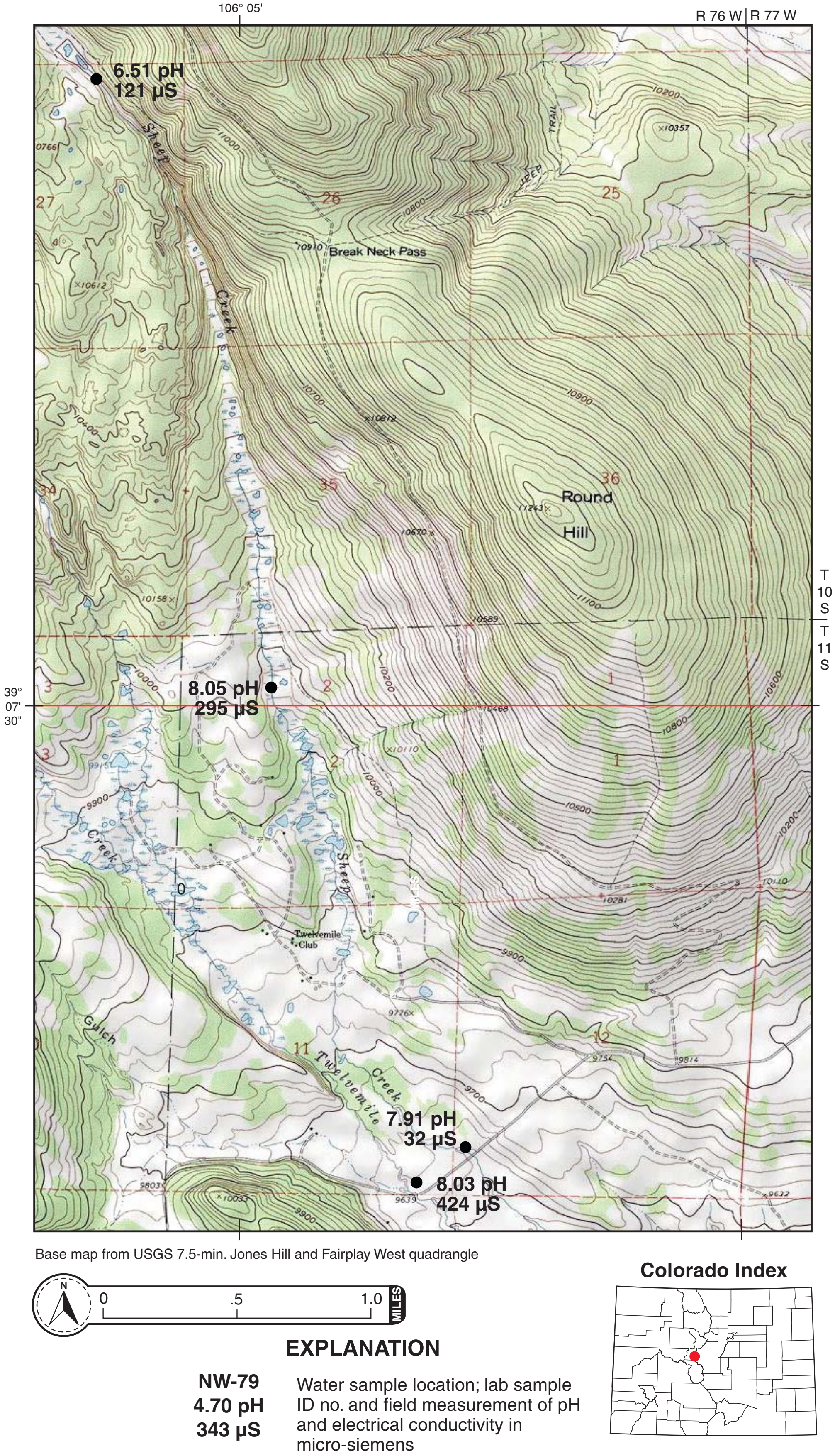
Sample NW-2000-2 was collected from a spring along the same tributary as sample NW-2000-1, but at an elevation of 11,670 ft (Figure 55). This is close to the location of the water test result from 1999 that had produced a pH of 5.30 and EC of 292 µS/cm. At this location, abundant talus from the western slopes of the QSP-altered portions of Red Amphitheatre (similar to conditions at sample location RA-14) filled the southern side of the drainage. Manganese-stained, propylitic Precambrian gneiss formed the northern side of the drainage. The water was clear with a flow of 5 gpm and pH of 5.79. The EC was 961 µS/cm, significantly more conductive than water 700 ft higher in the same drainage. The water showed evidence of natural ARD (Appendix A-10**)**, with aluminum and manganese concentrations exceeding State water quality standards by several orders of magnitude. Cadmium, fluoride, sulfate, and zinc also exceeded State water quality standards, while iron was below detection limits. The hardness was relatively high due to abundant dissolved calcium. The high calcium and magnesium contents are most likely due to the presence of abundant carbonate rocks in the immediate area.

Water sample NW-2000-3 was collected from the same location as sample NW-52 (Figure 55), but a year later. The stream was flowing at approximately 20 gpm from under talus after originating in a snowfield in the center of the drainage. The stream water had a pH of 7.37 with EC of 326 µS/cm. Abundant carbonate rocks, manganese-stained Precambrian gneiss, and quartzite colluvium/talus filled the drainage immediately above the sample site (Figure 56). The western side of the drainage basin is composed of strongly QSP-altered Precambrian gneiss as well as some dump material from the old mine. Abundant white precipitate, presumably aluminum hydroxide, was evident in the stream immediately below the sample collection point. The water sample exceeded State water quality standards for concentrations of cadmium, manganese, and zinc, whereas iron was below detection (Appendix A-10). It appears likely that contact with carbonate rocks created high hardness and neutralized acidic waters draining the lower part of Red Amphitheatre.

Overall, the results indicated that ARD was largely restricted to the main drainage from Red Amphitheatre and associated seeps passing through the QSP-altered rocks. Water from the small drainage immediately west of Red Amphitheatre, within unaltered porphyry talus and propylitically altered rocks, had neutral pH and low EC, indicating little ARD, until passing through the altered, pyritic talus from Red Amphitheatre at elevations below 12,000 ft where abundant metals are found dissolved in slightly acidic water.

TWELVEMILE CREEK

A report by the Colorado Division of Public Health and Environment (CDPHE, 1988) suggests that Twelvemile Creek (Figure 1), in the western part of South Park, may contribute to elevated cadmium concentrations in the South Platte upstream from Antero Reservoir. A brief reconnaissance in the area revealed no large, obviously altered terranes. A water test in Twelvemile Creek indicated slightly alkaline pH and low EC **(Figure 57)**. No sample was collected. Water tests nearby in Sheep Creek indicated near-neutral or alkaline pH, but relatively high EC. Much of the Sheep Creek drainage basin is underlain with the Minturn and Belden Formations (Tweto and others, 1978). The Belden Formation contains black calcareous shales, which probably cause the high pH and EC in the surface runoff. No samples were collected because of the lack of obvious indications of ARD and the alkaline pH.



Base map from USGS 7.5-min. Jones Hill and Fairplay West quadrangle

Figure 57. Map showing water test results in South Park in the Twelvemile Creek area.

7

NORTH-CENTRAL COLORADO

North-central Colorado, outside of the Front Range Mineral Belt, has few highly mineralized areas, or large areas showing intense alteration. In the isolated areas where streams are acidic or metal-rich, dilution rapidly mitigates the problem. Natural ARD occurs, but is not a serious problem in this area.

RABBIT EARS RANGE

The Rabbit Ears Range is an east-west trending range along the Continental Divide and forms the boundary between Middle Park to the south and North Park to the north (Figure 1). The Rabbit Ears Range is about 30 to 40 mi long, extending from the Park Range and Rabbit Ears Peak on the west to Bowen Pass and the Never Summer Range on the east. The nearest towns are Granby to the south and Rand to the north. Areas investigated for this report include the Poison Ridge area **(Figure 58)** in the central part of the range and the Parkview Mountain area near Willow Creek Pass **(Figure 59)**.

GEOLOGY

The Rabbit Ears Range comprises a belt of intrusive and extrusive, intermediate- to felsic-composition igneous rocks of mid-Tertiary-age that have intruded or overlie older Cretaceous and Tertiary sedimentary rocks. Sedimentary rocks include sandstones, siltstones, and shales. Some of the intrusions and the surrounding sedimentary rocks have been brecciated, mineralized, and altered (Anaconda Collection; Kinney and others, 1968; Nelson, 1973; Karimpour, 1982; Neubert, 1994). Alteration of the intrusive rocks that form the range is obvious in a few localities.

The altered intrusions host subeconomic porphyry-copper and molybdenum occurrences that were explored during the 1970–1983 time frame in the Poison Ridge and Parkview Mountain areas. However, little, if any, production has resulted (Neubert, 1994).

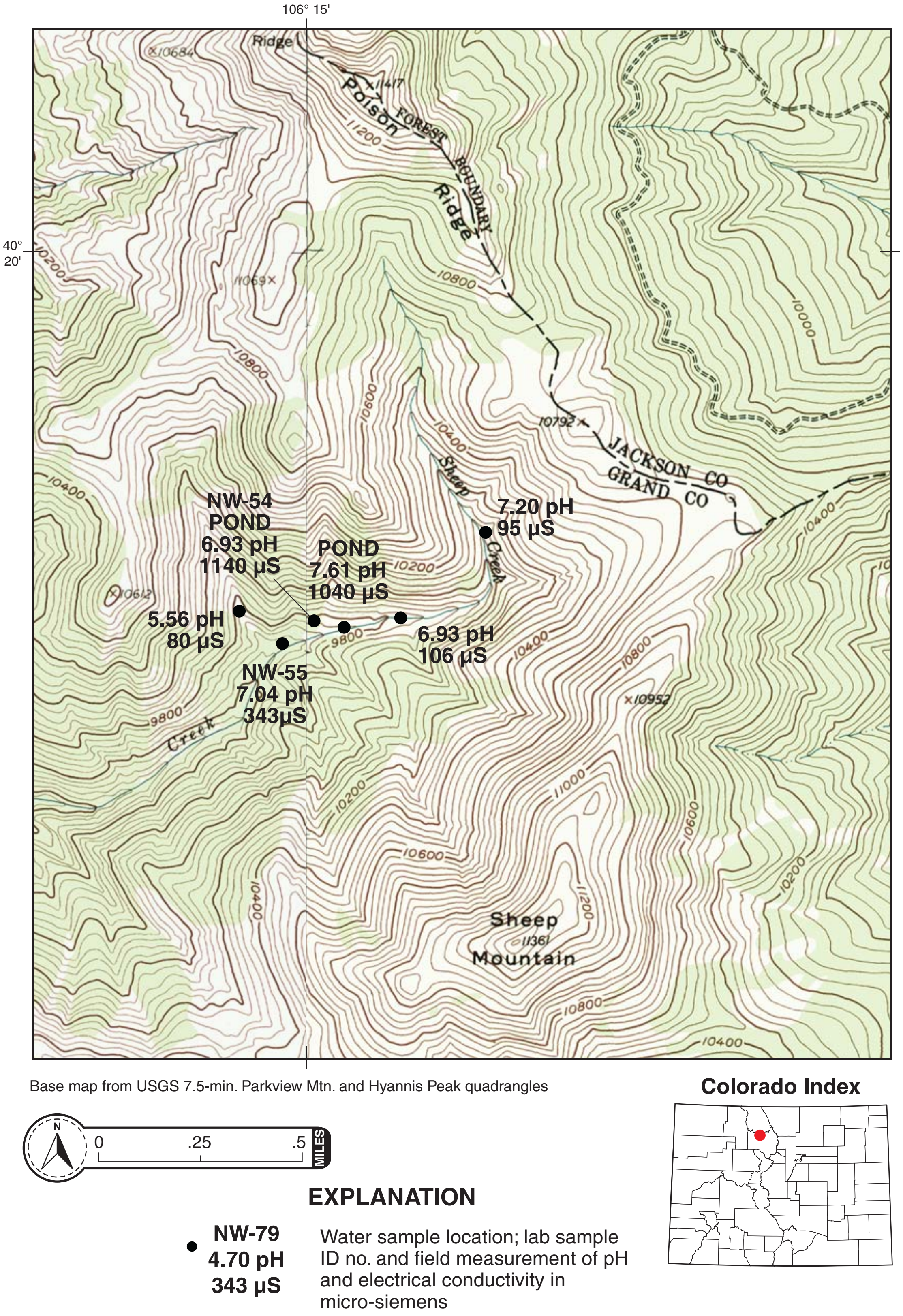
PRESENT WATER QUALITY INVESTIGATION

Poison Ridge

The altered Poison Ridge stock (Nelson, 1973) is exposed in Sheep Creek near the Continental Divide (Figure 58). Disseminated pyrite is common to abundant throughout much of the altered stock. In addition to pyrite, part of the stock contains subeconomic concentrations of copper, mostly as chalcopyrite. Previous studies by Anaconda have identified more than 50 million tons of mineralized rock averaging more than 0.2% copper in the primary ore and averaging 0.7% copper in the supergene ore centered at an elevation of about 9,800 ft (Karimpour, 1982). The only evidence of mining is a small prospect in the oxidized portion of the occurrence near Sheep Creek.

Two water samples were collected in this area (Figure 58). Sample NW-54 was from the lowest in a series of beaver ponds, in a meadow alongside a drill road, about 1.5 mi downstream from the headwaters of Sheep Creek, on the southwest side of Poison Ridge. Bedrock on the slopes above the pond and the talus pile alongside the pond consisted of brown- and red-stained, fine-grained intrusive rocks, or baked shale and altered porphyry. Some of the rocks had yellow stain, and a few pieces contained minor amounts of disseminated pyrite. Water in the pond had a bluish hue and an oily sheen on the surface. Although the pH was neutral at 6.93, the pond water had EC of 1,140 μS/cm and hardness of 589 mg/L, which are high for a headwater stream. Water bugs skimmed the surface. The pond water slightly exceeded State water quality standards in concentrations of iron, manganese, and sulfate **(Appendix A-11)**. The low copper content is somewhat surprising considering the abundance of copper sulfides in the area and the coloration of the water.

Sample NW-55 was from Sheep Creek, about 1,000 ft downstream from NW-54, and near a drill pad with at least two drill holes (Figure 58). At NW-55, abundant red precipitate was caught in algae. Red precipitate coated the creek bed beginning in the wetlands about 1,000 ft upstream of NW-54 and continuing for at least 1,000 ft downstream from NW-55. The creek had a 150-gpm flow with pH of 7.04, EC of 343 μS/cm, and alkalinity of 13 mg/L (as $CaCO_3$). Concentrations of iron and manganese slightly exceeded standards (Appendix A-11). Concentrations of calcium, magnesium, sulfate, and sodium were significantly lower

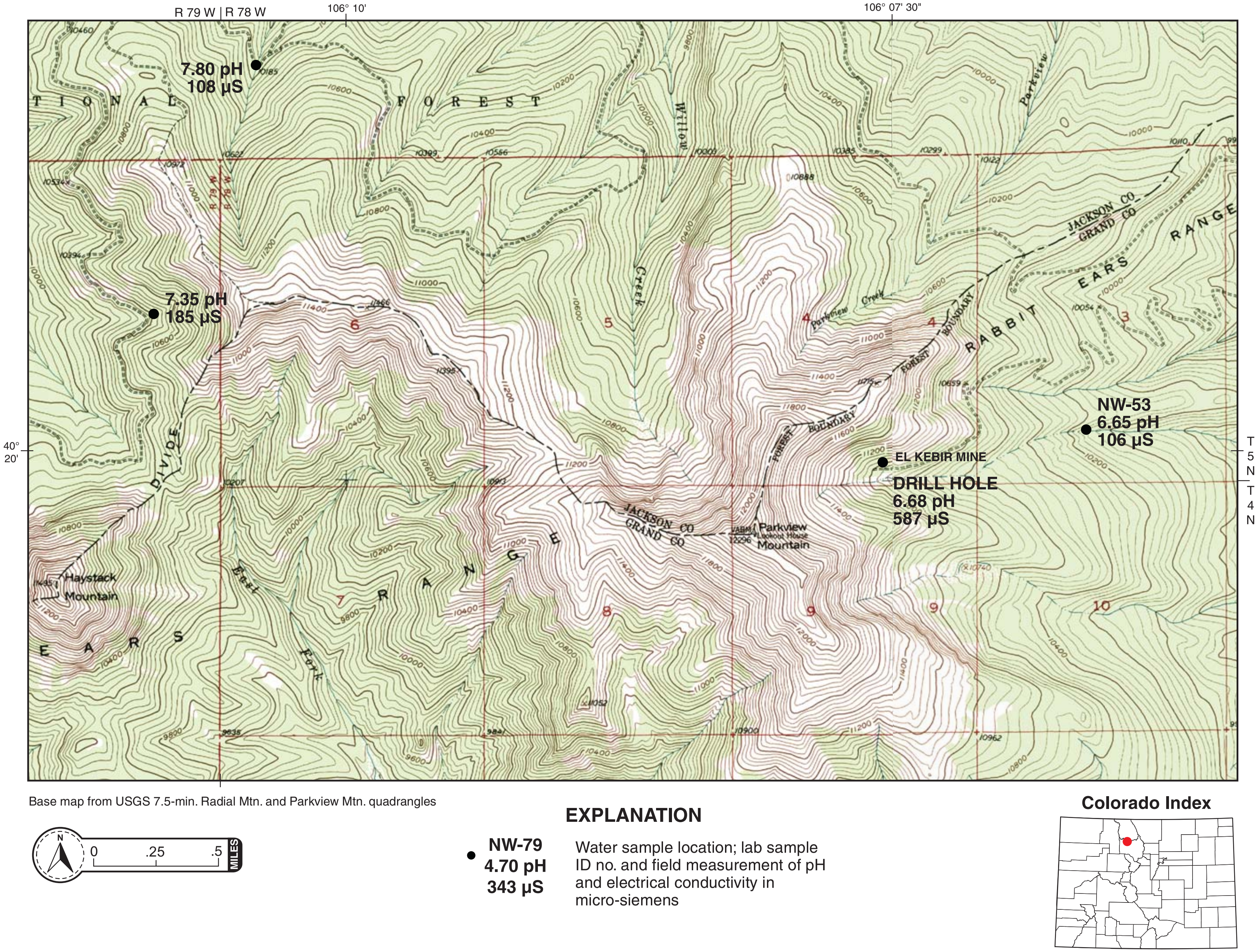


Base map from USGS 7.5-min. Parkview Mtn. and Hyannis Peak quadrangles

EXPLANATION

● **NW-79 4.70 pH 343 µS** Water sample location; lab sample ID no. and field measurement of pH and electrical conductivity in micro-siemens

Figure 58. Map showing water sample sites NW-54 and NW-55, and water test results near Poison Ridge.



Base map from USGS 7.5-min. Radial Mtn. and Parkview Mtn. quadrangles

Figure 59. Map showing water sample sites NW-53 and Parkview Drill Hole, and water test results from near Parkview Mountain.

than in NW-54, but the concentration of silicon was noticeably higher. Aluminum, copper, and zinc concentrations were elevated, but below State water quality standards. The dramatic drop in hardness, sulfate and conductivity from NW-54 apparently reflects precipitation of iron minerals, carbonates and sulfates.

Several water tests were conducted near Poison Ridge for this study (Figure 58). A water test from Sheep Creek immediately upstream from Forest Road 107, and about one-half mile upstream of NW-54, had pH of 7.2 and EC of 95 µS/cm. No precipitate was observed in the channel at this site. Progressing downstream in Sheep Creek, EC slightly increased and pH dropped slightly. Two beaver ponds in the wetlands on the north side of Sheep Creek had pH between 6.5 and 7.0 and EC of 900 to 1,100 µS/cm. An unmapped tributary of Sheep Creek, about 800 ft northwest of NW-55, had pH of 5.56 and EC of 80 µS/cm.

Parkview Mountain

A quartz-latite stock or plug is centered in the cirque on the east side of Parkview Mountain. Later intrusion of a granitic or monzonitic stock altered and brecciated the quartz-latite and the surrounding sedimentary rocks. In the altered rock, feldspar has decomposed to clay, and pyrite and its oxidation products are common along with minor molybdenite (Spiker, 1973; Neubert, 1994).

The only significant mine working in this area is the El Kebir adit, a copper-lead-zinc-silver mine (Figure 59), which is now caved but historically was about 350 ft long (Neubert, 1994). No water was draining from this mine working, but a drill hole slightly above and to the west of the adit, when examined during an abandoned mine inventory in 1992 (Sares, 1993), was discharging 1 to 2 gpm of water with pH of 6.73 and EC of 563 µS/cm. Drill-hole water flowing at 0.8 gpm was sampled in July of 1998 and had pH of 6.2 and EC of 532 µS/cm. Aluminum, iron, manganese, and arsenic concentrations exceeded State water quality standards (Appendix A-11, Parkview Drill Hole). The water was depositing abundant red-brown precipitate along its drainage path. Although this discharge seeped into the ground within about 200 or 300 ft of the drill hole prior to reaching a stream at the surface, the precipitate trail continued downhill, indicating higher intermittent flow rates. However, the precipitate deposit did not extend to the creek, which suggests that even during times of higher flow, water from the drill hole either seeps into the colluvium prior to reaching the stream, or precipitation of metals ceases prior to its confluence with surface water. Water from the drill hole was tested again in September of 1999, and indicated pH of 6.68 and EC of 587 µS/cm. The discharge seeped into the ground about 100 ft downhill from the drill hole. This drill-hole discharge probably closely approximates the groundwater quality in this area, although it is possible that the El Kebir adit may have some effect.

Sample NW-53 was from an unnamed tributary of Pass Creek that drains the cirque on the east side of Parkview Mountain (Figure 59). Because the creek was dry near the hydrothermally altered area within the cirque, this sample was collected almost a mile downstream. Within and immediately downstream from the cirque, water evidently flowed beneath the surface of talus, colluvium, and alluvium. At the sample site, the creek was flowing at about 40 gpm with pH of 6.65 and EC of 106 µS/cm. The water appeared to be clean, and none of the measured parameters exceeded State water quality standards (Appendix A-11). Any ARD emanating from the exposed altered rocks, or from the drill hole at Parkview Mountain, was apparently neutralized by clean water emerging in the mile of reach between the altered area and the sample location.

Iron-stained intrusive rocks are exposed on the ridge that forms the Continental Divide northeast of Haystack Mountain and northwest of Parkview Mountain. Most of the streams draining the altered area were dry in September 1999, but two water tests of flowing streams indicated pH values above 7 and EC values less than 200 µS/cm (Figure 59). None of the observed streams showed visible evidence of ARD, and no samples were collected.

NEVER SUMMER RANGE

The Never Summer Range is a north-trending range, part of which forms the Continental Divide (Figure 1). Much of the eastern slope of the Never Summer Range is within the northwest part of Rocky Mountain National Park. The range extends from about Porphyry Peaks on the south to Cameron Pass on the north. The Medicine Bow Mountains adjoin the range to the north. The nearest towns are Grand Lake, about 7 mi east-southeast, and Gould, about 7 mi to the west. Areas investigated for this report include the Illinois River and Jack Creek area **(Figure 60)**, and the Porphyry Peaks area, including the headwaters of Willow Creek, which drain into Middle Park **(Figure 61)**.

GEOLOGY

The Never Summer Range comprises a belt of Tertiary intermediate- to felsic-composition intrusions. These stocks, plugs, sills, and dikes intruded Precambrian granofels, gneiss, schist and amphibolite, and Tertiary clastic sedimentary rocks. Lying west of the crest of the range, the north-trending Never Summer thrust fault juxtaposes Precambrian metamorphic rocks against and above part of the Tertiary sedimentary sequence (Tweto, 1979; O'Neill, 1981; Braddock and Cole, 1990).

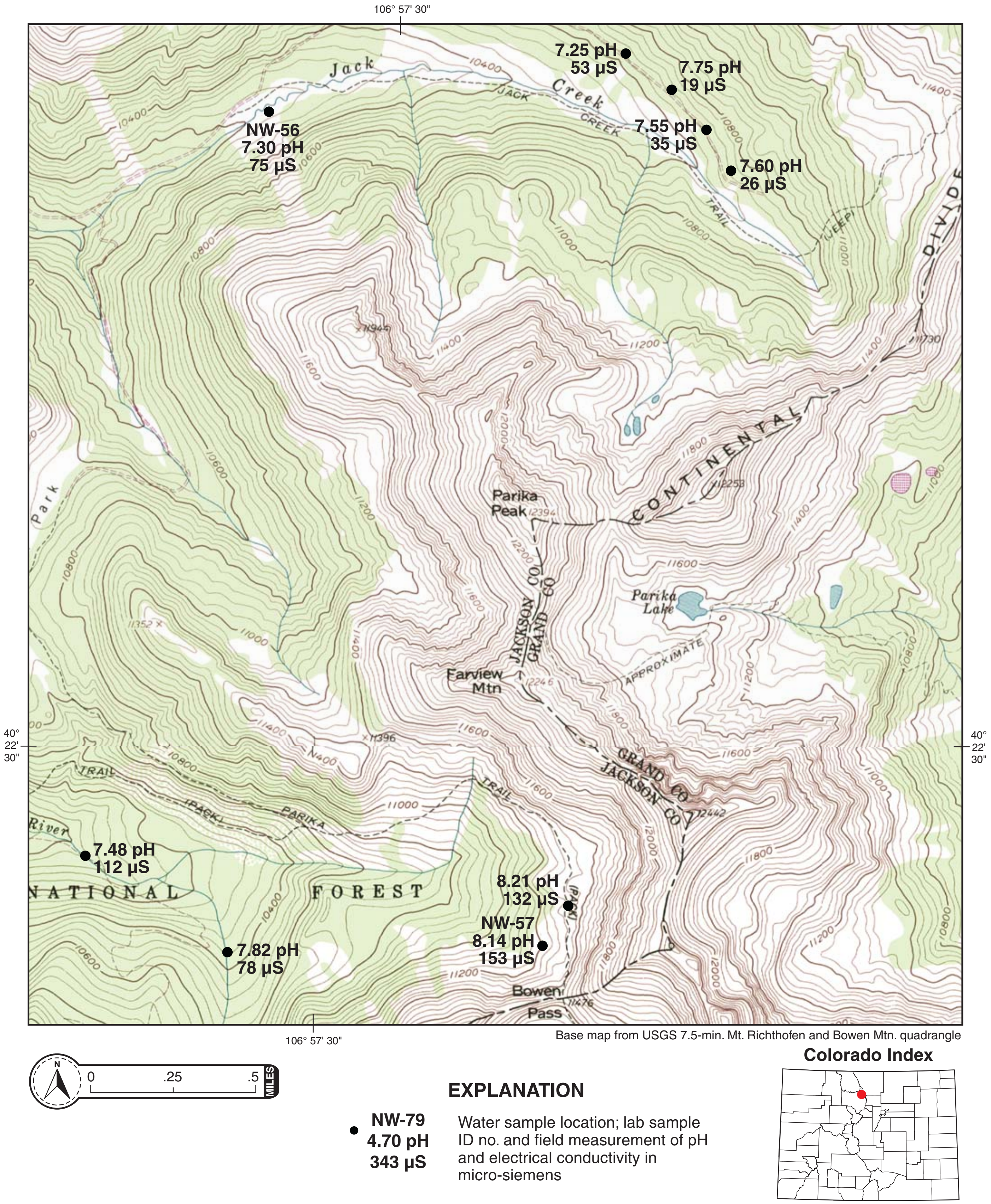
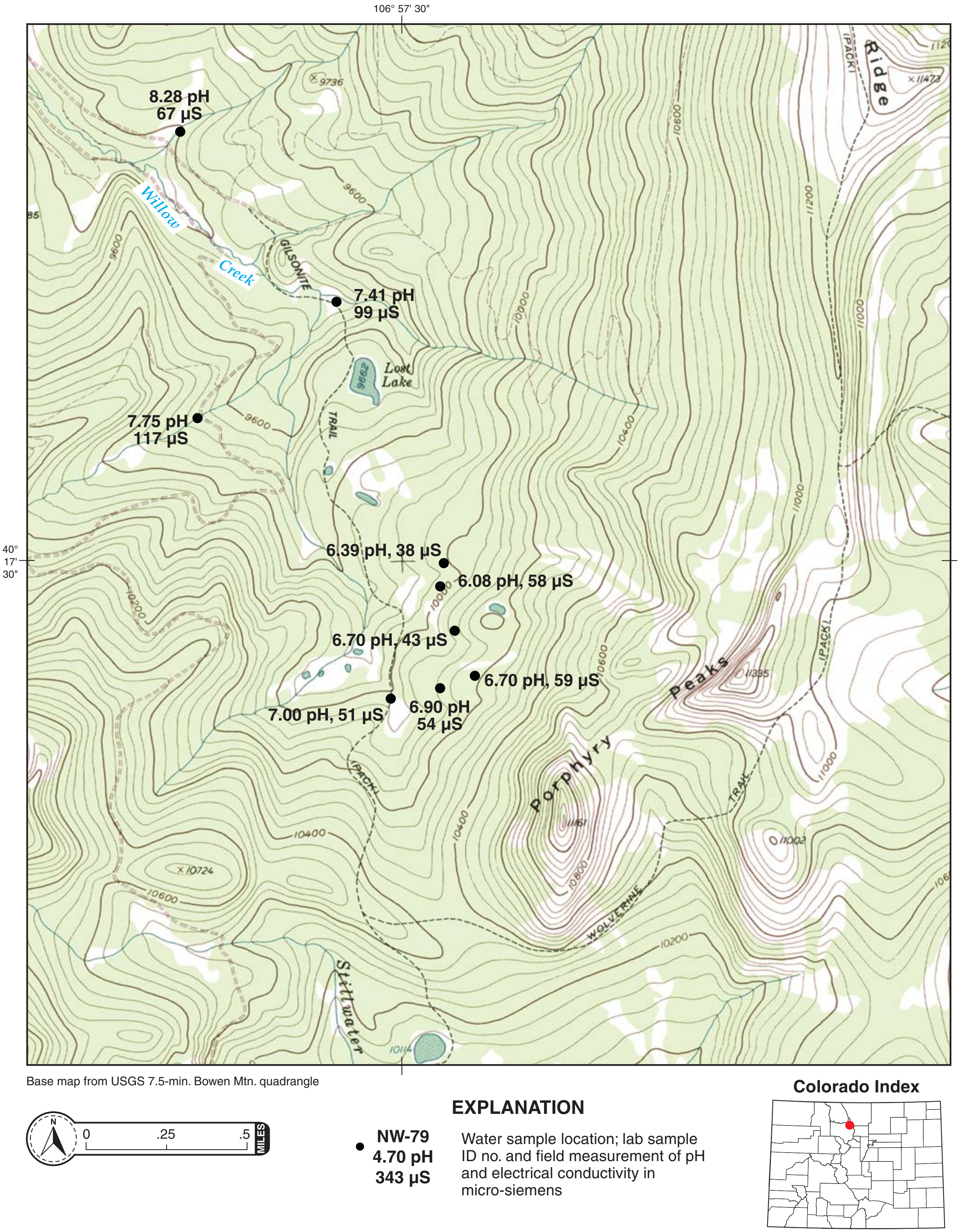


Figure 60. Map showing water sample sites NW-56 and NW-57, and water test results in the Illinois River and Jack Creek drainage basins.



Base map from USGS 7.5-min. Bowen Mtn. quadrangle

Figure 61. Map showing water test results near Porphyry Peaks.

The Teller mining district is on the west side of the Never Summer Range, straddling the Never Summer thrust fault. Faults with smaller displacement, associated with the thrust fault, host small fluorite-bearing base- and precious-metal vein deposits that were mined historically (Beekly, 1915; Pearson and others, 1981). In addition, weakly mineralized breccia pipes and breccia zones are exposed in this area. Buried intrusive rocks were drilled during exploration for molybdenum in the 1970s and 1980s (Anaconda Collection; Neubert, 1994).

PRESENT WATER QUALITY INVESTIGATION

Illinois River And Jack Creek

Near the headwaters of the Illinois River, and near the intersection of the north-trending Never Summer Range intrusive belt with the eastern end of the east-trending Rabbit Ears Range, a 1,800-meter by 1,200-meter breccia pipe with disseminated pyrite intruded Precambrian hornblende gneiss and amphibolite. This Tertiary pipe contains anomalous concentrations of arsenic, silver, and gold. Fissures related to the pipe are mineralized with galena and chalcopyrite (Anaconda file 93303.02, 1970; Metzger, 1974). This breccia pipe was briefly examined in 1999. The pipe is densely fractured and moderately iron-stained, but no surface runoff or seeps were observed. Water sample NW-57 was collected nearby to determine if the reported mineralization at the breccia pipe affected surface-water quality in this area. The sample was from an unmapped tributary about 1,000 ft north of Bowen Pass (Figure 60) where the flow was about 60 gpm, pH was 8.14, and EC was 153 µS/cm. This stream emerged from an area underlain by Precambrian amphibolite with minor iron staining. Most trace metals were not detected, and none of the metals exceeded State water quality standards. The relatively high EC for a headwater stream appears to be mostly due to calcium and sulfate (Appendix A-11). Water tests at several locations in this area showed neutral to slightly alkaline pH and moderate EC (Figure 60). No obvious indications of poor-quality water were observed, and no other samples were collected.

About two miles to the west, within the Illinois River drainage basin, about 200 acres of Tertiary sedimentary rocks cut by northwest-trending breccia zones contain rocks and soil with concentrations of arsenic exceeding 300 ppm, and anomalous concentrations of gold, silver, antimony, and thallium (O'Neill and others, 1981). During an abandoned mine inventory in 1997 (Ellis and Wood, 1998), samples were collected of water emerging from two small mine workings in this area. Both samples exceeded State water quality standards in arsenic, iron, fluoride, and manganese. High metal concentrations in host rock and soils suggest that some of the ARD associated with these small mines is probably natural. However, the presence of precipitate associated with the mine discharges and the lack of precipitate in the receiving streams upstream of the mines imply that a significant percentage of the ARD is mine related. No samples were collected upstream from the mines during the inventory or during this study.

A buried Tertiary rhyolite plug presumably underlies the exposed Precambrian biotite schist in the upper portion of Jack Creek in the vicinity of the Teller mining district (Pearson and others, 1981). The north-trending Never Summer Thrust Fault also cuts this area. Although surface expression of regional-scale alteration was not obvious, a water sample (NW-56) was collected because of minor iron staining coating the gravels of Jack Creek and past drilling activity in the area.

Water sample NW-56 was taken from Jack Creek (Figure 60) in the area of the buried intrusion and upstream from the significant mines of the Teller mining district. Many of the rocks in the streambed had a minor red coating that may be precipitate or may have been caused by oxidation of biotite within the Precambrian rocks. Where sampled, the creek was flowing at 650 gpm, pH was 7.30, EC was 75 µS/cm, and alkalinity was 30 mg/L (as $CaCO_3$). Most metals were not detected in the water sample, or were present at low concentrations. The iron concentration was 200 µg/L, but within the State water quality standard (Appendix A-11). Water tests conducted farther upstream in unmapped tributaries near the headwaters of Jack Creek had neutral pH and EC values less than 60 µS/cm (Figure 60). No obvious indications of ARD were observed, and no additional samples were collected.

Porphyry Peaks

Rocks exposed on the northwest side of Porphyry Peaks, near Lost Lake in the headwaters of Willow Creek, are strongly altered, fractured, and decomposed quartz latite porphyrys (Braddock and Cole, 1990). Alteration of the peaks is apparently argillic and iron staining is not intense, probably indicating limited sulfide abundance. The alteration of the trachyandesite in the saddle between the "Porphyry Peaks" is described as propylitic (with carbonate) by Braddock and Cole (1990). Numerous active landslides demonstrate the instability of the clay-rich Pierre Shale bedrock between Porphyry Peaks and Lost Lake. Water tests conducted in this area indicated nearly neutral pH and EC values of less than 120 µS/cm (Figure 61). Blocks of Cretaceous Niobrara Limestone have been mapped in the upper reaches of Willow

Creek (Braddock and Cole, 1990) and may be partially responsible for the slightly alkaline pH. No precipitate or other obvious indications of ARD were observed, and no samples were collected.

Bog-iron deposits exist in many headwater areas of Colorado. Springs and streams associated with the bog-iron deposits often discharge ARD. Many of these waters were sampled during the course of this investigation and were described in previous sections. A few smaller occurrences of bog-iron were briefly visited and either had no associated water, or water testing did not indicate an influence from ARD. These are described below. In addition, three bog-iron locations identified in literature were not visited, but are included here for completeness.

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OTHER AREAS OF INTEREST

Whitepine Area

A small bog-iron deposit is exposed near Tomichi Creek about 1.5 mi upstream of Whitepine (Figure 1). The iron was deposited in the swampy parts of Tomichi Creek by springs carrying iron-rich water (Harrer and Tesch, 1959). This site was not visited, and it is not known whether the springs are still active. In addition, it is not known whether mining activity has affected the springs.

Sangre De Cristo Mountains

Limonite appears in the north and south branches of Decker Creek, on the west slope of the Sangre de Cristo Mountains and south of Poncha Pass. The bog-iron deposit is about 800 ft long, 100 ft wide, and 8 ft or more thick (Harrer and Tesch, 1959). No active seeps were identified in the limonite deposit during a reconnaissance examination.

Limonite occurs at and near the Major Mine in Major Creek, about two miles southeast of Valley View Hot Springs, on the west slope of the Sangre de Cristo Mountains. Workings are developed on this bog-iron deposit (Harrer and Tesch, 1959). It is unknown whether any springs are active at this location, but topographic maps show few if any springs. Mines inventoried in this area by CGS were dry.

Del Norte Area

Limonite appears in flat layers along a ridge about 7 mi north of Del Norte and 2.5 mi north-northwest of East Butte. This bog-iron deposit trends N60W for 1,500 ft. It is about 800 ft wide and 5 ft or more thick (Harrer and Tesch, 1959). Brief reconnaissance in this area revealed no active springs.

Sargents Area

Small bog-iron limonite deposits are present along Indian Creek east of Sargents. The largest deposit is 10 ft thick and is exposed for 800 ft along a roadcut in sections 17 and 18 (Harrer and Tesch, 1959). This site was not visited, and it is unknown whether there are active springs at this location.

Kerber Creek

Ferricrete occurs along the Kerber Creek-Bonanza Road about 7 mi west of Villa Grove. The deposit is about 350 ft long, 50 ft wide, and 7 or more feet thick (Harrer and Tesch, 1959). No significant active springs were observed in the ferricrete during brief reconnaissance. Soda Springs, an alkaline spring with no associated ferricrete, is nearby but was not sampled.

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SUMMARY AND CONCLUSIONS

A total of 101 water samples were collected during this investigation in areas of Colorado characterized by hydrothermally altered rocks. With the exception of 15 samples **(Table 9)**, water samples were collected from sources with no mining-related influences on water quality. Eighty-one percent of the samples were acidic (pH < 7) or contained metal concentrations exceeding state standards, or both. Only 19 percent of the samples met State water quality standards for all or most of the tested parameters.

Of the 86 samples with no apparent anthropogenic influence **(Table 10)**, a pH below the standard of 6.5 was measured in 66 samples. Concentrations of total recoverable aluminum exceeded the State standard in 65 of the 86 samples, and dissolved manganese exceeded the secondary (aesthetic) drinking water standard of 50 µg/L in 58 samples. Dissolved copper and zinc concentrations exceeded hardness-related State water quality standards in 50 samples. Dissolved iron exceeded the secondary (aesthetic) drinking-water standard of 300 µg/L in 38 of 86 samples. Total recoverable iron exceeded the water quality standard of 1,000 µg/L in 35 samples. Sulfate exceeded the secondary drinking-water standard of 250 mg/L in 14 samples, and cadmium and lead exceeded their hardness-related standards in 38 and 11 samples, respectively. Nickel exceeded its hardness-related standard in 14 samples. Other parameters such as arsenic, thallium, silver, chromium, fluoride, and chloride exceeded standards five or less times each and these analytes were not detected in most samples.

Table 11 indicates parameter exceedances within the sampled areas. The box plots **(Figure 62a-f)** indicate the median, 25th percentile, 75th percentile, minimum and maximum concentrations for dissolved aluminum, iron, zinc, copper, manganese and sulfate by area sampled where three or more samples were collected. The box plots exclude samples identified as having potential mining-related impacts (Table 9) so that only natural ARD is shown.

The lowest median pH and highest median dissolved aluminum and dissolved iron concentrations were found in waters from the Grizzly Peak caldera and the Slumgullion areas, while waters from the Red

Table 9. Samples in natural acid rock drainage areas that were potentially affected by anthropogenic activity or disturbance.

Sample	Area	Rationale
NW-1	Silverton	Draining adit above
NW-13	Silverton	Adit above
NW-18	Montezuma	Excavations around springs below Landslide Peak
NW-19	Montezuma	Excavations around springs below Landslide Peak
NW-20	Montezuma	Excavations around springs below Landslide Peak
NW-22	Montezuma	Possibly impacted by abandoned mine
NW-40	Montezuma	Sampled from small adit in ferrosinter
NW-51	Ruby Range	Originates from hidden caved adit
NW-52	Red Amphitheatre	Downgradient of mine, possible groundwater input
NW-2000-3	Red Amphitheatre	Downgradient of mine, possible groundwater input
NW-53	Rabbit Ears	Below El Kebir adit
Parkview Drill Hole	Rabbit Ears	Drill hole
NW-88	Slumgullion	Adjacent to highway (high chloride)
NW-91	Slumgullion	Small mines above
NW-93	Kite Lake	Site is disturbed from excavation of ferrosinter

Mountain Pass, Montezuma and Ruby Range areas also had median pH values less than 4.5. The least acidic waters (highest median pH) were found in the Rico and Red Amphitheatre areas. The samples with the highest median manganese, zinc and sulfate concentrations were from the Red Amphitheatre and Slumgullion areas. The highest median and maximum copper concentrations were found in samples from the La Plata Mountains and the Grizzly Peak caldera. The highest median lead concentrations were found in the Ruby Range.

This investigation indicates that dissolved aluminum and manganese concentrations generally exceed State water quality standards in natural ARD waters draining hydrothermally altered terranes (**Tables 10 and 11**). Natural concentrations of copper, iron, cadmium, and zinc are typically elevated around larger mining districts and in areas associated with porphyry copper or molybdenum occurrences, such as the Montezuma and Allard stocks, as well as the stocks of the Ruby Range.

Surface waters associated with these hydrothermally altered areas vary significantly in chemical composition as a function of a number of parameters including: topography, host and country rock compositions, alteration type and volumetric extent, and ore deposit type. Some of these waters are extremely acidic but have low EC and generally low metal concentrations. Despite the low concentrations, some of the metals exceed State water quality standards because of low hardness. In general, these types of low pH and low conductance waters are found in tributaries high on mountain slopes where residence time is too short for significant water-rock reactions to occur, or in higher elevation sites where much of the pyrite has been oxidized

Table 10. Summary of water chemistry data from sites with no known anthropogenic influence. (Statewide table value standards are used)

Parameter	Number exceedances of water water quality standards (out of 86 samples)
pH	66
Aluminum (trec)	65
Antimony (trec)	0
Arsenic (trec)	3
Iron (trec)	35
Thallium (trec)	4
Zinc (trec)	2
Cadmium	38
Chloride	2
Chromium	2
Copper	50
Fluoride	3
Iron	38
Lead	11
Manganese	58
Nickel	14
Silver	2
Sulfate	14
Zinc	50

Table 11. Summary of water quality standard exceedances by area. (Statewide table value standards are used)

Area	Drainage Basin	Standard Exceedances
Carson Camp	Lake Fork of the Gunnison	Al, Mn, Fe, Cu, Zn
East Trout Creek	Rio Grande	Al, Mn, Fe, SO4
Grizzly Peak Caldera	South Fork Lake Creek	Al, Mn, Fe, Cu, Zn, Cd, Ni, SO4
Kite Lake	Rio Grande	Al, Mn, Fe, Cu, Zn, Cd, Ni
La Plata Mountains	La Plata River	Al, Mn, Fe, Cu, Zn, Cd, F, Pb
La Plata Mountains	East Mancos River	Al, Mn, Fe, Cu, Zn, Cd, As, Tl, Ni, Cr, SO4
Lake City Area, Red Cloud	Lake Fork Gunnison	Al, Mn, Fe, Cu, Zn, Mo (Miller, 1998)
Montezuma	North Fork South Platte River	Al, Mn, Fe, Cu, Zn, Cd, Ni, Cr, SO4
Montezuma	Snake River	Al, Mn, Fe, Cu, Zn, Cd, Pb, Tl, Ag
Never Summer Mountains	Illinois River	As (limited sampling)
Platoro-Summitville	Alamosa River	Al, Mn, Fe, Cu, Zn, Cd, As, Tl, SO4
Rabbit Ears Range	Colorado River	Al, Mn, Fe, As
Red Amphitheatre	Middle Fork South Platte River	Al, Mn, Zn, Cd, F
Red Mountain Pass	Red Mountain Creek	Al, Mn, Fe, Cu, Zn, Cd, Pb, As, Tl, Ag
Rico Mountains	East and West Dolores Rivers	Al, Mn, Fe, Cu, Zn, Cd, SO4
Ruby Range	Gunnison River	Al, Mn, Fe, Pb, Cu, Zn, Cd, As, Ag, Cl, SO4
San Juan Mountains	San Miguel River	Al, Mn (limited sampling)
Slumgullion	Lake Fork of the Gunnison	Al, Mn, Fe, Cu, Zn, SO4, F, Cl
Twelvemile Creek	South Platte River	(no samples)

and the metals leached. Headwater tributaries with this chemical characteristic add acidity to the receiving stream, but metal loading is minimal.

Surface waters and springs emerging at lower elevations in these regionally altered and highly pyritic terranes (without extensive carbonate rocks) are commonly acidic with relatively high EC and hardness. Major and trace ion concentrations are usually elevated, and these sources can add considerable metal loads to receiving streams. The increase in total dissolved solids and trace metals is a result of extended subsurface residence time, allowing percolating acidic water more reaction time with the altered and mineralized host rocks than at higher elevation sites. Natural poor-quality water associated with hydrothermally altered rock is not always acidic. In some cases, especially where carbonate rocks are present, such as in the Rabbit Ears Range, Red Amphitheatre near Alma, and in the western part of the Rico area, pH is circumneutral or slightly alkaline. Neutralization by carbonate minerals has likely raised the pH of the waters, but significant dissolved concentrations of aluminum, iron, manganese, and sulfate remain in the water. Trace metal concentrations are not usually elevated in these situations, but exceptions do occur dependent upon a number of physiochemical parameters.

Several generalizations can be made in terms of the trace metals, arsenic, fluoride and sulfate concentrations in ARD from areas sampled for this report. These are summarized in **Figures 62a-f and 63**.

Zinc and cadmium: These two elements commonly appear to be elevated above state standards in ARD, even when zinc is not a

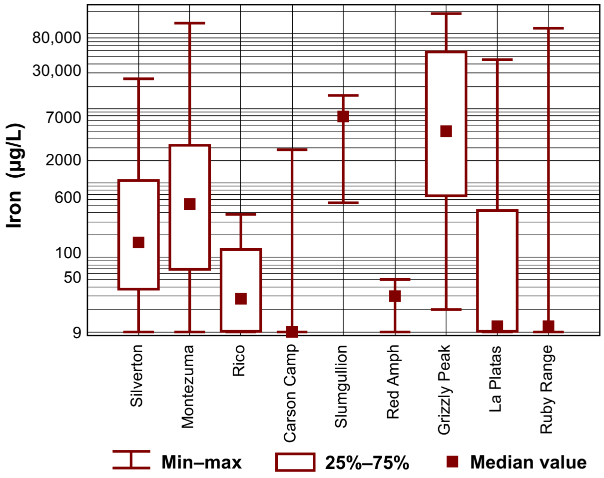

Figure 62a. Box and whisker plots showing median, percentiles, minimum and maximum concentrations of dissolved iron by area.

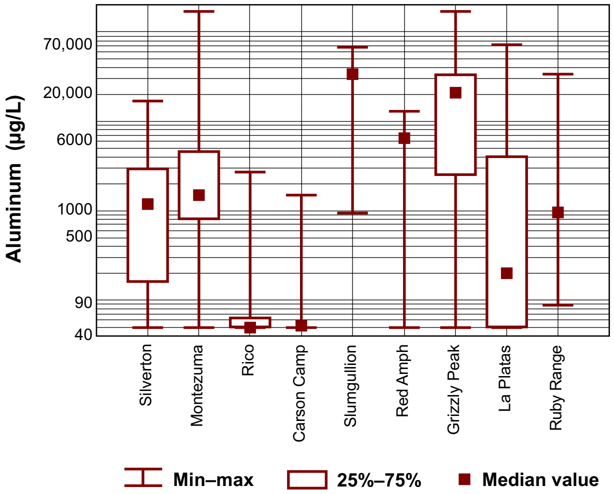

Figure 62b. Dissolved aluminum by location.

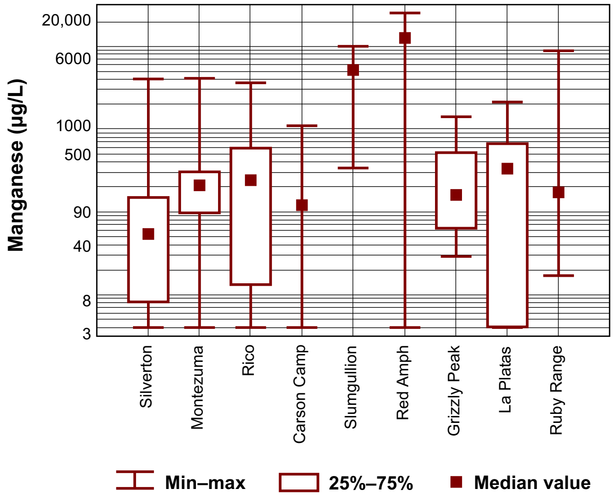

Figure 62c. Dissolved manganese by location.

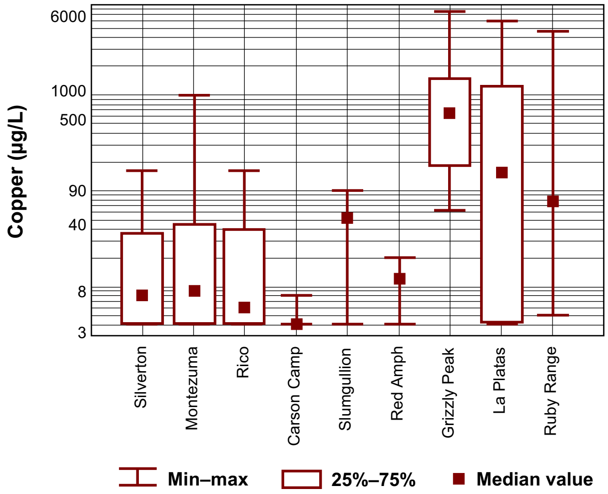

Figure 62b, c, d. Box and whisker plots showing median, percentiles, minimum and maximum concentrations of dissolved aluminum (b), manganese (c), and copper (d) by area. (note changing scale) prominent component of mineralization in the area (e.g. La Platas and Grizzly Peak caldera). Such behavior is consistent with the known high solubility, low sorption and high mobility of zinc in acid to neutral waters (Smith, 1999; Nordstrom and Alpers, 1999).

Copper: This metal commonly exceeds state standards in all ARD from "porphyry-type" mineralized areas assessed in this study (such as the La Platas, Grizzly Peak caldera, Montezuma) except Carson Camp and Red Amphitheater, even though copper sulfides are known in the mineralization in these two areas. NW-86 from Carson Camp is quite acidic (pH=3.45) but none of the trace metals exceed state standards. The exposed rocks in the immediate vicinity of this sample site do not appear to be strongly altered or fractured and thus may not have metals as readily available for leaching. The circumneutral pH (5.79) and high hardness, which are likely due to carbonate dissolution by ARD at Red Amphitheatre probably limit the solubility of copper in this area.

Lead: Lead exceeds state standards in only the most acidic waters in some of the areas with known lead sulfide mineralization (Montezuma, Ruby Range, La Platas, Red Mountain Pass). This is consistent with the generally low solubility of lead minerals and the low mobility of lead in sulfate-rich solutions compared to the relatively high solubilities of most copper and zinc ore minerals (Nordstrom and Alpers, 1999).

Arsenic: Arsenic exceedances appear in only a few areas with known arsenic-rich mineralization (La Platas, Summitville, Red Mountain Pass), with the exception of the Ruby Range, where arsenic-bearing mineralization is not reported. Arsenic will co-precipitate with iron hydroxides and thus can be rapidly removed from ARD when iron compounds are actively precipitating out of solution.

Thallium: This metal only exceeds state standards in samples with elevated arsenic and/or lead concentrations (Montezuma, La Platas, Red Mountain Pass, Summitville).

Fluoride: Fluoride exceedances generally only occur where known fluorite-bearing veins are reported — at Red Amphitheatre and the La Platas. However, the syenite country rocks in the La Platas are also known to be fluorine-rich, and may contribute to the elevated concentrations in the surrounding waters. In addition, waters draining the Slumgullion Slide show elevated fluoride. The fluoride in this area may be related to fluorine-rich, high silica rhyolite plugs near the slide scarp. Fluoride was also elevated in samples from some porphyry Mo/Cu areas (Montezuma and Grizzly Peak caldera) but surprisingly was not found in the one Redwell Basin sample near the Mt. Emmons porphyry Mo deposit in the Ruby Range. Recent studies by the USGS do show elevated fluoride in several springs in the Mt. Emmons area (R. Wanty, USGS, oral communication, 2002).

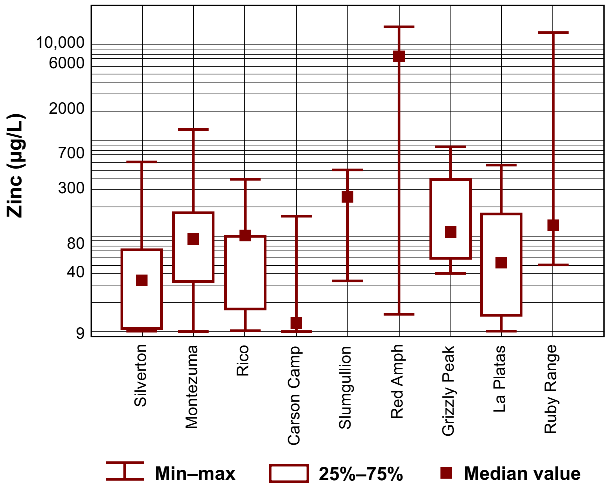

Figure 62e. Dissolved zinc by location.

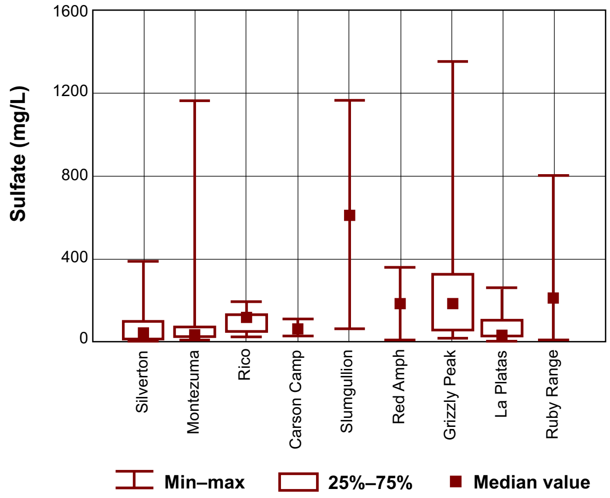

Figure 62e, f. Box and whisker plots showing median, percentiles, minimum and maximum concentrations of dissolved zinc (e) and sulfate (f) by area. (note changing scale)**.**

Silver: Silver only shows exceedances in areas of known silver-rich, base metal veins where lead is also elevated in these waters (Cinnamon Gulch in the Montezuma area, Ruby Range, Red Mountain Pass). The lack of elevated silver in two silver-rich areas, Red Amphitheatre and Rico, is probably partially due to the lack of very low pH waters sampled in these two areas

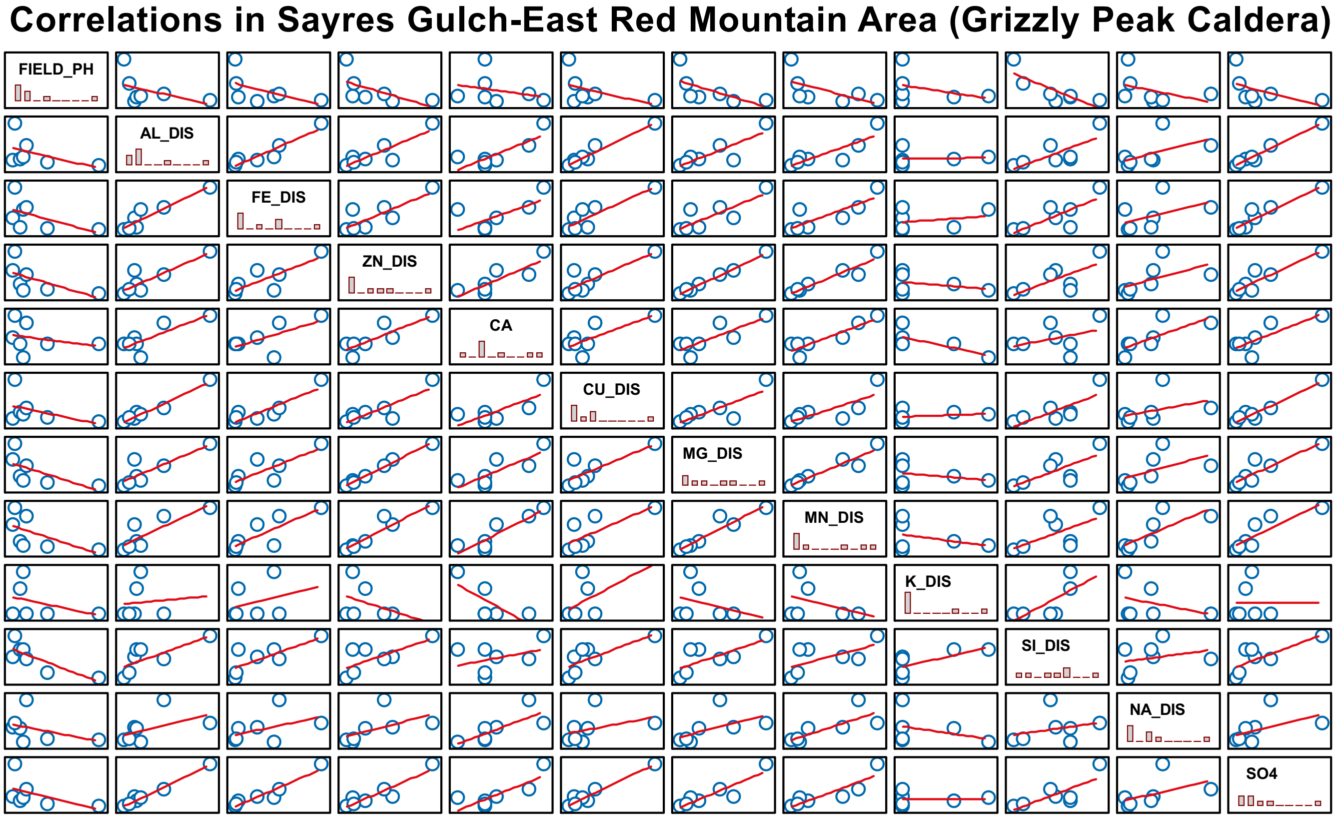

Figure 63. Correlation plots for waters from the Grizzly Peak caldera. This chart shows how dissolved constituents in NARD vary in concentration with respect to each other. Positive slopes indicate constituents vary similarly; negative slopes indicate an inverse relationship.

and the relatively low density of veining near these water sample locations.

Nickel: Nickel only exceeds State standards in the most acidic (pH<4) waters (Montezuma, La Platas, Red Mountain Pass, Kite Lake).

Iron: Iron is typically quite high when pH is very low due to pyrite oxidation, and generally below standards when pH is greater than 5. This is probably due to precipitation or adsorption of various iron phases, generally above pH 3.

Sulfate: The majority of sulfate concentrations above 100 mg/L occur in acid waters (pH < 4.5). The principal exceptions to this are areas with exposed carbonate rocks that have interacted with ARD to produce near-neutral waters with high sulfate concentrations (Red Amphitheatre, Rico) or where gypsum/anhydrite is present in the host rocks (i.e. Howard Fork; Rico). Since pyrite oxidation is generally the dominant source of sulfate in ARD, the sulfate abundance typically mirrors the iron abundance at low pH. Above a pH of about 3 to 3.5, the iron precipitates from the water, but sulfate tends to remain in solution (Smith, 1999). This can lead to moderately acidic waters with very little iron, but significant sulfate concentrations. High sulfate water, generally along with highly elevated (>75–90th percentile range) calcium and strontium (Mast and others, 2000a), with limited iron and high manganese concentrations, can also originate from gypsum dissolution (e.g., Rico and Howard Fork). The presence of gypsum in the unaltered black shales in the Rico and Rabbit Ears areas could also explain high sulfate, high manganese, and low iron concentrations in the higher pH waters draining these areas.

The chemical composition of water samples discussed in this report can be related to several broad geologic characteristics of the sampled areas. The most important features that influence water compositions are mineralization type, structural setting, size of the alteration system, and the host rock compositions.

Natural ARD waters that commonly exceed State water standards are often spatially associated with altered and mineralized rocks in caldera-related settings (Silverton, Lake City, Summitville-Platoro, Grizzly Peak). Most of the other areas with poor water quality are associated with extensive altered areas around disseminated, porphyry-type, molybdenum/copper or molybdenum systems (Montezuma, La Platas, Ruby Range, Rico, Red Amphitheater, Rabbit Ears Range). Both the caldera-related and porphyry-type environments are characterized by extensive fracturing as well as large areas of highly pyritized and altered rocks that are generally related to high-level intrusions. The extensive fracturing permits ready access by surface and groundwater to the metal-bearing and pervasively altered and pyritized rocks. In addition, large areas of acid-sulfate, argillic, and QSP-altered rock have severely limited potential to neutralize acidic water after it is generated (Plumlee and others, 1999). The main exceptions to the latter occur where carbonate rocks are present (Red Amphitheater and Rico) or in calcite-bearing regional propylitic altered rocks, such as are found in large caldera settings (Grizzly Peak, Red Mountain Pass). In the Red Amphitheatre and Rico areas, the carbonate rocks probably neutralized much of the original acidity generated, thus explaining the high hardness of the water samples. However, these circumneutral waters still had moderately elevated sulfate and metal concentrations (especially Al, Mn, Zn, and Cd). The elevated concentrations of zinc and cadmium in these higher pH samples can be explained by the high solubilities of these metals, even at neutral pH ranges, which contrasts with common metals like copper and lead that are soluble only at lower pH ranges (Smith, 1999). Even though circumneutral pH waters in these two carbonate-hosted areas exceed state standards for several metals (Al, Mn, Zn, Cd), the relative magnitude of the exceedances is quite low (except for Mn) compared to water from all of the other non-carbonate-hosted areas. Therefore, except for manganese and possibly zinc, such carbonate-rock-neutralized-ARD does not appear to be nearly as significant for metal loading as ARD from altered areas without carbonate rocks available for neutralization.

Under equilibrium conditions, the aluminum in such acid neutralized waters should precipitate (Nordstrom and Ball, 1986). The two areas of high dissolved aluminum in carbonate-rock-neutralized waters in the present study appear to represent disequilibrium conditions. In the case of Red Amphitheater, the aluminum can be seen to be rapidly precipitating from the neutralized waters, in agreement with the predicted low aluminum solubility in neutral waters, and it is likely to meet standards before the ARD reaches Buckskin Creek. In the case of Rico, most of the aluminum present in the neutralized waters appears to be present as precipitates (e.g. sample NW-69), as expected, and is likely to settle on the stream beds or can be suspended in colloids.

Where the altered rocks are dominantly clastic sediments (La Platas, Ruby Range, Rabbit Ears Range) the neutralization potential of the rocks is more limited. The availability of base cations (especially Ca and Mg) is generally much more limited in siliceous clastic sediments where carbonates and gypsum are absent. If the dominant sedimentary rock is a quartz-rich sandstone/siltstone, limited quantities of aluminum, calcium and magnesium are available for leaching. The low calcium and magnesium content of such rocks would limit the hardness of ARD resulting in exceedances of hardness-based standards at quite low metal concentrations. In the Red Mountain Pass area, low pH waters draining the acid-sulfate alteration assemblage also tends to be low in calcium and magnesium due to limited availability compared to that in nearby propylitic-altered rocks (Church and others, 2007; Bove and others, 2000).

In most of the areas, the dominant altered rocks are felsic intrusions, or subaerial lavas, pyroclastics, or volcaniclastic sediments. These rocks are rich in feldspar minerals that can both contribute aluminum to ARD and, when not completely obliterated by alteration, can provide some acid neutralization potential. Leaching of these rocks, when unaltered, will tend to produce waters with moderate hardness.

In all of the areas studied for this report, changes in water chemistry, from essentially unimpacted (high pH/low metal) to ARD (acidic/high metal) water are readily related to changes in alteration type and intensity. In particular, changes from propylitic or unaltered rocks to acid-sulfate, QSP or argillic altered zones are commonly reflected in dramatic changes in the local chemistry of tributaries and springs (Red Amphitheatre, Grizzly Peak, La Platas). Such behavior is expected based on inherent variations in acid generating capacity and acid neutralizing potential of the different alteration assemblages.

In general, the water samples from all of the areas show strong positive correlations between Al, Fe, Mn, Cu, Cd, Zn, Ni, Si and SO_4 with corresponding strong negative correlations to pH. Such correlations are probably most readily interpretable in water samples draining zoned alteration assemblages superimposed on a single rock type where the variations in water chemistry can be related to alteration assemblage. In the case of the Sayres Gulch area, near East Red Mountain in the Grizzly Peak caldera, the relatively large number of samples available from this altered area, that is largely limited to one rock type (Precambrian gneiss), allows correlations between water samples to be more readily interpreted than is possible in the other areas. These samples all show strong positive correlations between Al, Fe, Mn, Cu, Cd, Zn, Ni, Si, Ca, Mg and SO_4, with corresponding strong negative correlations to pH **(Figure 63)**. Such behavior is typical of most ARD in this study. The results for East Red Mountain are consistent with variable dilution of a fairly uniform composition ARD within rocks of similar lithology and alteration. Only potassium and sodium fail to show strong correlations with the metals. Potassium is positively correlated with silicon, and correlates moderately with decreasing pH, which is consistent with dissolution of sericite or potassium feldspar. Potassium shows weak negative correlations with hardness, magnesium, and calcium suggesting that potassium-bearing minerals are relatively inconsequential in acid-neutralization processes that involve the dissolution of minerals such as calcite, chlorite, or other minerals with potential to neutralize acidity. Sodium is most strongly positively correlated with manganese and hardness and the only negative correlation is a weak one with potassium. This suggests that the sources for sodium and potassium are completely different. Such sources could be leaching of plagioclase feldspars or amphiboles for sodium and leaching of potassium feldspar or sericite for potassium. Studies by the USGS in the Animas River basin suggest that an important source of sodium in volcanic terrane with regional propylitic alteration is fine-grained secondary albite. The manganese source is probably also greatest in the same regional propylitic rocks that have secondary albite where the manganese source is diopside, chlorite, epidote, and secondary manganese oxide coatings that can be remobilized (Bove and others, 2000). An additional source available in the Animas River basin is manganese silicate or carbonates, which are common in the polymetallic veins of the area (Mast and others, 2000a ; Bove and others, 2000).

Many of the areas examined during this study are in watersheds where both natural ARD and historic mining have affected water quality. Where warranted, these watersheds should be characterized in detail to: 1) better understand the natural ARD and anthropogenic processes affecting stream water quality, and 2) more objectively document or rank site characteristics with respect to possible contributions from anthropogenic sources. Detailed characterization is especially important in drainage basins slated for major mine-reclamation projects. Information derived from characterizations of regional and local watersheds is useful for determining realistic remediation goals, and for prioritizing mine sites for cost-effective reclamation that will provide measurable improvements to downstream water quality.

Some natural ARD areas constitute unique natural environments. As such, they may deserve protection from disturbances that would alter existing physical, chemical, and biological processes.

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COLORADO GEOLOGICAL SURVEY
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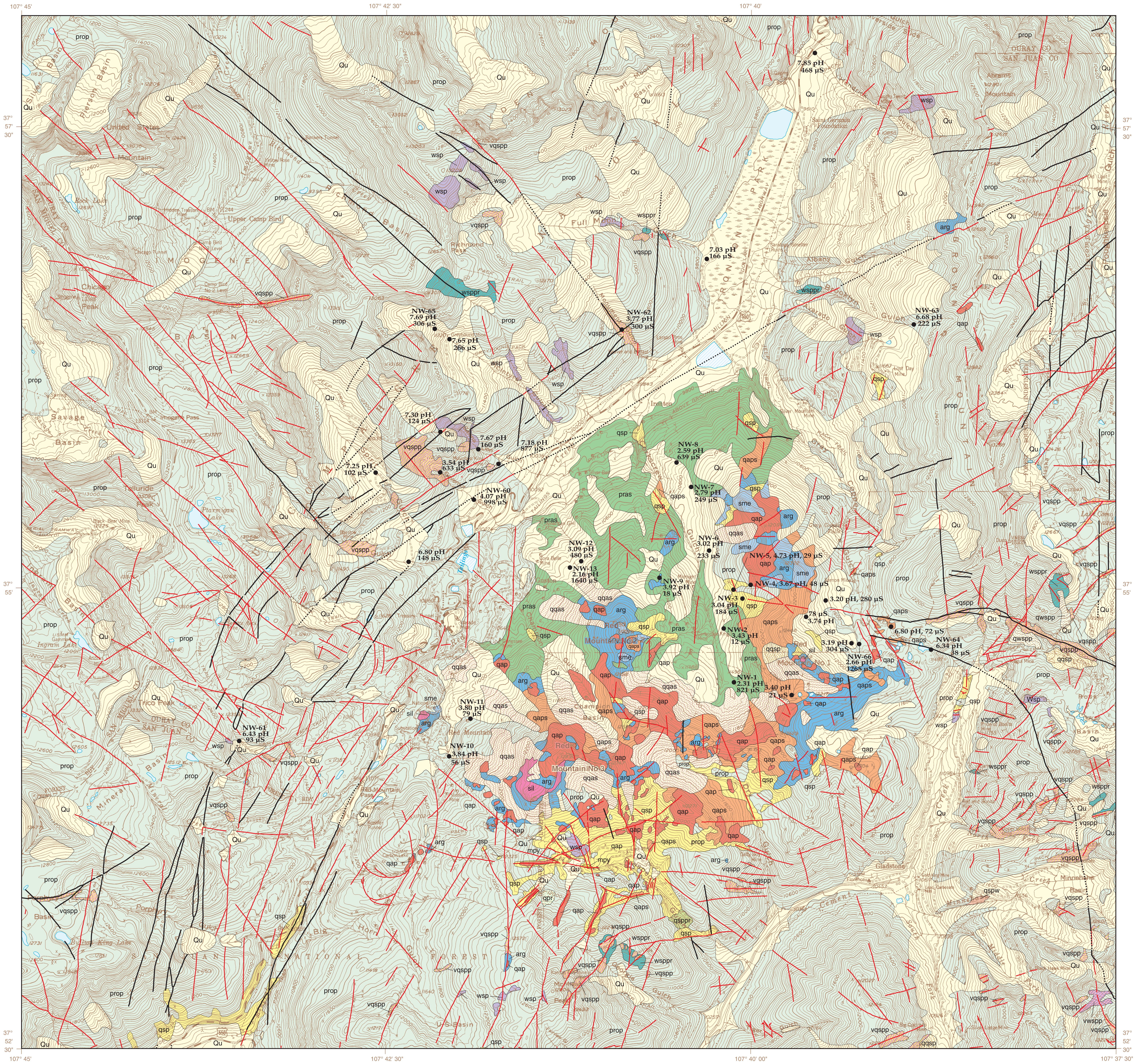
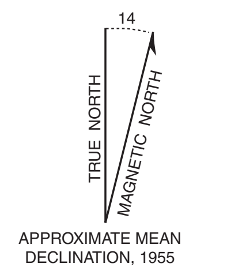
NATURAL ACID ROCK DRAINAGE
BULLETIN 54
PLATE 1
2011



Base map from USGS Ironton 7.5-minute quadrangle

DATA SOURCE: alteration from Bove, 2001, unpublished USGS compilation of AVIRIS data and field mapping; geology from Yager and Bove, 2002 (USGS MF-2377)

SCALE 1:24,000



EXPLANATION

Alteration Units

sil	**Silicic alteration assemblage—** Generally formed as replacements along mineralized pipelike to tabular hydrothermally brecciated masses, also along brecciated faults and strong fracture zones. This assemblage is comprised of gray- to very dark-gray, microcrystalline quartz, with pyrite and minor alunite, pyrophyllite, diaspore, leucoxene, and rutile. Within the breccias, quartz is cryptocrystalline to chalcedonic or forms anhedral microcrystalline grains in both the groundmass and within clasts. Small crystals of quartz commonly line cavities
qap	**Quartz-alunite-pyrophyllite assemblage—** Inner acid-sulfate assemblage dominated by quartz, alunite, pyrophyllite, and pyrite. May contain other minerals including diaspore, zunyite, and rutile
qsp	**Quartz-sericite-pyrite assemblage—** Characterized by the complete replacement of plagioclase, and k-feldspar phenocrysts by 25–50 volume percent fine-grained pervasive quartz, illite (sericite), and 10–20 percent finely disseminated and fracture-filling pyrite. Kaolinite may be present in varying amounts in some localities. Rocks typically have a bleached appearance and are variably oxidized. Thin stockwork quartz veinlets are locally present within this assemblage
qaps	**Quartz-alunite-pyrophyllite** (qap) **and quartz-sericite-pyrite** (qsp) **mix**
wsp	**Weak sericite-pyrite assemblage—**Reflects a weaker style of alteration than that characterized by the Qsp assemblage. Rocks affected by this style of alteration are found in areas of dense veining and also are present on the outer margins of broad Qsp zones (Bove and others, 2000). Weak sericitic assemblage contains 5–25 percent quartz, illite, and >5–10 volume percent pyrite. This assembage is characterized by the presence of weakly to unaltered plagioclase, and contains chlorite, which along with plagioclase is typically absent in the Qsp assemblage
mpy	**Massive pyrite zone—**Highly altered rock containing greater than 60 percent fine-grained pyrite
qspw	**Mix of quartz-sericite-pyrite** (qsp) **and weak sericite-pyrite** (wsp) **alteration**
pras	**Undifferentiated propylitic acid-sulfate assemblage —**Propylitically altered rocks are dominant over acid sulfate altered rocks
prop	**Propylitic assemblage—**Contains varying amounts of chlorite, epidote, calcite, and illite, in the pres-ence of metastable to stable primary feldspar crystals. Coexisting mineral phases of the pro-pylitic assemblage can be variable depending on several factors including rock type and degree of alteration. Incipient to weak stages of propylitic alteration are generally noted by the replacement of ferromagnesian minerals (biotite, pyroxene, and hornblende) by fine-grainied chorite, calcite, quartz, iron-oxides, and (or) epidote. In contrast, calcite and illite replace plagioclase, mostly along cleavage planes and microfractures, leaving the internal portions of the grains relatively unaltered. Weakly altered rocks are noted especially in the dark-colored lavas of the Henson Member of the Silverton Volcanics that cap many high ridges within study area (Burbank and Luedke, 1969). The weakly propylitized Henson Member is characterized by the presence of hematite along microfractures and microscopic granular disseminations
arg	**Argillic assemblage—**Bleached argillic zones, which form the broad outer margins around the inner quartz-alunite-pyrite and silicic zones, are characterized by the presence of dickite and quartz with varying amounts of pyrite. These zones are poorly to only moderately indurated and commonly recognized in the field by the presence of soft, waxy textured clays
sme	**Smectitic alteration asemblage—**Similar in appearance to argillic zones but characterized by presence of smectite, chlorite, and metastable feldspar grains
wsppr	**Mix of weak sericite-pyrite and propylitic altered rock**
qsppr	**Mix of quartz-sericite-pyrite** (qsp) **and propylitic** (prop) **altered rock**
vwspp	**Vein-related zones of weak sericite-pyrite mixed with propylitic altered rock**
vqspp	**Vein-related zones of quartz-sericite-pyrite mixed with propylitic altered rock**

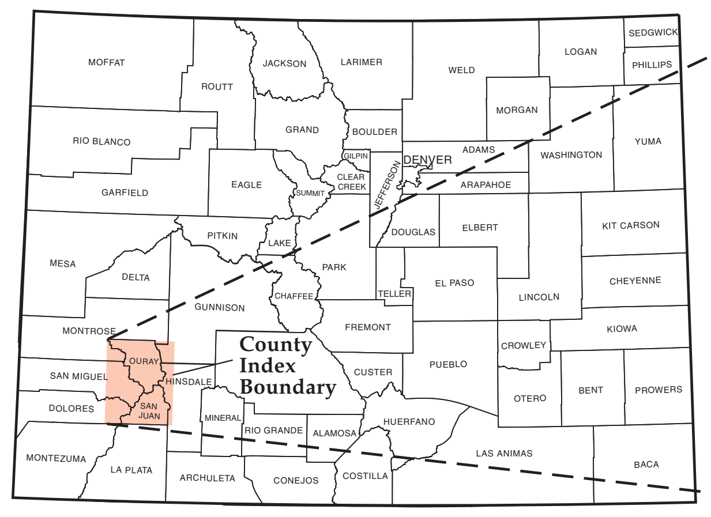
Quaternary Geologic Units

Qu	**Quaternary undifferentiated**
Qwspp	**Coarse talus and landslide deposits—**Consists of mixed weak sericite-pyrite to propylitic altered rocks
Qqsp	**Coarse talus and landslide deposits—**Consists of quartz-sericite-pyrite altered rocks
Qqas	**Coarse talus and landslide deposits—**Consists of mixed quartz-alunite-pyrophyllite (qap) and quartz-sericite-pyrite (qsp) altered rock
Qpr	**Coarse talus and landslide deposits—**Consists of propylitic-dominant material. Mapped only where alteration constituents within these deposits contrast from surrounding altered rocks

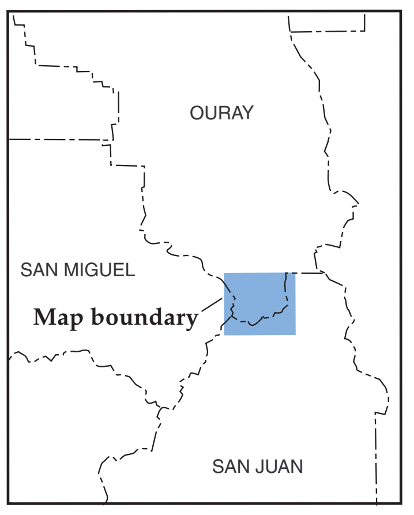
MAP SYMBOLS

—	**Vein**
—	**Fault—Dotted where concealed**
NW-64 ● **6.34 pH** **38 µS**	**Water sample location and test results—**Field mea-surement of pH and electrical conductivity in microsiemens

COLORADO INDEX



COUNTY INDEX



Map Showing Quaternary Geology, Hydrothermal Alteration, Water Sample Sites and Test Results in the Red Mountain Pass Area

By Dana J. Bove and John T. Neubert

John W. Hickenlooper, Governor
State of Colorado

Mike King, Executive Director
Department of Natural Resources

Vincent Matthews
State Geologist and Director
Colorado Geological Survey

COLORADO GEOLOGICAL SURVEY
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NATURAL ACID ROCK DRAINAGE
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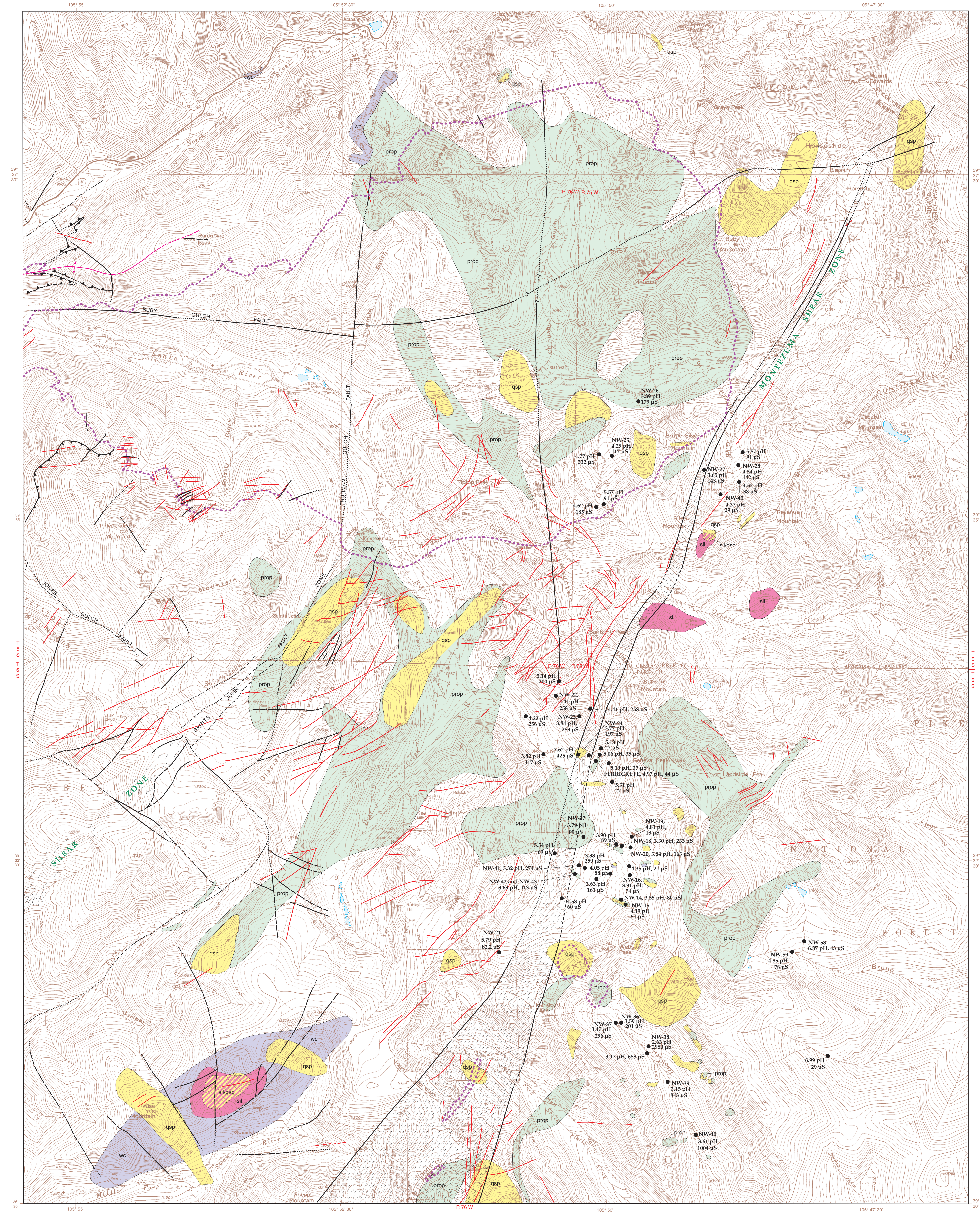
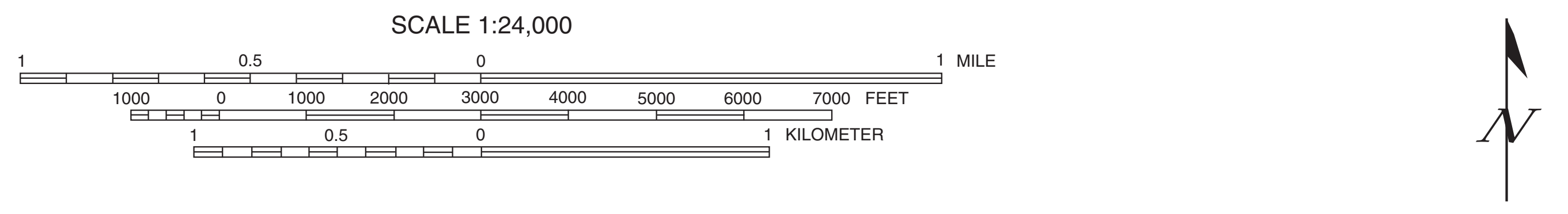


Base maps from USGS 7.50-minute quadrangles: Montezuma,
Keystone, Loveland Pass, and Grays Peak
Alteration from Cyprus Amax unpublished data from field mapping by A. Bookstrom
Montezuma Stock, shear zones,and faults from Neuerburg and Botinelly, 1972,
USGS MI I-750; Keystone quadrangle structure from Widmann and others, 2003,
CGS OF 02-3



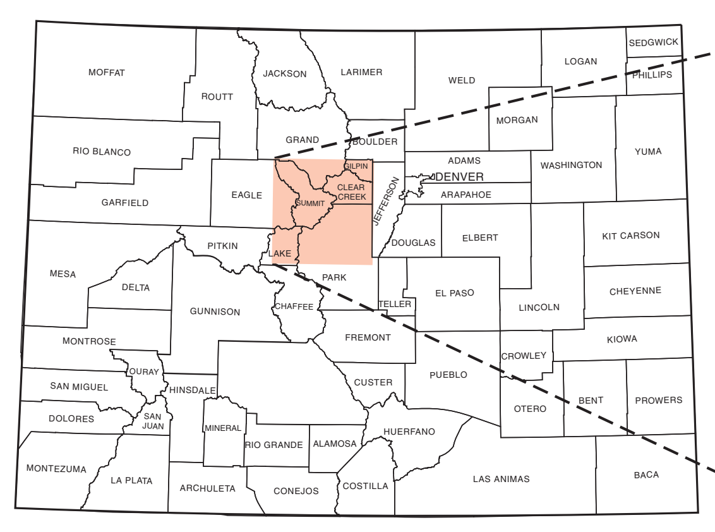
EXPLANATION

Alteration Units

sil	**Silicified and quartz veined**
qsp	**Quartz-sericite-pyrite**
sil/qsp	**Silicified and quartz veined with quartz-sericite-pyrite**
prop	**Propylitic**
wc	**Weak chloritic**

▪ ▪ ▪ ▪ ▪ ▪	**Outline of Montezuma Stock**
▬▬	**Fault or approximate boundary of shear zone**—Dashed where approx-imate and dotted where concealed
▲ ▲	**Thrust fault**—Sawteeth on upper plate
▬▬	**Vein (MoS_2; SiO_2-FeS; Ag-Pb-Zn-Cu)**
● 4.58 pH 60 µS	**Water sample location and test results**—Field measurement of pH and electrical conductivity (micro-Siemens)
〰	**Shear zone**

COLORADO INDEX



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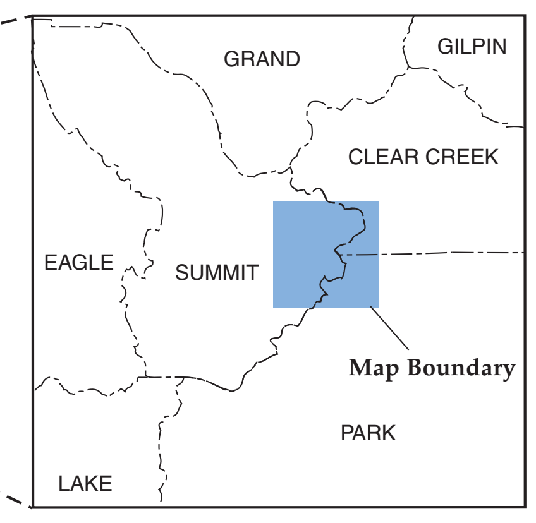
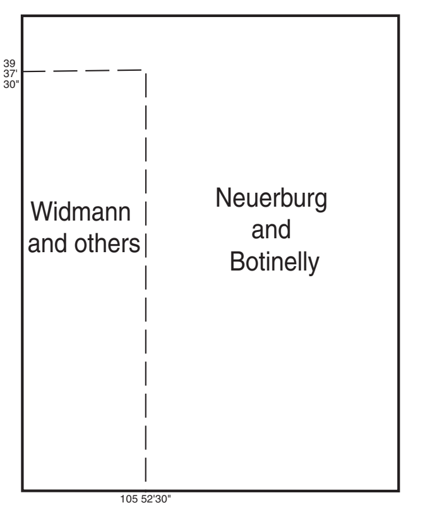


SOURCES OF STRUCTURAL GEOLOGY



Map Showing Hydrothermal Alteration, Water Sample Sites, and Test Results in the Montezuma Stock Area, Colorado

Hydrothermal alteration mapped by Art Bookstrom

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