

Alteration Map Showing Major Faults and Veins and Associated Water-Quality Signatures of the Animas River Watershed Headwaters Near Silverton, Southwest Colorado

By Dana J. Bove, Douglas B. Yager, M. Alisa Mast, and J. Brad Dalton

Pamphlet to accompany
Scientific Investigations Map 2976

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2007

For product and ordering information:
World Wide Web: <http://www.usgs.gov/pubprod>
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: <http://www.usgs.gov>
Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:
Bove, D.J., Yager, D.B., Mast, M.A., and Dalton, J.B., 2007, Alteration map showing major faults and veins and associated water-quality signatures of the Animas River watershed headwaters near Silverton, southwest Colorado: U.S. Geological Survey Scientific Investigations Map 2976, 18-p. pamphlet, 1 plate, scale 1:24,000.

Contents

Map Notes	1
Description of Alteration Units	1
Map Summary	4
Methods	4
Alteration Assemblages and Mineralization	4
Water-Quality Signatures associated with Alteration Assemblages	5
References Cited	6

Figures

1. Map showing generalized locations of hydrothermal alteration assemblages and geographic features	9
2. Generalized alteration map draped on hillshade rendering of 10-m-resolution digital elevation model	10
3. Photograph of propylitic altered Burns Member of the Silverton Volcanic Series	11
4. Photomicrograph of propylitic alteration of intermediate-composition, porphyritic lava of the San Juan Formation	11
5–8. Photographs of:	
5. Quartz-sericite-pyrite altered quartz monzonite intrusive	12
6. Silicified breccia body or “pipe” at National belle mine	12
7. Quartz-alunite altered dacite porphyry intrusive	13
8. Fine-grained massive quartz-alunite replacement of altered lavas or volcaniclastics of Silverton Volcanic Series	13
9. Photomicrograph of bladed and lath-shaped birefringence alunite crystals	14
10–12. Photographs of:	
10. High-level, argillic altered dacite porphyry intrusive	14
11. Silicified breccia body near Red Mountain No.3	15
12. Deep-level acid sulfate alteration in upper Prospect Gulch	15
13. Photomicrographs of unit qsp altered rock	16
14. Photograph of vein-related unit qsp assemblage	17
15. Boxplots comparing background water quality from different alteration assemblages in map area	18

Conversion Factors

To convert	Multiply by	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km ²)	0.3861	square mile (mi ²)

Map Notes

Sericite is a field and petrographic term to indicate fine-grained, micaceous material that is not differentiated by various analytical techniques to be either fine-grained muscovite or illite. X-ray diffraction (XRD), transmission-electron microscopy (TEM), and chemical analysis reveal that sericite in the map area is commonly very fine grained muscovite or phengite, with a layer charge close to 1.0 equivalent per $O_{10}(OH)_2$ for the micaceous layers (Eberl and others, 1987; Bove and others, 2002; D.J. Bove, unpub. data, 2005).

Pyrite oxidation: Although fine-grained pyrite is abundant in many of the alteration assemblages described in the following section, it is commonly oxidized in outcrops and other surficial deposits. The recognition of originally unoxidized pyrite grains is confirmed by pseudomorphic casts and oxidation products such as hematite, jarosite, goethite, and

other iron hydroxides. Examination of nearly 200 originally pyrite-rich outcrop samples shows complete pyrite oxidation in nearly 75 percent of the total sample set. The remaining samples with unoxidized pyrite were from outcrops mainly along stream drainages, gullies, or highly silicified zones. Drill core studies indicate that pyrite oxidation is deepest (as much as 100 m) along high ridges and broader areas, and tapers to near-surface levels towards valley bottoms. Coloration of the various pyrite-rich alteration assemblages described in the following section is largely a function of the species of oxidation of the mineral or phase (Dalton and others, 2007). The proximity to unweathered pyrite can be estimated by the mapped species of iron oxidation minerals (Dalton and others, 2007). Jarosite tends to reflect close proximity to unoxidized pyrite, whereas goethite and then hematite are present with increasing distance from these unoxidized zones (Dalton and others, 2007).

DESCRIPTION OF ALTERATION UNITS

QUATERNARY SURFICIAL DEPOSITS

Qu	Quaternary units, undivided —Lacks distinct spectral signatures as determined by remote sensing Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Dalton and others, 2007). Weak spectral signatures reflect either lack of altered material or presence of abundant vegetation
	Coarse talus and landslide deposits with strong spectral signature
Qqas	Predominantly quartz-alunite-pyrophyllite (unit qap) and fewer quartz-sericite-pyrite (unit qsp) altered rocks
Qqsp	Chiefly quartz-sericite-pyrite (unit qsp) altered rocks
Qwsp-pr	Mix of weak sericite-pyrite (unit wsp) and propylitic (unit pr) altered rocks

BEDROCK

Vein-related alteration

vqsp	Vein-related zones of quartz-sericite-pyrite (unit qsp) altered rock
vqsp-pr	Vein-related zones of quartz-sericite-pyrite (unit qsp) mixed with lesser propylitic (unit pr) altered rock
vqsp-arg	Vein-related zones of quartz-sericite-pyrite (unit qsp) mixed or grading into argillic (unit arg) altered zones
vwsp-pr	Vein-related zones of weak sericite-pyrite (unit wsp) mixed with propylitic (unit pr) altered rock
wsp-pr	Mixed weak sericite-pyrite (unit wsp) and propylitic (unit pr) altered rock
mpy	Massive pyrite zone —Highly altered rock containing greater than 60 percent fine-grained pyrite

Pervasive alteration

wsp	Weak sericite-pyrite —Characterized by weak to moderately altered plagioclase and meta-stable chlorite (these minerals are typically absent where increased alteration intensity produced unit qsp altered rock). Potassium feldspar, where present, generally unaltered. Contains between 15 and 25 percent microcrystalline quartz; less silicified than unit qsp counterparts. Sericite is also abundant along with about 5–10 volume percent finely disseminated pyrite
qsp	Quartz-sericite-pyrite —Characterized by complete replacement of plagioclase and partial to complete replacement of potassium feldspar (where present) by 25–55 percent fine-grained pervasive quartz, sericite, and 10–20 percent finely disseminated and fracture-filling pyrite. Kaolinite may be present in varying abundances in some localities. Rocks

typically have a bleached appearance and are variably oxidized. Thin stockwork quartz veinlets are locally present within this assemblage. Veinlet densities are anomalously high (0.3–1.5/m²) in a 1 km² area centered around peak 3,792 m, informally named Mount Moly (fig. 1).

Detailed studies in Red Mountains area (fig. 1) (Bove and others, 2005; Bove and others, 2002) demonstrate that sericite in unit **qsp** assemblage is predominantly mixtures of 2M₁ and 1M polytypes. Mean thickness measurements of sericite particles in Red Mountains area range from 11 to 36 nanometers (nm), and average 17 nm (Bove and others, 2002). These sericites lack an illite/smectite (I/S) component, and have very low expandabilities (<4 percent), approximating end-member composition (zero expandability). Detailed mapping and XRD studies demonstrate that some of the larger unit **qsp** zones in map area grade outward into a marginal facies characterized by a decrease in silicification and sericite crystallinity. These marginal facies rocks contain between 15 and 25 percent microcrystalline quartz, abundant sericite, sporadic chlorite, and about 5–10 volume percent finely disseminated pyrite. Sericite in marginal zones consists mainly of 1Md polytype and contains a substantial I/S component (15–20 percent expandable). Sericite particle sizes from this zone, where studied in Red Mountains area (Bove and others, 2002), range from 4 to 8 nm, which is significantly smaller than sericites within the central unit **qsp** zone. Transitions in unit **qsp** assemblage from center to margins (as suggested by preceding mineralogical details) are consistent with changes due to temperature variation and distance from centers of hydrothermal alteration (Bove and others, 2002; Srodon and Eberl, 1984).

- wsp-hyd** **Mix of weak sericite-pyrite (unit wsp) and hydrothermal propylitic altered rock**—Present only on margins of Mount Moly porphyry hydrothermal system. Characterized by incipient to partial replacement of plagioclase by sericite; biotite and pyroxene are altered to chlorite, sericite, and fine opaque minerals. These rocks are generally less silicified than their unit **qsp** counterparts and contain fewer quartz-sulfide stockwork veinlets. Hydrothermal propylitic altered rock, which formed contemporaneously with the Mount Moly porphyry hydrothermal system (Bove and others, 2007), is composed of fresh to weakly altered feldspar, chlorite- and epidote-altered biotite and pyroxene, and abundant veins and fractures filled with pyrite, chlorite, magnetite, and quartz. Hydrothermal propylitic altered rocks of Mount Moly porphyry system can be distinguished from earlier formed regional propylitic (unit **pr**) assemblage largely by presence of pyrite, quartz, and chlorite veinlets in hydrothermal propylitic altered rocks. Finely disseminated pyrite is generally scarce in regional propylitic altered rock.
- qsp-wsp** **Mix of quartz-sericite-pyrite (unit qsp) and weak sericite-pyrite (unit wsp) altered rocks**
- qsp-pr** **Mix of quartz-sericite-pyrite (unit qsp) and propylitic (unit pr) altered rock**

Acid sulfate suite

Formed by replacement of original volcanic host rocks by low-pH, sulfate-rich solutions. These solutions were localized along fault and hydrothermal breccia zones and permeated outward throughout intensely fractured wallrock. Centers of acid sulfate altered rock are internally zoned and generally transition outward from silicified, quartz-alunite-pyrophyllite (typically quartz-alunite with pyrophyllite increasing laterally), to argillic (dickite dominant), and then into smectite and (or) propylitic altered rock; however, variations in this generalized zonation are common. Acid sulfate alteration in Red Mountain Pass area (fig. 1) occurred at about 23 Ma (Lipman and others, 1976; Gilzean, 1984; Bove and others, 2001) as determined by K-Ar and ⁴⁰Ar/³⁹Ar dates on alunite.

- sil** **Silicified**—Generally formed as replacements along mineralized, pipe-like to tabular, hydrothermally brecciated masses and along brecciated faults and strong fracture zones. Silicified volcanic rocks and breccias range from light-gray to highly bleached granular aggregates and dark jasperoidal masses composed of a microcrystalline mosaic of quartz (>75 percent), pyrite (5–25 percent), leucoxene (trace), and minor dickite, alunite, pyrophyllite, and diaspore. Within the breccias, quartz is cryptocrystalline to chalcedonic or forms anhedral microcrystalline grains in both the groundmass and within clasts. Small

quartz crystals commonly line cavities. Mineralized and silicified breccia bodies as typified in Red Mountain Pass area (fig. 1) are surficially expressed as prominent silicified knolls (45–150 m wide) that rise from 8 to 60 m above valley bottom. Oxidized ores were present in upper 100 m of some of these silicified breccia bodies and consisted of lead and iron carbonates and sulfates with galena cores; various iron oxides and arsenates; botryoidal masses of sphalerite and oxidized galena; along with spongy quartz, dickite, kaolinite, diaspore, pyrophyllite, and alunite. Oxidized ores in silicified deposits graded downward into silver-rich copper ores of enargite, tetrahedrite, stromeyerite, bornite, and chalcopyrite, which gradually diminish downward into increasing amounts of low-grade pyrite

qap **Mixed quartz-alunite and quartz-alunite-pyrophyllite altered rocks**—Inner quartz-alunite and more distal quartz-alunite-pyrophyllite alteration zones of acid sulfate suite are defined by presence of quartz, alunite, natroalunite, pyrophyllite, dickite, and pyrite and minor to trace amounts of zunyite, sulfur, svanbergite, and tridymite. These highly silicified rocks typically contain between 30 and 80 percent fine-grained quartz, with a mean of 50 percent. Pyrite, present as disseminations and along tiny fracture networks, typically ranges from 20 to 30 weight percent within these rocks. Alunitized rocks are characterized by the breakdown of all primary rock constituents with the exception of zircon and resorbed quartz phenocrysts, where present. Biotite, hornblende, and primary opaque minerals are altered to leucoxene; hematite and jarosite formed as near-surface oxidation products of pyrite. Alunite content typically decreases and pyrophyllite increases with lateral distance away from central quartz-alunite dominant alteration zones. Quartz content diminishes to an average of about 30 percent in distal pyrophyllite-rich zones where alunite content is at a minimum.

Compositional data as determined by AVIRIS remote spectroscopy (Dalton and others, 2007) indicate that alunite in map area ranges mostly from a nearly pure potassium end member to intermediate potassium and sodium compositions. However, natroalunite has been identified in some localities by AVIRIS mapping (Dalton and others, 2007) and XRD methods (Sole and others, 2007). An individual chemical analysis of alunite from Red Mountain Pass area (Hurlburt, 1894) shows presence of potassium and sodium in roughly equal proportions

qap-s **Predominantly mixed quartz-alunite and quartz-alunite-pyrophyllite altered rocks (unit qap) mixed with lesser quartz-sericite-pyrite altered rocks (unit qsp)**

arg **Argillic**—Characterized by presence of dickite and quartz with varying amounts of pyrite. Rocks are generally bleached and clay rich, containing a distinctive soft, white waxy clay that is pseudomorphous after feldspar and occurs along fractures. Rocks are poorly to only moderately indurated and contain trace amounts to 40 percent fine-grained quartz. Argillic zones form broad outer margins around quartz-alunite and quartz-alunite-pyrophyllite (unit **qap**) and silicified (unit **sil**) zones

smect **Smectitic**—Similar in appearance to argillic (unit **arg**) zones but characterized by presence of smectite, chlorite, and metastable feldspar grains. Smectitic alteration zones formed from hydrothermal fluids and are present on or near outermost margins of acid sulfate alteration centers. Smectites from Red Mountains area are dioctahedral with compositions ranging from beidellite to montmorillonite (D.J. Bove and H.A. Lowers, unpub. data, 2005; Luedke and Hosterman, 1971)

pr-as **Mixed propylitic (unit pr) and alteration units of acid sulfate suite**—Propylitic altered rocks are generally dominant over acid sulfate altered rocks. Contacts of this mixed assemblage are largely inferred. Mineral mapping by AVIRIS was severely restricted in these highly vegetated areas; field observations were also limited due to lack of outcrop or precipitous slopes. However, both data sources indicate that propylitic and acid sulfate altered rocks are present in these areas

Regional propylitic suite

pr **Propylitic**—Contains varying amounts of chlorite, epidote, calcite, and illite or sericite, in the presence of metastable to stable primary feldspar crystals. Rocks of propylitic assemblage are characteristically green to pistachio green in color owing to the

presence of chlorite and (or) epidote, respectively. Plagioclase phenocrysts, most notably the calcic cores, show significant replacement by mixtures of epidote, chlorite, calcite, and illite, whereas groundmass is altered to fine aggregates of these secondary minerals. Appearance of epidote in some lithologies may denote a higher degree of alteration, although calcite instead of epidote can predominate within these altered grains. Although calcite and epidote coexist in some rocks, these minerals more typically occur to the exclusion of one another. Calcite and chlorite can be quite abundant in these rocks; however, chlorite is nearly ubiquitous, whereas calcite is locally absent. Percentages of illite or sericite range from 10 to 20 volume percent in some samples.

Incipient to weak stages of propylitic alteration are generally noted 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 (or fine muscovite) replace plagioclase, mostly along cleavage planes and microfractures, leaving internal parts of grains relatively unaltered. Weakly propylitic altered rocks are noted especially in the dark-colored lavas of the Henson Member of the Silverton Volcanics that cap many of the high ridges within study area (Burbank and Luedke, 1969). The weakly propylitized Henson Member is also characterized by presence of hematite along microfractures and as microscopic granular disseminations.

Coexisting mineral phases of propylitic assemblage can be quite variable depending on several factors, including degree of alteration and nature and composition of protolith, as briefly discussed in the preceding. Additional factors include stratigraphic position or relative depth of burial. Propylitic assemblages were broadly differentiated into two major subgroups: (1) chlorite, epidote, calcite (CEC) dominant (Dalton and others, 2004), and (2) chlorite, illite or fine muscovite, calcite (CIC) dominant as discussed in Bove and others (2005).

Map Summary

Methods

Hydrothermal alteration assemblage maps were compiled from the following sources: (1) detailed field mapping (scale 1:12,000) and associated XRD analysis, (2) mineral mapping by remote spectroscopy (AVIRIS) (Dalton and others, 2007), and (3) mapping by aerial photography at a scale of 1:24,000. Mapping by Ringrose (1982) was also used in this compilation. Field and remote spectroscopic identification of mineral phases was confirmed by whole rock XRD. XRD studies of more than 200 samples were performed using standard clay XRD techniques (Moore and Reynolds, 1989). These XRD results are in a relational database (Sole and others, 2007).

Geologic structures were compiled and generalized from multiple published and unpublished sources (Burbank and Luedke, 1964; Steven and others, 1974; Luedke and Burbank, 1975a, b; Lipman, 1976; Luedke and Burbank, 1987; Luedke, 1996) (see Index Map). Unpublished mapping of the Ironton quadrangle by D.J. Bove and J.P. Kurtz in 1997–1999 was included. Veins and faults are undifferentiated, including those major faults related to the San Juan and Silverton caldera complex. Structural offset is often difficult to determine at the surface due to infilling of structural features by vein quartz that demarks the location in several places of vein-related quartz-sericite-pyrite alteration (unit *vqsp*). In previous

geologic mapping, structural features were also generalized and referred to as veins or mineralized faults (Burbank and Luedke, 1964), alluding to the ambiguity in determining structural offset along these features.

Alteration Assemblages and Mineralization

Most mineralization and associated hydrothermal alteration in the map area (figs. 1, 2) were temporally and genetically associated with three major episodes of high-level magmatism between about 27 and 10 Ma (Bove and others, 2001). These events postdate collapse of the San Juan, Uncompahgre, and nested Silverton calderas (28–27 Ma) (Yager and Bove, 2007) by about 5–15 m.y. (Lipman and others, 1976; Bove and others, 2001). Caldera collapse and resurgent doming created a favorable structural environment for later mineralization and hydrothermal activity. In general, deuteric activity was temporally associated with caldera development and caused regional propylitic alteration (unit *pr*), which characterizes a major part of the study area (Burbank, 1960). Rocks affected by this alteration type contain abundant calcite, epidote, and chlorite (figs. 3, 4), which contribute to the intrinsic acid neutralizing capacity of this alteration assemblage (Desborough and Yager, 2000; Bove and others, 2005; Yager and others, 2005).

The earliest important mineralizing and related hydrothermal event, at about 26–25 Ma, was related to several calc-alkaline intrusions emplaced over a broad region of the western San Juan Mountains (Bove and others, 2001). The Mount Moly (informal name) area, centered around the 3,792

m peak between South and Middle Forks Mineral Creek (fig. 1), is the only known mineralized hydrothermal system of this type and age in the study area. This area is characterized by subeconomic molybdenum-copper mineralization and more than 19 km² of intensely altered and pyritized rock (Ringrose, 1982). Hydrothermal alteration assemblages change outward from a central quartz-sericite-pyrite zone (unit **qsp**), characterized by stockwork quartz veining (fig. 5), into a zone of undifferentiated weak sericite-pyrite and hydrothermal propylitic altered rock (unit **wsp-hyd**), and finally into regional propylitic altered rock (unit **pr**). Zones of oxidation extend to depths of about 100 m below the ground surface, beneath which secondary copper was enriched to as much as 700–800 ppm (Bove and others, 2005). Relatively narrow, silver-bearing base-metal veins are present mostly on the periphery of the hydrothermal system.

Two large centers of acid sulfate altered and mineralized rock in the Red Mountains and Ohio Peak–Anvil Mountain areas (fig. 1) are related to high-level dacite intrusions emplaced about 23 Ma (Bove and others, 2001). The Red Mountains system encompasses a roughly 19 km² area that was host to breccia-pipe and fault-hosted mineralization (Burbank and Luedke, 1969; Bove and others, 2000). The deposits were noted for rich silver-lead-copper ores; individual deposits typically contained from 50 to a few hundred ounces/ton silver, 15–40 percent lead and copper, and minor gold. Near Red Mountain Pass, the breccia bodies are surficially expressed as prominent silicified knolls (45–150 m wide) that rise from 8 to 60 m above the valley bottoms (fig. 6). The Ohio Peak–Anvil Mountain system (17 km²), although similar in size and genesis, was generally devoid of economically important mineralization, as shown by the paucity of mines in the area (Church and others, 2007).

The acid sulfate assemblages in the Red Mountains and Ohio Peak–Anvil Mountain areas (figs. 7–10) are deeply rooted and extend as much as 300 m beneath the surface. At higher elevations, alteration of the acid sulfate suite grades outward from silicified or quartz-alunite centers (included in unit **qap**) into argillic (unit **arg**) and further into smectitic (unit **smect**) and (or) propylitic altered rock (unit **pr**) (fig. 11). Acid sulfate centers at lower elevations, or in the deeper parts of the hydrothermal system, grade laterally from silicified or quartz-alunite centers (included in unit **qap**; containing diaspore, svanbergite, and zunyite), into quartz-pyrophyllite-minor alunite (included in unit **qap**; dickite absent), and then into pervasive quartz-sericite-pyrite assemblages (unit **qsp**) (fig. 12). Sericite in these pervasive quartz-sericite-pyrite zones (unit **qsp**) is replaced by pyrophyllite in the deeper acid sulfate alteration centers. Ore mineralizing fluids postdate all but late-stage veins of the acid sulfate assemblages. A change in clay mineral species from dickite at higher elevations to pyrophyllite at depth indicates a progressive cooling of the hydrothermal fluids as they rose from the core of the acid sulfate system. Pervasive zones of quartz-sericite-pyrite altered rock (unit **qsp**) (fig. 13A, B) at lower elevations also reflect the deeper hydrothermal system. These zones become

less silicified at their margins, where sericite is generally less crystalline and formed at lower temperatures (Bove and others, 2002).

A number of small, 18–10 Ma, high-silica rhyolite intrusions and dikes crop out in the map area (upper Boulder Gulch, California Mountain, Denver Hill, Houghton Mountain, and Horseshoe Bend; fig. 1). These intrusions are part of a bimodal (basalt-rhyolite) igneous suite associated with extensional tectonism that began about 25–23 Ma in the southwestern San Juan Mountains (Lipman and others, 1976; Bove and others, 2001). Pervasive quartz-sericite-pyrite zones (unit **qsp**) (0.7–1 km²) surround the California Gulch, Horseshoe Bend, and Houghton Mountain intrusions; these rocks are locally cut by a dense network of <1 mm quartz veinlets. The rhyolite near Denver Hill is generally very weakly altered; however, it is locally silicified and pyritized, especially near its brecciated margins. Rare molybdenite mineralization, local fluorite, and huebnerite are also associated with these intrusions (Bove and others, 2005).

Economically important, post-18 Ma vein mineralization in the western San Juan Mountains is closely associated with intrusion of high-silica alkali rhyolite (Lipman and others, 1973; Bartos, 1993). Veins are mostly a polymetallic variety (silver, lead, zinc, copper, ± gold) and formed as fracture or fissure fillings. The Sunnyside mine (fig. 1) was a major gold producer (Casadevall and Ohmoto, 1977), and, up until closure in 1991, produced more than 800,000 ounces gold and 14 million ounces silver (Bartos, 1993; Bove and others, 2005). The veins within the San Juan and inner nested Silverton calderas are either concentric or radial to the ring fracture zone, or trend parallel to graben faults related to resurgent doming of the San Juan–Uncompahgre calderas (Burbank and Luedke, 1969). Zones of hydrothermally altered rock related to the veins consist of narrow envelopes that are superimposed over regional propylitic altered (unit **pr**) rock (Ransome, 1901; Burbank and Luedke, 1969).

As much as 75 percent of the rocks outside the large and pervasive hydrothermal systems (Mount Moly, Red Mountains, and Ohio Peak–Anvil Mountain) (fig. 1) is propylitic altered (unit **pr**). In contrast, rock affected by pervasive alteration (units **qsp**, **wsp**, and **qsp-wsp**) make up only about 20 percent of the rock outside these pervasive altered areas—much of this associated with the rhyolite intrusions previously described. Vein-related alteration zones (units **vqsp**, **vqsp-pr**, **vqsp-arg**, and **vwsp-pr**) (fig. 14), which generally extend two to three times the width of veins, approximate nearly 5 percent of this area.

Water-Quality Signatures Associated with Alteration Assemblages

Water-quality samples were collected at selected stream and spring sites throughout the watershed during summer low-flow conditions in 1997–1999. All sites were minimally affected by historical mining disturbance and were assumed to

be representative of premining background. Detailed descriptions of collection methods and analytical techniques can be found in Mast and others (2000).

To explore the relation between geology and water quality, sites were grouped by the dominant alteration assemblage upstream from the sampling site on the basis of the major hydrothermal alteration assemblages mapped in the study area, including propylitic (unit **pr**), quartz-sericite-pyrite (unit **qsp**), and the acid sulfate suite (AS in fig. 15). Water draining weak sericite-pyrite (unit **wsp**) and the mixed **wsp-hyd** assemblages are combined simply as WS in figure 15. Boxplots were used to compare background water chemistry from different alteration types for pH and dissolved calcium, sulfate, copper, manganese, and zinc concentrations (fig. 15). Copper, manganese, and zinc were chosen because they are dissolved constituents that are potentially most toxic to aquatic organisms in the study area (Besser and Brumbaugh, 2007; Besser and Lieb, 2007; Besser and others, 2007). Sulfate concentrations and pH are indicators of the extent of pyrite oxidation, and calcium concentrations are a general indicator of weathering.

Background springs and streams in the study area had a wide range of compositions that were spatially related to the degree of bedrock alteration. Streams and springs draining propylitic altered rock (unit **pr**) typically had the highest pH values and lowest dissolved-metal concentrations of the four assemblages. Although not shown in figure 15, these waters also were characterized by measurable alkalinity and low dissolved iron and aluminum concentrations. Propylitic altered (unit **pr**) rock, which occurs throughout the study area, contains as much as 30 percent calcite, the dissolution of which largely produces the neutral surface-water composition characteristic of this alteration assemblage. A few samples from this assemblage had low pH and elevated metal concentrations. Most of these were downstream from localized mineralized structures or vein systems within the propylitic altered (unit **pr**) country rocks.

In contrast to the propylitic (unit **pr**) assemblage, streams and springs draining the quartz-sericite-pyrite (unit **qsp**) alteration assemblage were characterized by low pH and high sulfate concentrations, reflecting an abundance of pyrite and a lack of acid-neutralizing minerals such as calcite. The samples influenced by quartz-sericite-pyrite (unit **qsp**) assemblages also were enriched in zinc, copper, and manganese relative to the propylitic (unit **pr**) samples due to the base-metal sulfide mineralization more commonly associated with this alteration assemblage. Surface water draining assemblages of the acid sulfate suite (AS in fig. 15) was similar to that of the quartz-sericite-pyrite (unit **qsp**) assemblage, having slightly higher pH values and lower metal concentrations.

Samples draining WS-altered rock (fig. 15) generally were intermediate in composition between the quartz-sericite-pyrite (unit **qsp**) and propylitic (unit **pr**) samples, perhaps reflecting a greater abundance of reactive minerals such as chlorite, feldspar, and calcite than the quartz-sericite-pyrite (unit **qsp**) assemblage. Although base metal concentrations

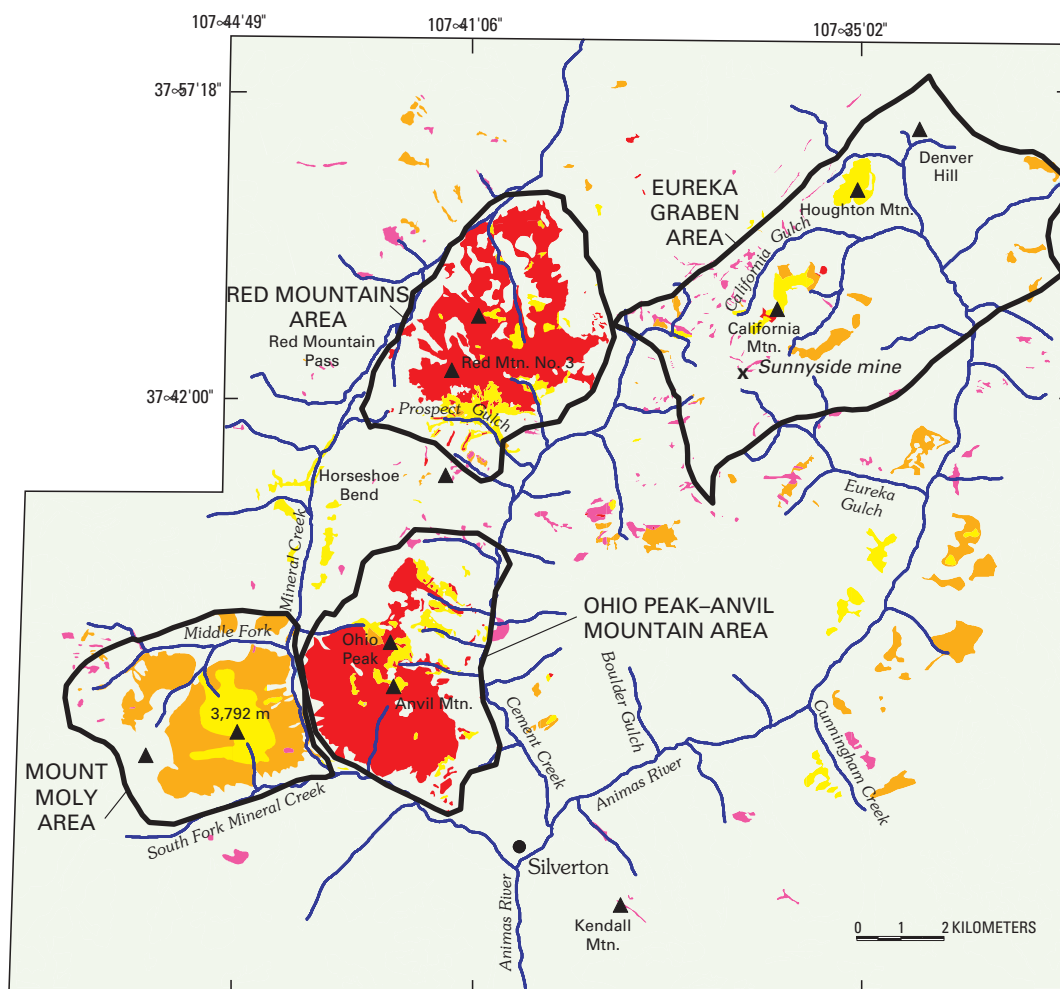
were elevated in only a few WS samples, most had sulfate concentrations similar to those of the quartz-sericite-pyrite (unit **qsp**) samples. Some of the highest pH samples in this alteration assemblage had sulfate concentrations above 1,000 mg/L and relatively low zinc and copper concentrations. This water-quality signature may be a result of the dissolution of vein-filling gypsum or anhydrite, which could produce high concentrations of calcium and sulfate without the associated acidity and metals from sulfide oxidation.

References Cited

- Bartos, P.J., 1993, Comparison of gold-rich and gold-poor quartz-base metal veins, western San Juan Mountains, Colorado—The Mineral Point area as an example: Society of Economic Geologists Newsletter, no. 15, 11 p.
- Besser, J.M., and Brumbaugh, W.G., 2007, Status of stream biotic communities in relation to metal exposure, Chapter E18 in Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 823–835.
- Besser, J.M., Finger, S.E., and Church, S.E., 2007, Impacts of historical mining on aquatic ecosystems—An ecological risk assessment, Chapter D in Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 87–106.
- Besser, J.M., and Leib, K.J., 2007, Toxicity of metals in water and sediment to aquatic biota, Chapter E19 in Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 837–849.
- Bove, D.J., Eberl, D.D., and McCarty, D.K., 2002, Characterization and modeling of illite crystal particles and growth mechanisms in a zoned hydrothermal deposit, Lake, City, Colorado: American Mineralogist, v. 87, p. 1546–1556.
- Bove, D.J., Hon, Ken, Budding, K.E., Slack, J.F., Snee, L.W., and Yeoman, R.A., 2001, Geochronology and geology of late Oligocene through Miocene volcanism and mineralization in the western San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 1642, 30 p.

- Bove, D.J., Lowers, H.A., Blum, A.E., and Plumlee, G.S., 2005, In-situ acid weathering reactions in areas affected by large-scale and pervasive hydrothermal alteration in the southern Rocky Mountains—Implications regarding acid-producing mine dump stability: *Geological Society of America Abstracts with Programs*, v. 37, no. 7, p. 394.
- Bove, D.J., Mast, M.A., Dalton, J.B., Wright, W.G., and Yager, D.B., 2007, Major styles of mineralization and hydrothermal alteration and related solid- and aqueous-phase geochemical signatures, Chapter E3 *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 161–230.
- Bove, D.J., Mast, M.A., Wright, W.G., Verplanck, P.L., Meeker, G.P., and Yager, D.B., 2000, Geologic control on acidic and metal-rich waters in the southeast Red Mountains area, near Silverton, Colorado, *in* ICARD 2000; the Fifth International Conference on Acid Rock Drainage, Volume 1: Society for Mining, Metallurgy, and Exploration, Inc., p. 523–535.
- Burbank, W.S., 1960, Pre-ore propylization, Silverton Caldera, Colorado, *in* Geological Survey Research 1960: U.S. Geological Survey Professional Paper 400–B, article 6, p. B12–B13.
- Burbank, W.S., and Luedke, R.G., 1964, Geology of the Iron-ton quadrangle, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–291, scale 1:24,000.
- Burbank, W.S., and Luedke, R.G., 1969, Geology and ore deposits of the Eureka and adjoining districts San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 535, 73 p.
- Casadevall, Thomas, and Ohmoto, Hiroshi, 1977, Sunnyside mine, Eureka mining district, San Juan County, Colorado; Geochemistry of gold and silver base metal deposition in a volcanic environment: *Economic Geology*, v. 72, p. 1285–1320.
- Church, S.E., Mast, M.A., Martin, E.P., and Rich, C.L., 2007, Mine inventory and compilation of mine-adit chemistry data, Chapter E5 *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 255–310.
- Dalton, J.B., Bove, D.J., Mladinich, C.S., and Rockwell, B.W., 2004, Classification of spectrally similar materials using the tetracorder algorithm—The calcite-epidote-chlorite problem: *Remote Sensing of Environment*, v. 89, p. 455–466.
- Dalton, J.B., Bove, D.J., Mladinich, C.S., and Rockwell, B.W., 2007, Imaging spectroscopy applied to the Animas River watershed and Silverton caldera, Chapter E2 *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 141–160.
- Desborough, G.A., and Yager, D.B., 2000, Acid-neutralization potential of minerals in intrusive bedrocks in the Animas River headwaters, San Juan County, Colorado: U.S. Geological Survey Open-File Report 00-0165, 14 p.
- Eberl, D.D., Srodon, J., Lee, M., Nadeau, P.H., and Northrup, H.R., 1987, Sericite from the Silverton caldera, Colorado—Correlation among structure, composition, origin, and particle thickness: *American Mineralogist*, v. 72, p. 914–934.
- Gilzean, M.N., 1984, Nature of a deep hydrothermal system, Red Mountain district, Colorado: Berkley, Calif., University of California M.S. thesis, 104 p.
- Hurlburt, E.B., 1894, On alunite from Red Mountain, Ouray County, Colorado: *American Journal of Science*, v. 48, p. 130–131.
- Lipman, P.W., 1976, Geologic map of the Lake City caldera area, western San Juan Mountains, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–962, scale 1:48,000.
- Lipman, P.W., Fisher, F.S., Mehnert, H.H., Naeser, C.W., Luedke, R.G., and Steven, T.A., 1976, Multiple ages of mid-Tertiary mineralization and alteration in the western San Juan Mountains, Colorado: *Economic Geology*, v. 71, p. 571–588.
- Lipman, P.W., Steven, T.A., Luedke, R.G., and Burbank, W.S., 1973, Revised volcanic history of the San Juan, Uncompahgre, Silverton, and Lake City calderas in the western San Juan Mountains, Colorado: U.S. Geological Survey Journal of Research, v. 1, p. 627–642.
- Luedke, R.G., 1996, Geologic map of the Ophir quadrangle, San Juan, Hinsdale, and Ouray Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1760, scale 1:24,000.
- Luedke, R.G., and Burbank, W.S., 1975a, Preliminary geologic map of the Howardsville quadrangle, Colorado: U.S. Geological Survey Open-File Report 75–432, scale 1:20,000.
- Luedke, R.G., and Burbank, W.S., 1975b, Preliminary geologic map of the Silverton quadrangle, Colorado: U.S. Geological Survey Open-File Report 75–433, scale 1:20,000.

- Luedke, R.G., and Burbank, W.S., 1987, Geologic map of the Handies Peak quadrangle, San Juan, Hinsdale, and Ouray Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1595, scale 1:24,000.
- Luedke, R.G., and Hosterman, J.W., 1971, Clay minerals, Longfellow mine, San Juan County, Colorado: U.S. Geological Survey Professional Paper 750-C, p. 104–111.
- Mast, M.A., Evans, J.B., Leib, K.J., and Wright, W.G., 2000, Hydrologic and water-quality data at selected sites in the upper Animas River watershed, southwestern, Colorado, 1997–1999: U.S. Geological Survey Open-File Report 00–53, 20 p.
- Moore, D.M., and Reynolds, R.C., Jr., 1989, X-ray diffraction and the identification of clay minerals: New York, Oxford University Press, 322 p.
- Ransome, F.L., 1901, A report on the economic geology of the Silverton quadrangle, Colorado: U.S. Geological Survey Bulletin 182, 265 p.
- Ringrose, C.R., 1982, Geology, geochemistry, and stable isotope studies of a porphyry-style hydrothermal system, west Silverton district, San Juan Mountains, Colorado: Aberdeen, Scotland, University of Aberdeen Ph.D. dissertation, 257 p., 19 plates.
- Schwarz, T.E., 1883, Remarks on occurrences of ore in mines near Silverton: Colorado Scientific Society Proceedings, v. 1, p. 134–144.
- Sole, T.C., Granitto, Matthew, Rich, C.L., Litke, D.W., and Pelltier, R.T., 2007, Digital databases and CD-ROM for the Animas River watershed, Chapter G *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 1079–1096.
- Srodon, J., and Eberl, D.D., 1984, Illite, *in* Bailey, S.W., ed., Micas: Mineralogical Society of America, Reviews in Mineralogy, v. 13, p. 495–544.
- Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-764, scale 1:250,000.
- Yager, D.B., and Bove, D.J., 2007, Geologic framework, Chapter E1 *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, p. 107–140.
- Yager, D.B., McCafferty, A.E., Stanton, M.R., Diehl, S.F., Driscoll, R.L., Fey, D.L., and Sutley, S.J., 2005, Net acid production, acid neutralizing capacity, and associated geophysical, mineralogical, and geochemical characteristics of Animas River watershed rocks near Silverton, Colorado: U.S. Geological Survey Open-File Report 2005–1433, 75 p.



EXPLANATION

Generalized hydrothermal alteration assemblages

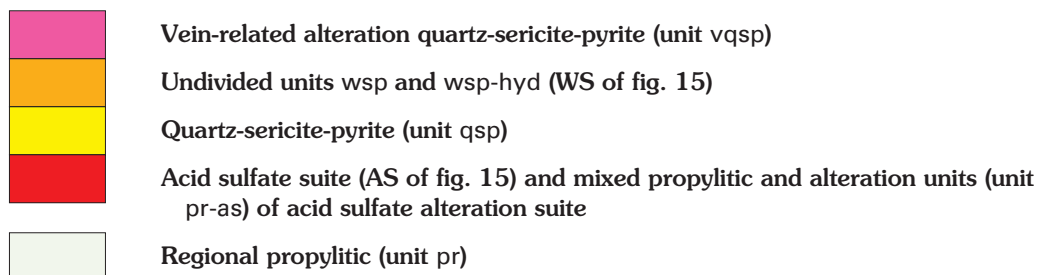


Figure 1. Generalized locations of hydrothermal alteration assemblages and geographic features. Solid triangle, prominent peak; peak labeled 3,792 m is informally named Mount Moly.

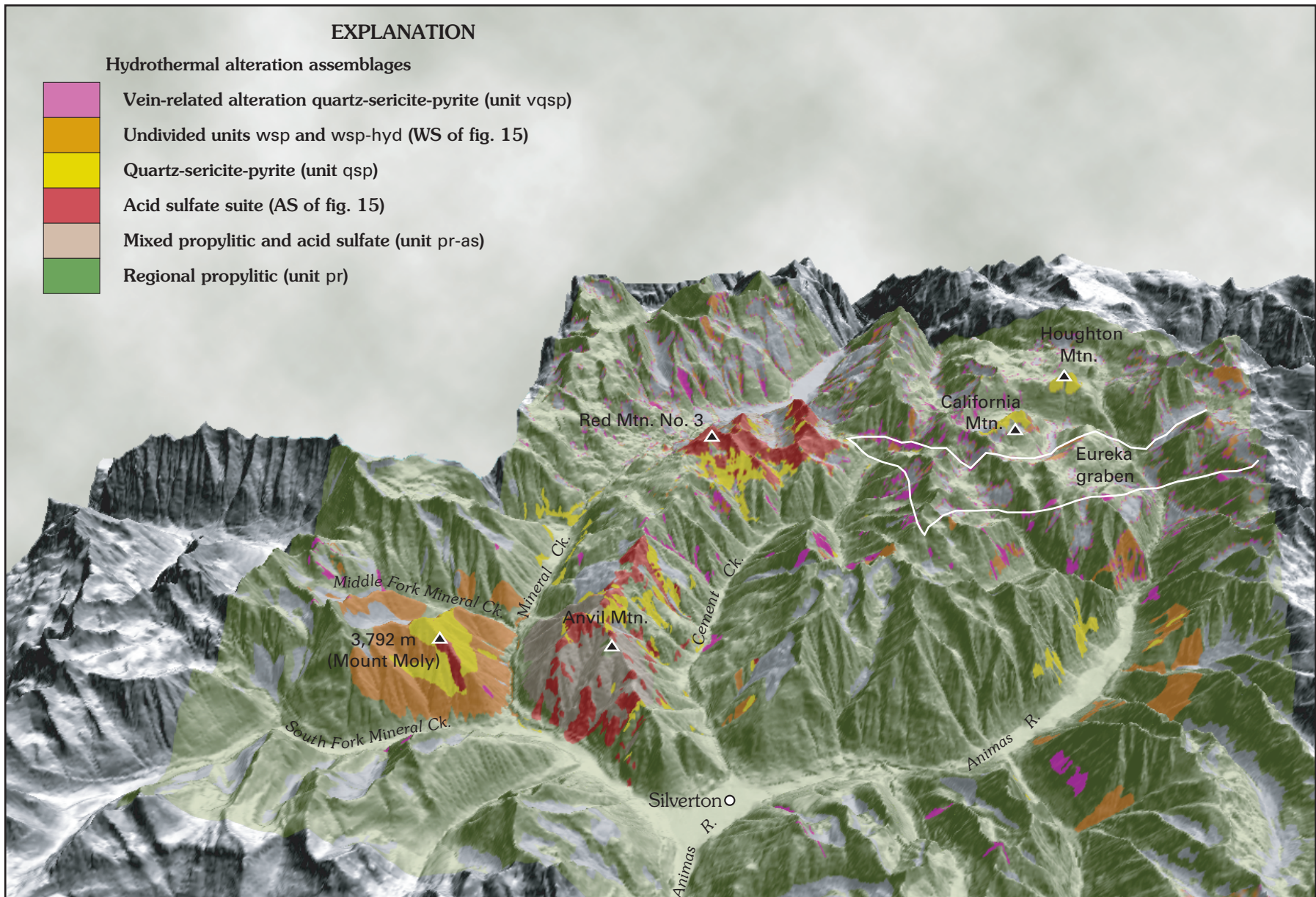


Figure 2. Generalized alteration map draped on hillshade rendering of 10-m-resolution digital elevation model, showing major tributaries to Animas River. Note that acid sulfate suite as mapped in figure 1 is subdivided into the acid sulfate suite (red unit; AS of fig. 15) and a mix of propylitic and acid sulfate altered rocks (light brown unit; unit pr-as) that are mapped on Anvil Mountain. Image approximately 32 km across. White solid line, Eureka graben. Solid triangle, prominent peak or mountain. View toward north.



Figure 3. Propylitic altered (unit pr) Burns Member of the Silverton Volcanic Series lavas. Plagioclase phenocrysts (light-green, tabular to equant grains) have been altered to a mixture of chlorite and epidote and minor sericite. Darker green groundmass is also altered to a mixture of same constituents. Sample about 4.5 cm across.

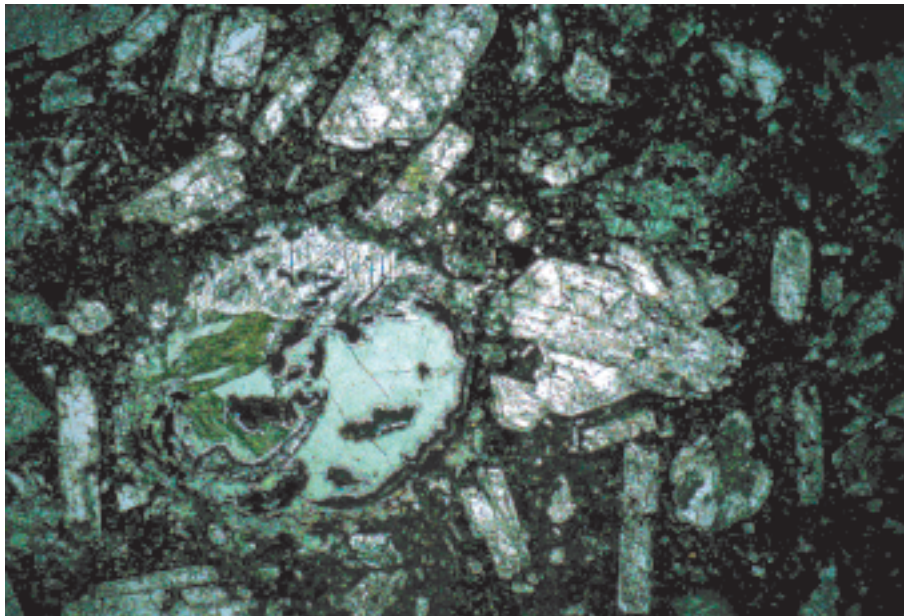


Figure 4. Photomicrograph (plane light) showing propylitic (unit pr) alteration of intermediate-composition, porphyritic lava of the San Juan Formation. Chlorite, epidote, and calcite partially replace plagioclase phenocrysts and groundmass. Chlorite has infilled a round vesicle near center of photograph. Note rhombohedral cleavage of calcite altered areas and infiltration of epidote along cracks and cleavage planes in plagioclase phenocrysts. Field of view 6 mm.



Figure 5. Quartz-sericite-pyrite (unit qsp) altered quartz monzonite intrusive with dense stockwork quartz veinlets. Sample from 1 km² area of unit qsp alteration centered around peak 3,792 m (informally referred to as Mount Moly) (fig. 1) due to nearby molybdenum exploration. Stockwork veinlet densities are anomalously high (0.3–1.5/m²) in this area of intense alteration; note offset in veinlets. Slab nearly 9 cm across.



Figure 6. Silicified breccia body or “pipe” at National Belle mine, near Red Mountain Pass (fig. 1). Oxidized ores dominated by galena were present in upper 100 m of this and other similar deposits, either attached to walls of caves, as broken detached masses within caverns, or as bedded deposits with clayey mud and sand filling caves (Schwarz, 1883). Lead ores mined in these upper levels accounted for most of the early production. Intermingled with cave ores were abundant fine “spongy” quartz, crystalline dickite/kaolinite, diaspore, pyrophyllite, and alunite. Beneath the upper oxidized zone, ores included enargite, galena, chalcocite, bornite, tetrahedrite-tennantite, sulfobismuthites, and stromeyerite (Schwarz, 1883). Note ladder for scale (approximately 10 m long; in top part of outcrop, just left of center).

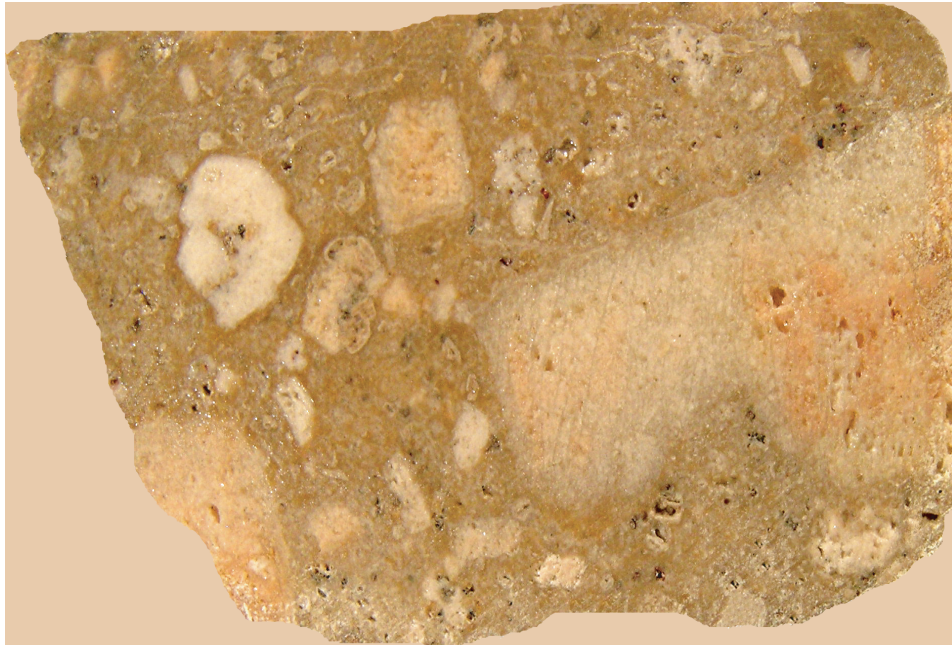


Figure 7. Quartz-alunite altered dacite porphyry intrusive (mapped as unit qap of acid sulfate suite). Feldspar pseudomorphously replaced by alunite and minor quartz. Light-brown groundmass altered to a fine-grained mixture of quartz and alunite. Sample 4 cm wide.



Figure 8. Fine-grained massive quartz-alunite replacement (mapped as unit qap of acid sulfate suite) of altered lavas or volcaniclastics of Silverton Volcanic Series; sample collected near Anvil Mountain (fig. 1). Note light-pink color, conchoidal fracture, and absence of porphyritic texture. Sample 9 cm wide.

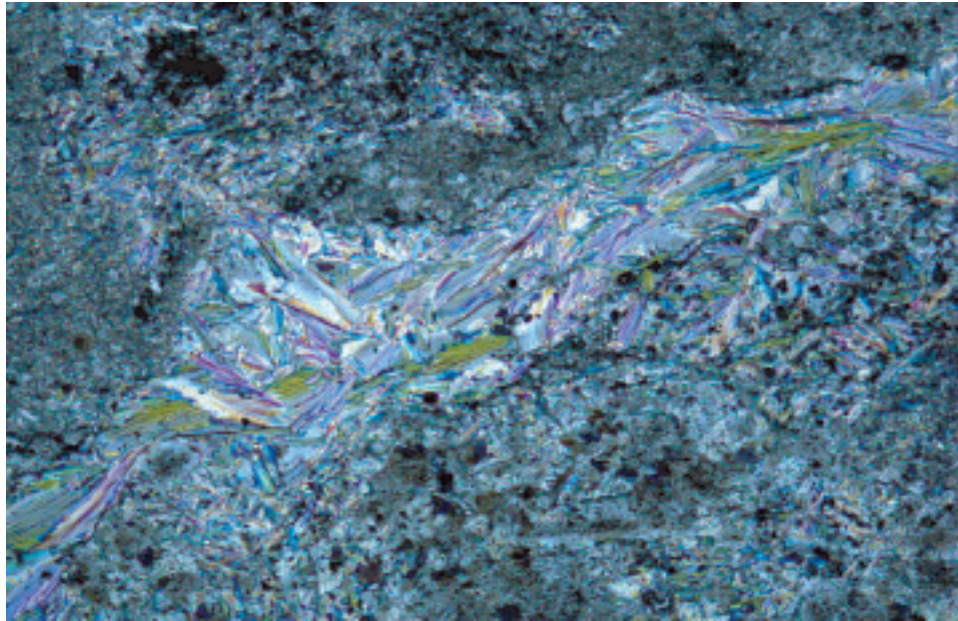


Figure 9. Photomicrograph (crossed-polarized light) showing bladed and lath-shaped birefringent alunitic crystals formed in a small fracture. Groundmass replaced by fine-grained alunitic, quartz, and disseminated pyrite (tiny opaque and equant grains). Photomicrograph is characteristic of rocks mapped as unit qap of acid sulfate suite. Field of view 2.3 mm.



Figure 10. High-level, argillic altered dacite porphyry intrusive rock. Relict feldspar phenocrysts have been replaced by white, waxy, dickite. Dickite is soft and easily scratched with a fingernail. Sample 5 cm wide.

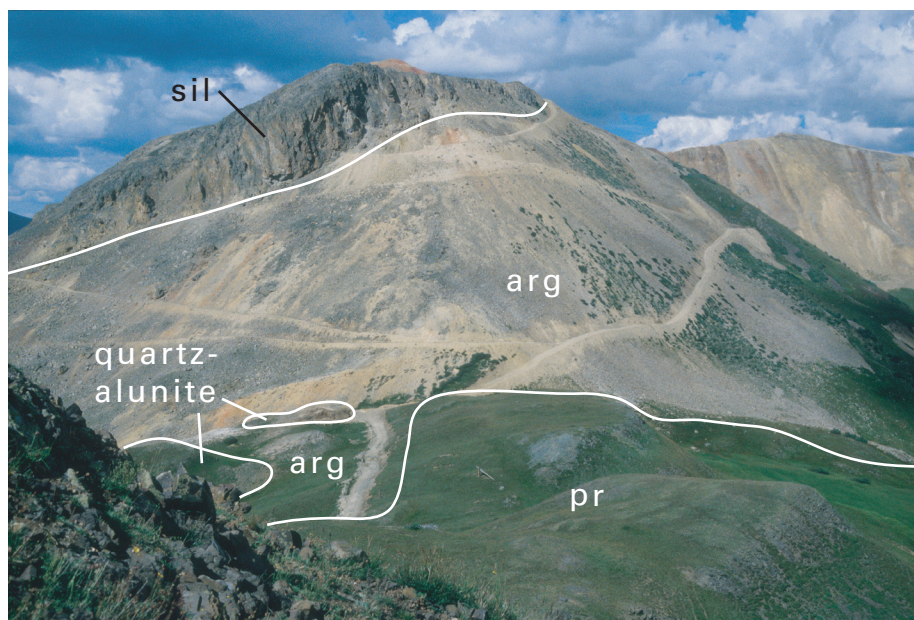


Figure 11. Silicified breccia body (unit sil) near Red Mountain No. 3 (fig. 1), depicting lateral transition of acid sulfate assemblage at high levels of hydrothermal system. Clays in high-level argillic assemblage (unit arg) consist of dickite in the absence of pyrophyllite. Argillic assemblage grades laterally into propylitic (unit pr) altered rocks; unit qsp assemblage is not part of lateral transition in upper levels of hydrothermal system. Small centers of quartz-alunite altered rock (included in unit qap assemblage in Description of Alteration Units) also lack pyrophyllite within and at their margins.



Figure 12. Exposure of deep-level acid sulfate alteration in upper Prospect Gulch south of Red Mountain No. 3 (fig. 1). Zone at center of photograph depicts highly silicified center (unit sil) that grades outward to an assemblage of quartz-alunite-pyrophyllite (unit qap), into pervasive unit qsp altered rocks. Pyrophyllite increases as quartz and alunite decrease laterally from composite unit qap centers. A large, quartz-alunite altered hydrothermal breccia (eastern margin of which is exposed on far left of photograph) grades outward into quartz-alunite-pyrophyllite (unit qap), and then into a pervasive unit qsp assemblage. Sericite at margins of these centers was replaced by pyrophyllite.

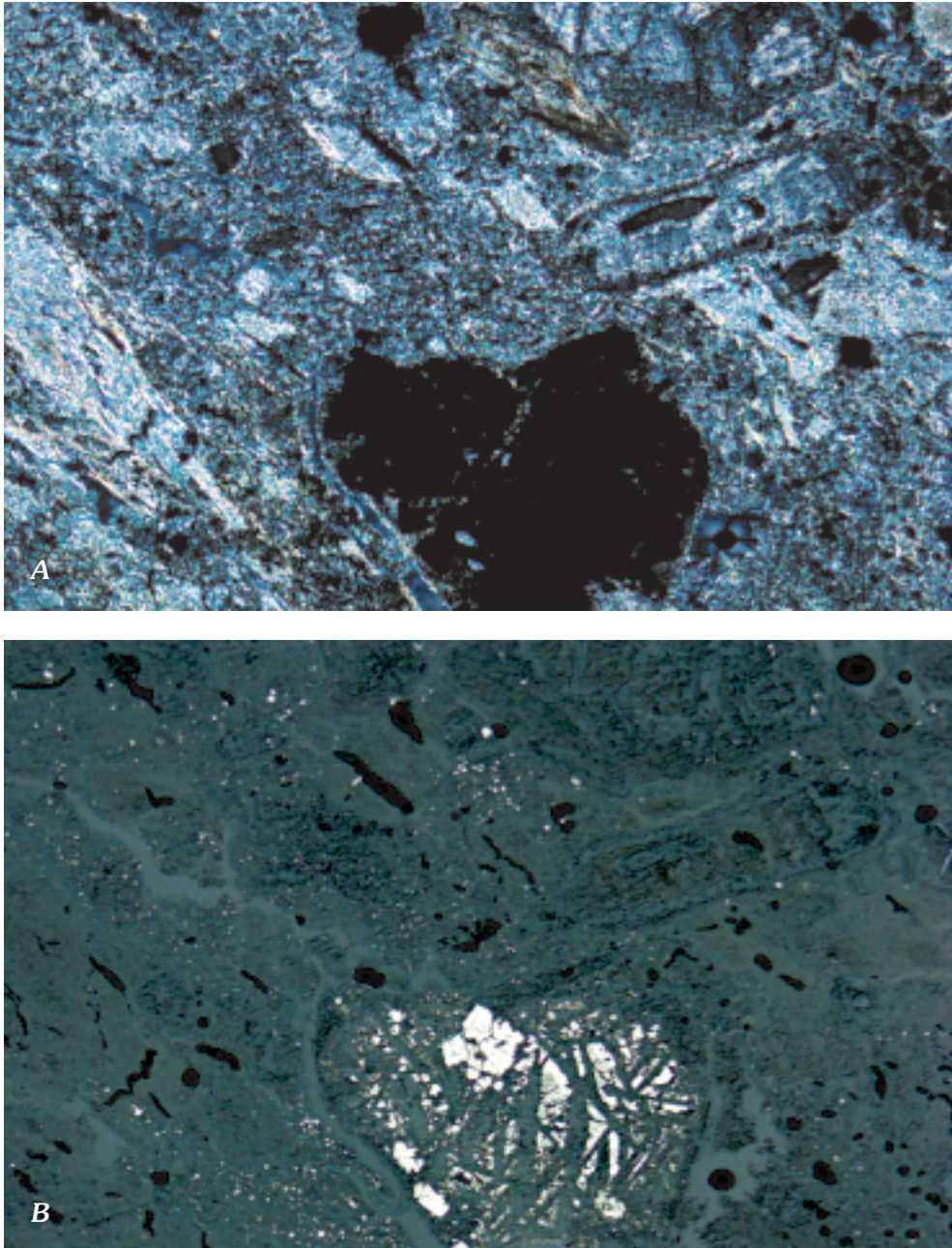


Figure 13. Photomicrographs of unit qsp altered rock. *A*, crossed-polarized light, and *B*, plane light. Outlines of altered feldspar phenocrysts generally denoted by coarser and brighter sericite. Groundmass largely replaced by quartz and sericite. Much of finer grained pyrite (fine opaque grains) is oxidized and thus not reflectant as shown in figure 13*B*. Field of view 2.3 mm.



Figure 14. Vein-related unit qsp assemblage (unit v-qsp) flanks a narrow quartz vein (<0.5 m). Bleached unit qsp zone cuts unit pr altered lavas of Burns Member. Note hammer for scale (center front).

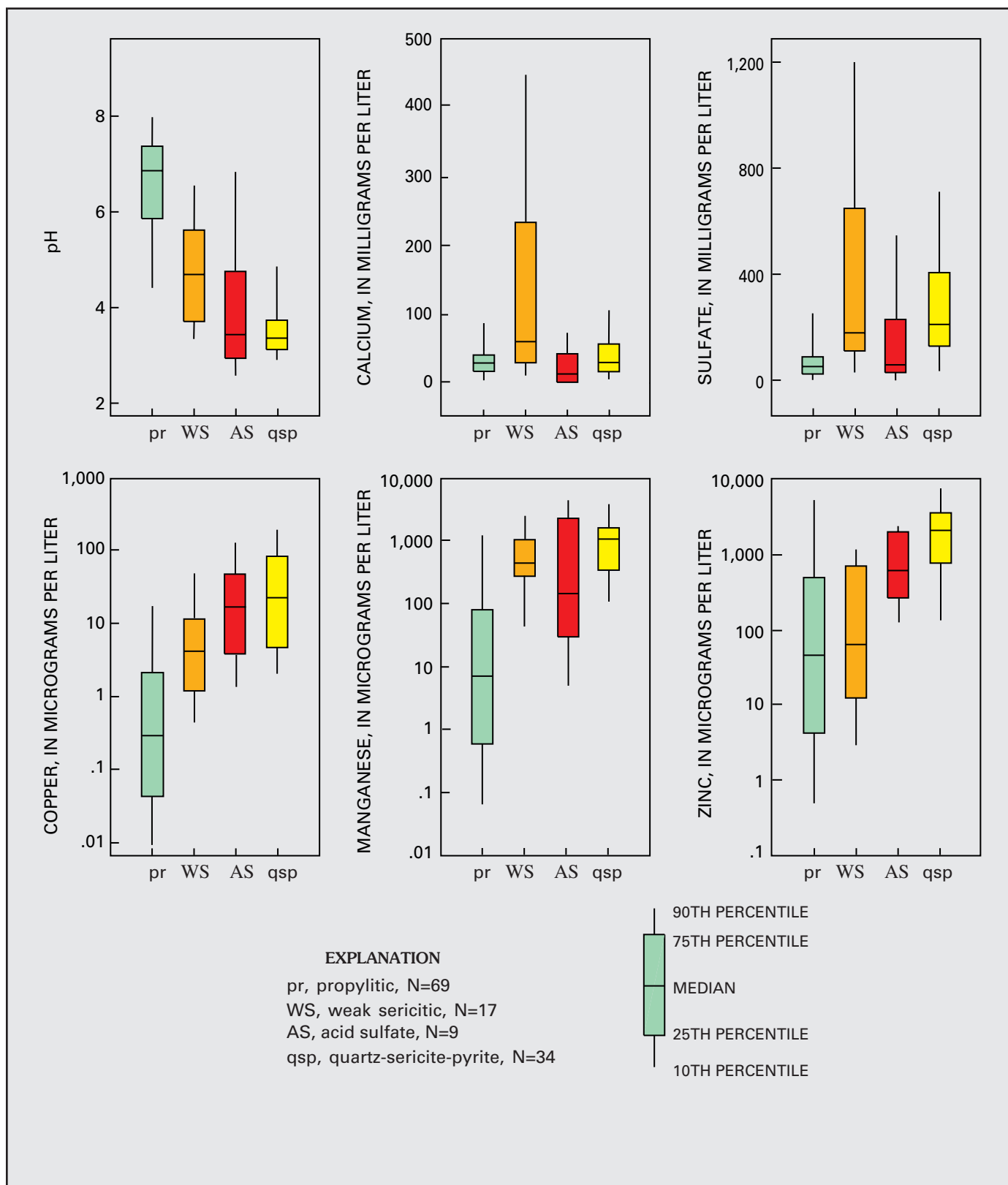


Figure 15. Boxplots comparing background water quality from different alteration assemblages in map area. All water draining rocks of acid sulfate assemblages grouped as AS; water draining units wsp and wsp-hyd combined as WS (shown as undivided units wsp and wsp-hyd on figs. 1 and 2).