Natural Versus Mining-Related Water Quality Degradation to Tributaries Draining Mount Moly, Silverton, Colorado

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ABSTRACT

Geological, hydrological, and geochemical information synthesized in a Geographical Information System (GIS) for water and rock surrounding South and Middle Forks of Mineral Creek, northwest of Silverton, Colorado, was analyzed to distinguish between the natural and the mining-related sources of metals to surface waters in the watershed. An important natural source of metals to surface water emanates from a porphyry molybdenum deposit south and upslope from the Middle Fork of Mineral Creek. Interaction of surface and ground water with fractured, altered rocks and permeable, Quaternary-age surficial deposits produces downstream water quality that does not meet current State of Colorado water quality standards for metals and pH. GIS site characterization and three-dimensional modeling distinguish surficial deposits as volumetrically substantial, significant sources of naturally occurring metals that strongly influence water quality and complicate ongoing mine-site mitigation efforts. Our findings indicate that regional hydrologic and geologic information needs to be evaluated before realistic water-quality guidelines are established and mitigation recommendations are confidently implemented.

INTRODUCTION

The red, yellow, and white precipitates from water draining hydrothermally altered rock are strong visual indications of poor water quality in non-mining-affected tributary basins near Silverton in southwestern Colorado. Mining in this region has disturbed the natural ecosystem and has further degraded water quality. One important question that needs to be addressed in mined regions is "what are the environmental effects of mineralized but unmined areas compared to the environmental effects related to mining?" The answers to this question are important because the water quality in a mined watershed will depend not only the mining-related, but also on the non-mining-related geochemical loading sources. The strategies used to address this question in our study included: (1) collecting geochemical, mineralogic, and hydrologic data in headwater stream-reaches that are not affected by mining, (2) synthesizing all data collected into a GIS, (3) GIS modeling to aid in the identification of major- and trace-element sources to surface water, (4) three-dimensional modeling of a volumetrically important surficial deposit that was identified to adversely affect the watershed, and (5) performing field-leach tests, using the method of Hageman and Briggs (this volume) on both non-mining-affected surficial deposits composed of altered rock, and on mine wastes located on the periphery or downslope from the headwater stream reaches. Field-leach tests were performed to gain some understanding of the acid-generating potential of the non-mining-affected surficial deposits for comparison with mine wastes.

The occurrence of pervasively altered and mineralized country rock in mining districts complicates the determination of factors that contribute to water quality. Data integration for mineralized but unmined sites at the headwater regions of a watershed provides an indication of the geochemical baseline conditions that exist today and provides insight into what the geochemical backgound conditions were prior to mining (Miller, 1998). Information collected in non-mining-affected regions may be compared with areas affected by mining to better understand what restoration goals are achievable. Data synthesis in a GIS permits the simultaneous

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visualization of the relationships among acidic and metal-rich waters, altered rocks, and Quaternary deposits in both mined and unmined areas. Once the geospatial relationships in the GIS are evaluated, understood, and quantified, then these data may be used by Federal agencies and local stakeholder groups in making better informed decisions about mined land restoration.

SITE DESCRIPTION

The study area is in the rugged and spectacular San Juan Mountains between South and Middle Forks of Mineral Creek (Figure 1). Topographic relief in the study area reaches 1,000 m and the elevation reaches over 4,000 m above sea level. The ecoregion is classified as the Southern Rocky Mountain Steppe (Bailey, 1995).

Geologic Setting

The general stratigraphy of the region consists of a Precambrian crystalline basement overlain by Paleozoic and Mesozoic sedimentary rocks and by a Tertiary volcanic cover (Luedke and Burbank, 1963; Steven, et al., 1974; Lipman, et al., 1973; Luedke and Burbank, 1987; Luedke and Burbank, 1996). Tertiary volcanism in the San Juan Volcanic Field began about 35 Ma with the eruption of intermediate composition lavas, pyroclastic flows, and mudflows. The oldest Tertiary volcanics, the San Juan Formation (SJF), consist primarily of mudflows and pyroclastic flows with subsidiary lava flows. The change in tectonic regime from Laramide compression to Tertiary extension coincides with a shift in style of volcanism that is characterized by catastrophic eruption of silicic magma-forming calderas (Lipman, et al., 1972). Locally, these are the San Juan caldera (28.2 Ma) followed by the nested Silverton caldera (27.6 Ma) (Lipman et al., 1976; Bove et al., 1999).

Caldera-forming arcuate ring fractures and tangential radial fractures preserved near the periphery of the calderas provided pathways for intrusive magmas and later hydrothermal fluids and ore deposition (Figure 1) (Varnes, 1963; Burbank and Luedke, 1969; Casadevall and Ohmoto, 1977). These Tertiary, volcano-tectonic structures occur as regionally pervasive features with lengths that extend for thousands of meters. Grabens formed in the central cores of the calderas in response to resurgent magma, which domed and faulted the overlying volcanics. The grabens were later extensively mineralized (Casadevall and Ohmoto, 1977). San Juan caldera collapse was followed by eruption of post-collapse, intermediate-composition Silverton Volcanic Series (SVS) lava flows that infilled the San Juan caldera (Lipman, 1973). The SVS volcanics contain much of the mineralization in the upper Animas River watershed (ARW).

Porphyry intrusions that are intermediate to silicic in composition have intruded the SJF and SVS rocks along the southwest margin of the Silverton caldera (Figure 1). The oldest and least evolved intrusions are the 26.6 Ma Sultan Mountain and the 25 Ma, Mount Moly[5] stocks (Lipman et al., 1976; Ringrose, 1982; Bove et al., 1999). These stocks are part of a monzonitic intrusive event that resulted in hydrothermal alteration and cogenetic mineralization that produced a low grade, porphyry-style molybdenum deposit in the study area (Ringrose, 1982).

Regional tilting and uplift in the San Juan Volcanic Field during latest Miocene to Pleistocene time (Steven, 1996), along with extensive glaciation has caused erosion and downcutting to expose a mineralized and hydrothermally altered terrain. Acid rock drainage to surface water throughout the upper ARW is likely in part caused by the geologically recent, accelerated exposure by weathering and erosion of the hydrothermally altered rocks that has taken place in the San Juan Volcanic Field over the last 4 to 5 Ma (Steven, 1996).

Geology and Mineralogy of the Study Area

Older SJF and only remnants of the SVS lavas are preserved within the study area. A prominent peak, locally referred to as Mount Moly, marks the center of the study area (Figure 2A). The study area was chosen because: (1) water quality sampling could be done in areas that are unaffected by mining and (2) it displays similarities to a typical low-grade, Mo-Cu porphyry with a mineralogically zoned alteration profile. A typical porphyry ore deposit is zoned from a potassic central core, outward through a halo of quartz-sericite-pyrite to a zone of propylitic alteration (chlorite-epidote-calcite) (Guilbert and Lowell, 1974).

The caldera-related faulting that characterizes the central core of the Silverton caldera is not so extensive in the study area. Mineralized faults and fracture systems, however, that are sub-parallel or tangential to the caldera structural margins do occur (Figure 2A). Base-metal sulfide vein mineralization that developed near

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[5] **Previous workers refer to a prominent peak labeled 12,442 on the Silverton, 1:24,000-scale topographic map as "Mount Moly" (Ringrose, 1982).**

the periphery of the Mo-Cu porphyry and along the fracture systems was mined in the late 19th century. Minerals associated with the base-metal veins include sphalerite, tetrahedrite-tennantite, galena, and pyrite (Ringrose, 1982). Field-leach data on the only major and several of the minor mines is presented below and compared with field-leach data collected from non-mining-affected surficial deposits.

Although faults are not prevalent in the study area, the rocks are highly jointed. Up to eight fracture sets were recognized at a given outcrop (Ringrose, 1982). The prevalent joints aid in accelerating the freeze-thaw weathering process, which continually exposes fresh rock surfaces to water-rock interaction. Well-developed joint sets, oriented sub-parallel to slope, that dip 10° to 30° to the southeast or northwest are observed throughout the study area. These shallow-dipping joints may serve as efficient flow paths near the surface.

Hydrothermal Alteration

The major alteration zones in the study area are depicted in Figure 1. An intense zone of alteration is centered near Mount Moly and is characterized by stockwork, quartz-pyrite-molybdenite veinlets, in a bleached-white, quartz-sericite-pyrite (Q-S-P) altered host rock, with jarosite- and goethite-stained surfaces (Figure 1). As much as 5 volume percent pyrite occurs in core samples drilled near the Mount Moly summit in the Q-S-P zone. The next alteration halo is composed of patches of sericitic plus minor argillic alteration. The mineral assemblage in this zone is composed of patchy occurrences of Q-S-P alteration; the presence of kaolinite is used to identify the argillic assemblage. The most intense zone of alteration consists of masses of quartz, andalusite, pyrophyllite, and pyrite, which is characteristic of a high-temperature, potassic hypogene mineralization event (Henley and McNabb, 1977). This potassic assemblage is located in the midst of a pervasive sericitic alteration zone southeast of the Mount Moly summit (Ringrose, 1982) and was also identified in areas southwest of the Mount Moly summit by the first author. An aureole of propylitic plus pyrite alteration is found outward from the transitional sericitic zone. The periphery of the alteration is characterized by a propylitic assemblage composed of chlorite, epidote, ± calcite, ± pyrite, illite, and opaque oxides. Outward from the Mo-Cu porphyry-related propylitic assemblage, a regional propylitic event is recognized that has affected most igneous rocks of Tertiary age in the upper ARW (Burbank and Luedke, 1969).

ANALYTICAL METHODS

Geochemical, Mineralogic, and Field-Leach Analyses

Whole-rock samples were collected from each alteration assemblage throughout the study area and analyzed by the ICP-MS method at a U.S. Geological Survey laboratory to determine trace-element abundances (Table 1) and by X-ray diffraction to characterize alteration mineral assemblages. The toe and upper surface of the north-slope Mount Moly debris fan were sampled using a 2-meter stainless steel soil auger to determine the mineralogy of part of the fan. Water-saturated auger samples were air-dried for later passive-leach and X-ray diffraction analysis (Table 2).

Surface water and springs were sampled in the Mineral Creek tributaries in the summer and fall from 1995 to 1998 (Mast et al., this volume).

A field-leach test (Hageman and Briggs, this volume) and passive-leach studies (Fey et al., this volume) were used to compare the acid generating potential of mine wastes and non-mining-affected surficial deposits in the study area and in one other location in the upper ARW.

The mine wastes were collected from three sites located downstream from or near the periphery of the Red Tributary study area (Figure 2C) using the 30-cell composite sampling method described in Hageman and Briggs (this volume). Only the Bonner mine has recorded mineral production. The other two mines sampled, the Paradise Portal and the Ruby Trust mines, which are located in areas that drain into the Middle Fork of Mineral Creek (Figure 2C), do not have known mineral production. The Bonner Mine adits were constructed to exploit base-metal veins that formed along a northeast-southwest-oriented structural zone in propylitic host rocks of the SJF. The Paradise portal appears to have been driven beneath a ferricrete deposit amongst propylitic to weakly sericitic rocks of the SJF that eventually intersected Q-S-P altered rocks. The Ruby Trust mine adit was constructed in propylitic rocks of the SJF.

Locations of non-mining-affected surficial deposits sampled for the field-leach test include: (1) the north slope Mount Moly debris fan (Figure 2B), (2) a colluvium deposit derived predominantly from weakly sericitic and propylitized rocks located 0.4 km downstream from the north slope Mount Moly debris fan and north of the Red Tributary, and (3) an additional non-mining-affected debris fan located about 1.4 km north of Silverton, upslope and to the east of Mineral Creek.

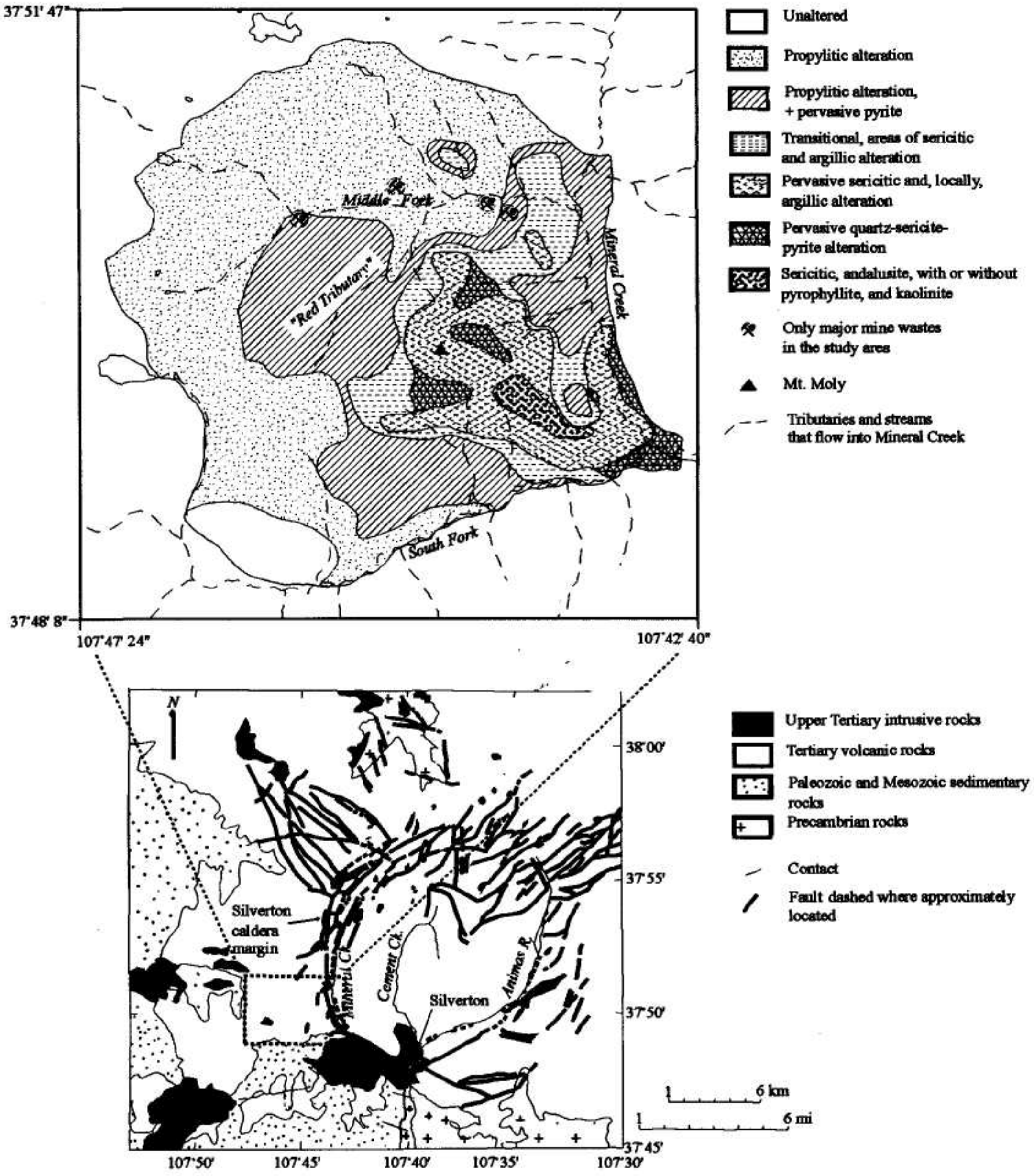

Figure 1 Generalized regional geologic map near the study area (below). Study area shown by dot outlined box. Enlarged ARC/INFO GIS coverage (above) of the study area that indicates the spatial relationships between zoned alteration patterns (Ringrose, 1982), mines, and tributaries of Middle and South Forks that flow into Mineral Creek. Alteration pattern contacts are gradational

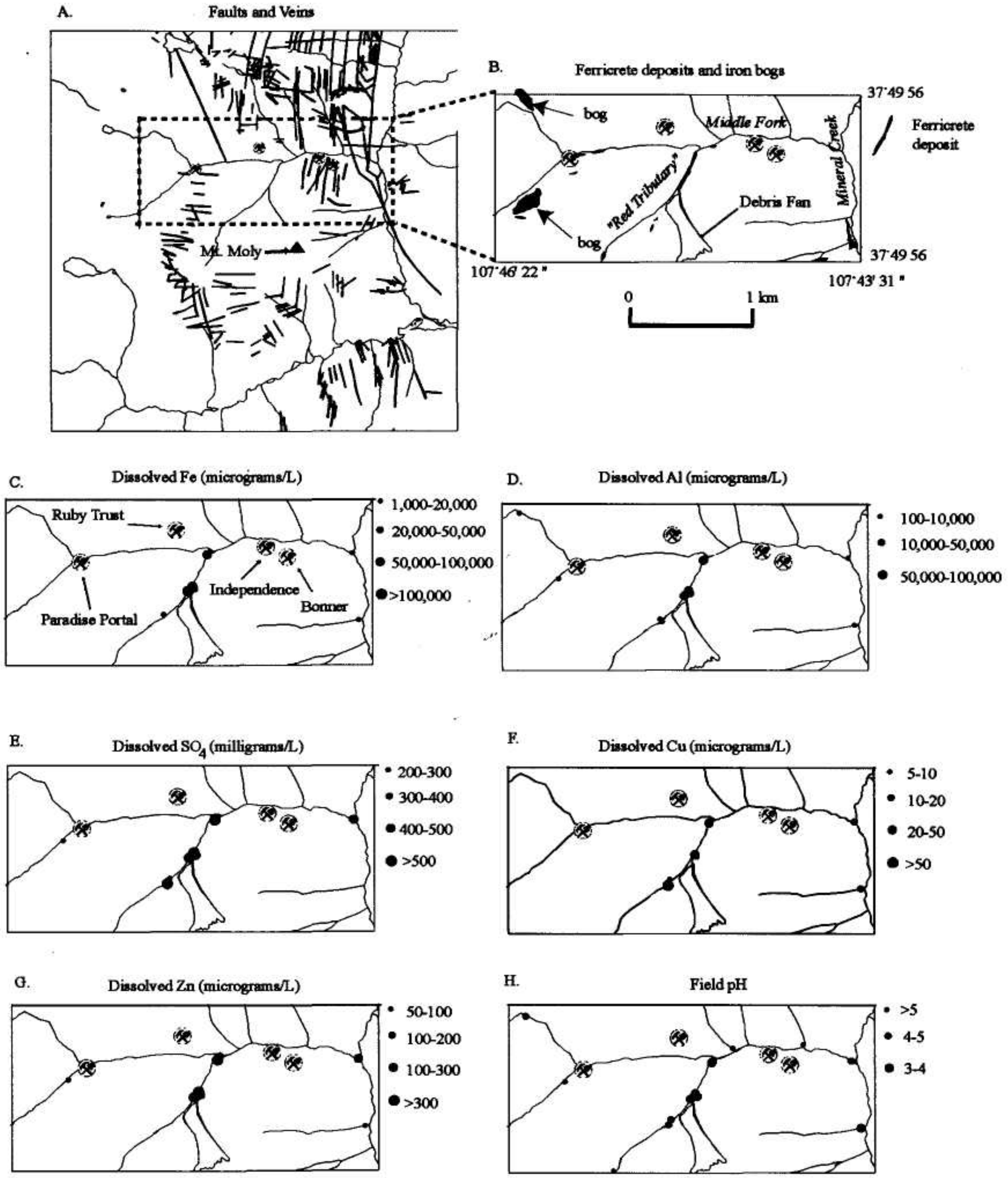

Figure 2 ARC/INFO GIS coverages for faults and veins (AX ferricrete and iron bogs (B), proportional dot maps (symbol size increases with increasing concentration) of stream geochemical analyses for dissolved iron, aluminum, sulfate, copper, zinc, all in micrograms/L except for sulfate reported in mg/L(C thru G). Field pH (H). Mines are indicated with the "pick and shovel" symbol. North-slope debris fan is indicated in (B).

These surficial deposit sites were chosen because they are representative of non-mining-affected areas that were derived from rocks that have varying intensities of alteration. Intense alteration is present upslope from both of the debris fans sampled.

GIS and Spatial Modeling

A GIS database was constructed using ARC/INFO[6] software to analyze the spatial relationships between surface-water-quality data (Mast et al., this volume) in addition to alteration mapping (Ringrose, 1982), mine location, and geologic structure information. The resultant GIS map products are visually intuitive and permit the identification of sites where surface water is adversely affected by mines, altered rocks, and surficial deposits derived from altered areas. A subset of our GIS database (Figure 2; Yager, 1999) provides water-quality information for a non-mining-affected stream reach designated as the "Red Tributary" for this study. The Red Tributary is located below the north slope of Mount Moly (Figure 2B) and is informally named for the over 1-m-thick ferricrete that is composed of reddish-hued, iron, oxyhydroxide precipitates on and adjacent to the streambed near its confluence with the Middle Fork of Mineral Creek (Figure 2B). This GIS database and spatial modeling approach differs from the more traditional graphical display of data and from the time-intensive manual cartographic mapping techniques. GIS data items may be rapidly added or subtracted to soft-copy map views and hard-copy maps that are printed and brought to the field to compare and contrast various pertinent data. GIS thematic proportional dot maps (larger dots represent higher concentrations or higher values, Figure 2) were constructed to show where metals, pH, and sulfate do not meet State of Colorado recommended stream standards (Colorado Department of Health, 1984). Analysis of the GIS maps helped further guide field studies in the Red Tributary.

Due to the close correspondence between low pH and high major- and trace-element concentrations near the north slope Mount Moly debris fan, a three-dimensional model of the fan was constructed with Earth Vision software (Figure 3). The model constructed aided in calculating the volume of the deposit. A 10-meter-resolution digital elevation model (DEM) and an ARC/INFO digital coverage of the debris fan were imported into Earth Vision to construct the model. A thickness of 5 meters was subtracted from every DEM cell that was located inside the debris fan coverage boundary. Field observations indicate that the fan thickness is greater than 5 meters in many locations. The resultant volume subtracted from the DEM was used to determine the fan volume.

RESULTS AND DISCUSSION

Effect of Hydrothermal Alteration on Surface-Water Quality

Water-quality data integrated into a GIS indicate where altered rocks, which have minimal buffering capacity, affect the Red Tributary waters. These data also show the spatial relationship between acidic major- and trace-element-rich Red Tributary surface water and the north slope Mount Moly debris fan.

Propylitically altered rocks crop out in the headwater reaches of the Red Tributary. Water-quality samples collected from sites that intersect the propylitic zone have higher pH values, and with the exception of sulfate, lower major- and trace-metal concentrations. Rocks in the headwater reaches of the Red Tributary likely have significant buffering capacity. Permeability, primarily due to the clastic and fractured nature of the volcaniclastic SJF rocks, combined with the presence of calcite ($CaCO_3$) and secondary hydrous alteration phases such as chlorite (Desborough et al., 1998), supply the buffering capacity. Water-quality samples collected downstream have lower pH values and higher major- and trace-element concentrations where waters have intersected zones of more intensely altered rocks (Figure 2). An increase in dissolved Fe, Al, Zn, and lower pH are observed where Red Tributary waters flow adjacent to the north slope debris fan (Figure 2). The north slope debris fan is composed of rocks that were weathered from the quartz-sericite-pyrite alteration assemblage. The debris fan appears to function as a porous flume for water rock interaction. Surface and shallow ground-water reacts with the minerals in the fan, including pyrite, which increases acidity and further degrades water quality along the Red Tributary. All of the aforementioned observations are related to a stream reach of the Red Tributary that is located upstream from any mining activity.

Geochemical Composition of Whole Rocks

The highest trace-element anomalies were observed in veins on the east slope of Mount Moly (Table 1).

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

Ferricrete is a term used to describe a conglomerate that has been cemented by iron oxide derived from the oxidation and precipitation of Fe-rich solutions (Lamplugh, 1902).

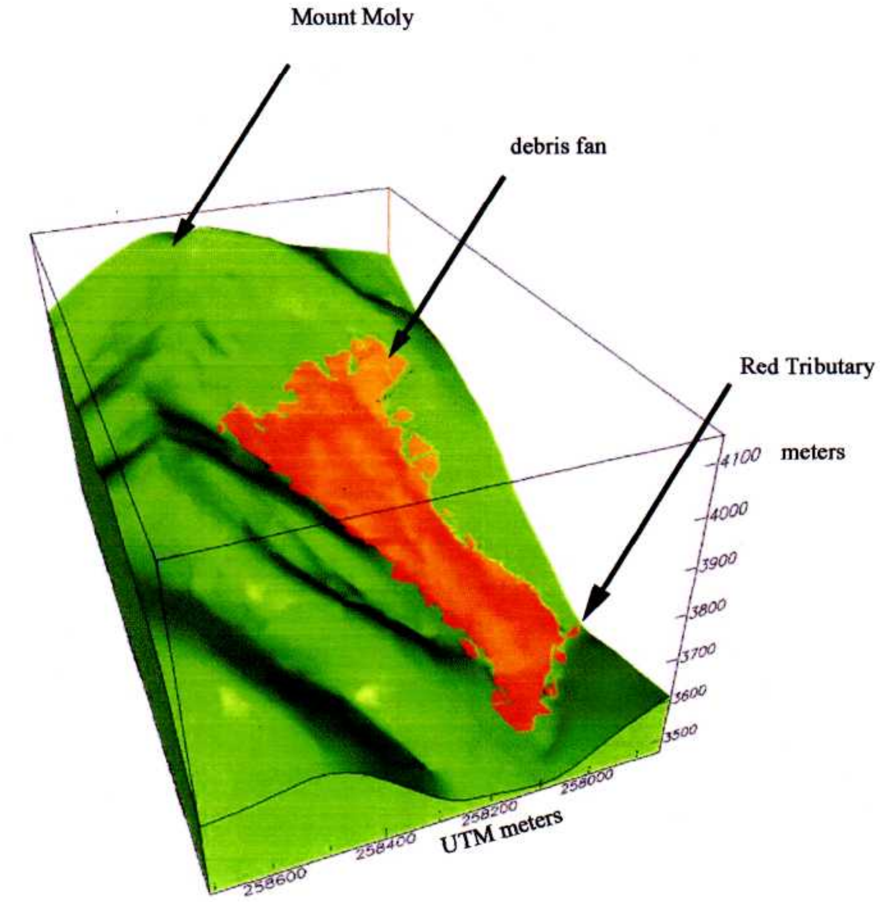

Figure 3 Two-dimensional rendering of a three-dimensional model for the north-slope Mount Moly debris fan. View is to the southwest. Color version of Figure 3 (back of this volume).

Copper concentrations in rocks range from 6 to 1,200 ppm, exceeding average crustal abundances (Fortescue, 1992) by 11 to 17 times. Molybdenum concentrations range from 2 to 1,700 ppm, which exceeds crustal abundances from 2 to 1,700 times. Lead concentrations range from 11 to 37,000 ppm, which exceeds crustal abundances by as much as 2,800 times. These data are indicative of why the Mount Moly area was a target for mineral exploration in the 1970's.

GIS Maps Depicting Stream Toxicity

GIS was successfully used to integrate stream-water quality and bedrock alteration information (Figure 1) in addition to geologic structures, mine site, and surface-water-quality data (Figure 2). The surface-water-quality GIS maps indicate where current water-quality standards are not met. The maps show where dissolved Fe, Al, Cu, Zn, and SO4, and pH all do not meet the State of Colorado recommended class 1 aquatic-life criteria for waters with a hardness of 100 µg/L $CaCO_3$ (Figure 2, C-H). The Red Tributary has elevated Fe concentrations (1,000 to over 100,000 (µg/L) (Mast et al., this volume) exceeding by 100 times the class 1 aquatic-life criteria (Colorado Department of Health, 1984). Although high iron concentrations are now recognized as potentially having an adverse effect on aquatic life (Nordstrom et al., 1999), the toxic effects of iron on aquatic life is less well known than for some other metals such as copper and zinc. Iron was recently identified as causing toxicity for *Ceriodaphnia dubia* based on tests run on metalliferous mine sediment pore waters (Nordstrom et al., 1999).

Aluminum concentrations range from 100 to over 70,000 µg/L, which exceeds the State of Colorado recommended aluminum allowance (100 µg/L) for waters that have a hardness of 100 µg/L $CaCO_3$ (Colorado Department of Health, 1984). Chronic toxicity levels for aluminum in waters have been found to be as low as 1,900 and 3,280 µg/L for *Ceriodaphnia dubia* and fathead minnows, respectively (USEPA, 1988). High concentrations of aluminum in the Red Tributary emanate from propylitic to weakly sericitic and Q-S-P alteration zones upstream. Aluminum is likely leached from ubiquitous chlorite and also from illite present in altered primary phases and in the matrix of propylitized and Q-S-P altered host rocks.

Non-Mining-Affected Surficial Deposits and Their Potential Effect on Water Quality

Much emphasis is appropriately placed on the effect past mining activity has had on the ARW. Perhaps overlooked, but important flow-paths for waters, however, are non-mining-affected surficial deposits that are derived from altered source rocks. The north slope Mount Moly debris fan located near the Red Tributary is one such deposit that is composed predominantly of quartz-sericite-pyrite altered rocks with secondary jarosite- and goethite-stained surfaces and weakly sericitic altered rocks with pervasive, fine-grained, disseminated pyrite. Samples were collected from the base of several north slope debris fan auger holes near where surface waters have dissolved iron concentrations > 100,000 µg/L (Figure 2C). The samples collected have a yellow to brownish-yellow hue (10YR-8/8 to 10YR 6/8, Munsell Soil Color Chart). X-ray diffraction analyses of auger cuttings collected from the debris fan were used to confirm the occurrence of schwertmannite with subsidiary amounts of ± goethite, clinochlore, jarosite, muscovite, and quartz (Table 2). The thickness and lateral extent of the deposit are unknown due to the limitations of the manual augering equipment and the development of a 1-meter-thick soil zone that obscures the schwertmannite-bearing deposit beneath.

Schwertmannite [$Fe_{16}O_{16}(OH)_{9.6}(SO_4)_{3.2}\bullet 10H_2O$] is a recently identified mineral (Bigham et al., 1994; Schwertmann et al., 1995) that forms under acidic conditions in both mined and natural mineralized settings. The anionic charge potential and high surface area (Bigham et al., 1994) make schwertmannite a potential adsorption site for metal cations. Mixtures of schwertmannite and goethite (α-FeOOH) precipitate from acid-sulfate waters at a pH range between 2.6 and 4, whereas the sulfate mineral jarosite [(H, K, Na) $Fe_3(OH)_6(SO_4)_2$] forms at a pH near 2.6 (Bigham et al., 1996). The north slope debris fan appears to be a major source of metals and sulfate loading to the Red Tributary (Mast et al., this volume).

Analysis of GIS coverages (Figures 2C, D, E, G, and H) indicate that acidic and metal-rich waters strongly correlate with the location of the north slope Mount Moly debris fan. Other surficial deposits located throughout the ARW that are derived from altered rocks will likely interact with waters in a similar way to that observed in the north slope Mount Moly debris fan. These deposits are porous and permeable due to their clastic nature and provide ample opportunity for water-rock interaction.

Field-Leach Test and Passive-Leach Experiments on Surficial Deposits and Mine Wastes

Field- and passive-leach tests were completed to provide an indication of the acid-generating potential of the non-mining-affected surficial deposits as compared to mine wastes located near the Red Tributary (Table 3). The field-leach and passive-leach tests do not directly represent the acid-producing conditions of mine wastes and surficial deposits in nature. These tests, however, do provide some indication of the acid-generating potential of these types of deposits. Three of the surficial deposits sampled generated acidity in the leach tests. The lowest pH observed was in the auger cutting material collected at the base of the north slope Mount Moly debris fan. A field-leach test performed on a colluvium-derived deposit, sample SDY9913, located just downstream and to the north of the Red Tributary, had a resultant pH that approximated that of deionized water. The colluvium was weathered from an upslope source of propylitic and weakly sericitic rocks that likely have significant buffering capacity due to the presence of chlorite (Desborough et al., 1998). Specific-conductance measurements collected from surficial deposit surfaces are generally lower than those observed for mine wastes. Low conductivity measurements observed in field-leach tests for the north slope debris fan suggest that acidic conditions are enhanced with sustained water-rock interaction as initially acidic water moves toward the toe of the fan. Acidic conditions and higher metal concentrations are attained as water flows throughout the fan and reacts with acid-generating minerals such as pyrite.

Field-leach tests on mine wastes in the region generally indicate lower pH and higher specific-conductance as compared with the surficial deposits. Propylitic host rocks that are prevalent in regions where base-metal veins were mined may supply some buffering capacity and may help explain some of the low specific conductance measurements observed for the Bonner and Ruby Trust Mines. Differences in specific-conductance values between mine wastes and surficial deposits are partly caused by the concentrated nature of sulfide minerals in mine wastes as compared with the more diffuse presence of sulfides in surficial deposits.

Three-dimensional modeling of the north slope debris fan

In light of the acid-generating potential of the north slope Mount Moly debris fan, and due to its close spatial relationship to stream inputs of major and trace elements, a three-dimensional model of the fan was constructed (Figure 3) with use of Earth Vision software. The three-dimensional model provides a simple tool to calculate the debris fan volume and thus compare the results to volumes for selected mine wastes in the upper ARW. Such analyses are important because the debris fan material will generate acidic major- and trace-element-rich waters long after remediation of mine wastes is achieved.

A conservative estimate of the volume of material in the fan is -500,000 m^3. Further quantification of the abundances of pyrite and other acid-producing phases in the fan will help determine the potential effect that the debris fan will have on water quality in the future. Average mine-waste-pile volume estimates in the ARW are below 10,000 m^3 (Herron et al., 1998). Land managers may find volume comparisons between surficial deposits and mine wastes useful to consider when they evaluate what restoration goals are achievable in a watershed. Restoration work on mine wastes may improve water quality locally, however, where surficial deposits derived from altered rocks are present upstream from remediated sites, their effect on water quality may be large and ongoing long after mine waste remediation activity is completed.

A direct comparison between the affect that debris fans derived from altered rocks and mine wastes will have on surface water is an oversimplification because of the differences in grain size and clast sorting and in the percentage of sulfides in the two deposit types. Dispersed distribution of metals and water-quality degradation associated with debris fans derived from mineralized terrain is quite variable when compared to the concentrated, point-source nature of metals in mine wastes. Field and passive-leach experiments nonetheless indicate that minerals present in the debris fans have a potential to generate acidity and contribute major and trace elements into the ARW.

CONCLUSIONS

The volume determinations for the non-mining-affected north slope Mount Moly debris fan, when assessed in context with water quality, bedrock alteration assemblage, and field-leach data, implicate the debris fan as a volumetrically large, acid producer and major- and trace-element loader to surface water. Water quality samples collected adjacent to mines located downstream from the non-mining-affected Red Tributary and the north slope Mount Moly debris fan may now be assessed with the knowledge that significant geochemical loading occurs upstream. Field-leach test comparisons between non-mining-affected surficial deposits derived from altered rocks and mine wastes provide an indication that both deposit types have the potential to generate acidity. GIS data synthesis for water and rock has aided in the identification of where non-mining-affected areas are affected by acid rock drainage. The Red Tributary is an example of a proportionately large source of acidic drainage that is unaffected by mining. Quantitative geochemical-loading determinations for the Red Tributary (Mast et al., this volume), along with GIS map displays and analysis aid in determining what the environmental effects of mineralized but unmined areas are for tributaries that flow into Mineral Creek from Mount Moly. These data may now be evaluated to predict what restoration goals are realistically achievable in the Middle Fork of Mineral Creek.

Table 1 ICP-MS data for whole rocks and vein samples near Mount Moly. Analytical uncertainty for each element is approximately ±5 to 10 %. Al Meier analyst, U. S. Geological Survey (ppm, parts per million).

Field Number	*Description*	*Latitude*	*Longitude*	*Cu ppm*	*Zn ppm*	*Mo ppm*	*Pb ppm*
SDY-9701	Propylitically altered monzonite porphyry, 1 vol % pyrite.	37° 50' 3"	107°43" 33"	18	52	12	41
SDY-9705A	Weak sericitically altered monzonite porphyry,	37° 50' 4"	107° 43'53"	56	63	17	1,200
SDY-9705B	Vein in monzonite	37° 50' 4"	107° 43'53"	1,200	72,000	1,700	37,000
SDY-9706	Propylitically altered monzonite porphyry, 1 vol % pyrite.	37° 49" 59"	107° 43'58"	35	48	16	50
SDY-9707	Q-S-P altered, stockwork-veined monzonite porphyry.	37° 49'57"	107° 49'57"	34	53	15	49
SDY-9717	Stockwork-veined monzonite porphyry, pyrite oxidized.	37° 49'46"	107° 44" 44"	7	20	4.5	46
SDY-9719	Weak sericitically altered lava, pyrite oxidized.	37° 50' 22"	107° 44' 46"	37	65	6.7	16
SDY-9718A	Q-S-P altered lava.	37° 50' 6"	107° 44'34"	15	45	2.2	190
SDY-9738	Weak sericitically altered monzonite porphyry, 3 to 5 vol % pyrite.	37° 49'16"	107° 44'9"	140	20	8.6	17
SDY-9739	Q-S-P altered monzonite porphyry, 2 vol % pyrite.	37° 49'18"	107° 44'9"	110	10	37	21
SDY-9740	Weak sericitically altered	37° 49'23"	107° 44'11"	18	20	19	12
SDY-9741	Q-S-P altered monzonite	37° 49' 33"		13	20	2.5	11
SDY-9742	Quartz-sericite-pyrophyllite altered lava (?), pyrite oxidized.	37° 49'55"	107° 44'16"	6	20	2.9	31
SDY-9743A	Weak sericitically altered	37° 50" 1"	107° 43'51"	72	46	14	41
SDY-9743B	Q-S-P altered vein, pyrite oxidized.	37° 50' 1"	107° 43'51"	27	27	16	140
ODY-9731	Propylitically altered lava.	37° 49'50"	107° 45'49"	11	72	0.78	20

Table 2 Mineralogy of north slope Mount Moly debris fan soil auger samples, determined by X-ray diffraction

Sample	*Description*	*Latitude*	*Longitude*	*Minerals Identified*
SDY9902D	Debris fan toe, auger cuttings 1-2 meter interval	37°50'19"	107°45t)2"	schwertmannite, quartz, muscovite, clinochlore, jarosite
SDY9904B	Upper debris fan surface 1-2 meter	37°50'16"	107°4501"	schwertmannite, quartz, goethite, muscovite, clinochlore, jarosite
SDY9906	Debris fan toe, auger cuttings 0-2	37°49'13"	107°45'06"	schwertmannite, quartz, muscovite, clinochlore, jarosite

Table 3 Field-leach test results for non-mining-affected surficial deposits and mine wastes. Sample SDY9902D was leached by the passive-leach method described in Fey et al. (this volume). Most samples were collected near Mount Moly with the exception of those from the debris fan located east of Highway 550 near Silverton. Philip Hageman and Michael Anthony of the U.S. Geological Survey completed field-leach test experiments. Samples were filtered using a 0.45 µm filter and acidified for later metals analyses.

Sample	*Description*	*Location*	*PH of filtered (0.45 µm) leachate*	*Specific conductance µS/cm of filtered (0.45 µm) leachate*
SURFICIAL DEPOSITS				
SDY9908	North slope Mt. Moly debris fan, south of Red Tributary.	37°50'2" 107°44'49"	4.45	16
SDY9902D	North slope Mt. Moly debris fan auger cuttings, south of Red Tributary.	37°50'19" 107°45'02"	4.10	N.A.
SESFAN	Debris fan south side Mt. Moly.	37°49'13" 107°44'11"	4.16	22
SDY9913	Colluvium deposit north of Red Tributary.	37°50'26" 107°44'59"	5.68	5
SDY9917	Debris Fan, east of Highway 550.	37°49'2" 107°41'55"	3.92	54
MINE WASTES				
Ruby Trust Mine	N. of Middle Fork of Mineral Creek.	37°50'45" 107°45'7"	3.73	105
Paradise Portal Mine	Base of Paradise basin.	37°50'32" 107°45'52"	3.87	1,594
Bonner Mine	E. of Red Tributary.	37°50'36" 107°44'13"	3.89	63

The approach used in this study to: (1) develop a GIS database, (2) synthesize and evaluate water quality, geology and alteration data, in a spatial context, and (3) focus on local geochemical anomalies in the field demonstrates the benefits of using GIS to integrate and interpret geographic, geologic, and geochemical data.

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