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Geochemical Investigations and Interim Recommendations for Priority Abandoned Mine Sites on U.S.D.A. Forest Service Lands, Mineral Creek watershed, San Juan County, Colorado; paper edition

by

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ABSTRACT

Field observations, sampling of mine dumps and mine drainage waters, and laboratory studies of dump materials have been made at mining areas deemed to be on public lands administered by the USDA Forest Service in the Mineral Creek watershed. Results of chemical analyses of dump materials, leachates of those materials, and of surface waters draining mines or dumps provide indications of where acid is generated or consumed, and what metals are mobilized below mines or dumps. Information on 25 sites is reviewed and reclamation priorities are ranked into four classes (high, medium, low priority, or no work required).

The western side of the upper Animas watershed (the Mineral Creek watershed) has a history of mining and prospecting for about 130 years. The intensity of mining-related disturbance is higher than in most parts of the San Juan Mountains region, but actually is much less than the eastern half of the watershed (US BLM lands) and none of the mines moved millions of tons of rock and ore as in some of the eastern mines. The majority of the roughly one thousand mining sites on the USFS lands are very small (less than 100 tons or 70 cubic yards of dump material), are more than 2 miles from a major stream, or are so inaccessible as to prohibit reclamation. Twenty five sites have been considered by others to have significant size and potential for significant environmental degradation. These most significant mining areas were evaluated by multiple criteria, including tendency to generate acid or liberate toxic metals, observed acidic pH or dead vegetation (“kill zones”) below dumps or adits, potential mobility of metals, and likelihood of transport into streams of the watershed. In the author’s opinion, no single measurable parameter, such as metal concentration, is reliable for ranking significance or feasibility of reclamation. Rather, subjective estimates are required to evaluate combinations of, or interactions among, several parameters. The most subjective estimate in ranking feasibility of reclamation is the amount of natural and mine-related contamination at each mining area. Mitigation of natural contributions at mines or unmined areas is beyond the scope of these Abandoned Mine Lands (AML) investigations, but must be considered when planning reclamation. Available information for the 25 problem sites is adequate for ranking, but at some sites additional information on groundwater conditions is needed for a more reliable ranking and evaluation of reclamation methods.

Introduction

More than 100 years of hardrock mining in the Silverton area has left a legacy of thousands of mine, prospect, and mill sites that are both a cultural attraction and a likely threat to aquatic life. The U.S. Geological Survey (USGS) has a program of integrated geologic-hydrologic-biologic-chemical studies underway in the upper Animas watershed as part of the Abandoned Mine Lands Initiative to provide Federal land managers a scientific rationale for cost-effective restoration of public lands affected by historic mining (Buxton and others, 1997). Information and interpretations reported here are part of the mine site, or metal source, component of the project.

Field studies by the author in the summers of 1997 and 1998 focussed on historic mines and prospects identified by others as being entirely or partly on public lands; a limited number of sites on private property were studied for comparison where the owner provided access and approval to sample. One goal of this work was to identify or rank problem sites. Chemical analyses of samples collected in 1997 are on hand and will be reported as soon as quality assurance computations are completed; limited amounts of chemical results are available for 1998 samples. Partial results cited herein for elements of prime interest out of the 60 or more determined by chemists are not likely to be revised in the final data report.

This report will consider only mining areas on USDA Forest Service (USFS) lands in the Mineral Creek watershed, which is the western part of the upper Animas watershed (fig. 1). My work in the field was guided by the maps and information in Lovekin and others (1997). I attempted to start my work with an open, unbiased perspective, thus did not review the work by Herron and others (1997) until after reaching many of my own interim conclusions. Comments made here on specific sites are more descriptive interpretations than quantitative assessments. Ranking of sites by magnitude of environmental degradation or priority for reclamation is complex. In my opinion, the geologic and chemical data that are available for these mining sites can not be placed into a formula and a definitive number computed to express the priority or the hazards of the site. Hydrologists and other environmental scientists use metal loadings (concentration of a metal multiplied by volume of flow) as a definitive measure for a stream (Leib and others, 1998). This is very useful for describing mine drainage, as has been done well by Herron and others (1997) and Wright and others (1998a), but we do not yet have a comparable measurement to quantify amounts of toxic metals mobilized from solids in mines or on mine waste dumps. This report focuses on mines with drainage, partly because those waters can be characterized and quantified, but also because it is water leaving a mine site that is having the greatest impact on the watershed.

The impact of an abandoned mine on a watershed is a complex function of many factors, some of which are tonnage, metal concentrations, metal mobility or leachability, buffering capacity of rocks, permeability, and amount of water. A fundamental distinction can be made between sites that are dry and those that are wet for most of the year; dry dumps pose much fewer problems because there is much lower likelihood of metals being mobilized into nearby streams or groundwater (except during snowmelt and major storm events) and will be largely ignored here. Work in progress on mine dump solids (mineralogy, bulk chemistry, leachability) will be reported later, along with complete chemical analytical results for use in various project databases.

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Methods

Field and laboratory studies for this program utilized methods that were developed for the AML program and efforts have been made to maintain consistency among the many scientists working in the Colorado and Montana study areas. First, sites on public lands were selected using information gathered by previous workers who made inventories for the BLM (US Bureau of Mines, reported by Hite, 1995) or USFS (Colorado Geological Survey under the direction of M. A. Sares, reported in Lovekin and others (1997) for the Columbine Ranger District of the San Juan National Forest). Because of the limited amount of time available to me in 1997 and 1998, and the large number of potential sites, I focused my work on sites within 2 miles of major streams that had dumps larger than about 100 cubic yards and had access reasonable for reclamation work (Nash and others, 1998). Of the more than 500 sites identified by previous investigations, the majority are smaller than 100 cubic yards, thus deemed unlikely to be significant contributors to the watershed, and are not considered further in this study. Site locations were identified on USGS 1:24,000 topographic maps and recorded using a standard global positioning system (GPS) instrument with an accuracy of about ± 200 feet. On-site work included brief description of rock types, rock alteration, ore mineralogy, an estimate of size, and collection of a representative sample of the entire dump. Composite samples were collected from 30 subsites uniformly distributed over the top and sides of each dump; at each subsite dump rocks from a 0.5 m^2 area, to a depth of 10 cm, were mixed and a portion was passed through a 2 mm sieve to yield about 100 g. of sample. The -2mm fraction is deemed most likely to be involved in short-term reactions and contributing to runoff. Water draining adits and dumps was noted at about 50 sites; pH and conductivity were measured at all sites and at some, a single reconnaissance water sample was collected for chemical analysis and comparison with leach tests described below. The field water samples were filtered through a disposable 0.45 um cellulose filter and 1:1 nitric acid added to stabilize metals.

Lab studies were initiated to describe the bulk mineralogy and chemistry of the -2 mm samples, and their reactions in deionized water. A suite of 120 samples was collected in 1997, including some representative samples of mill tailings and unmined mineralized rocks for comparison with the dump samples. Most of the 120 sites were on BLM lands. X-ray diffraction (XRD) studies by George Desborough, USGS, have been made to determine the major minerals in the -2 mm dump samples. The XRD studies confirm the presence of many sulfate minerals that are not reliably identified in macroscopic examinations: 50% of the samples contain jarosite family minerals, 10% contain anglesite, 3% contain alunite, and 3% contain gypsum. Sulfide minerals are common: 25% of samples have pyrite, 30% have sphalerite, and 30% have galena. Calcite, an important acid-buffering phase, was detected by XRD in only three samples. Quartz is present in most samples, and aluminosilicates such as feldspars, micas, and kaolinite are present in 45 to 60 percent of the samples. The aluminosilicate pyrophyllite was detected in 10% of the samples, only in the vicinity of Red Mountain.

Lab tests were made to determine metal leachability and acid generation using both the EPA 1312 end-over-end tumble method and a passive leach developed by George Desborough (Nash, Desborough, and Fey, 1998). In the passive method, 100 grams of rock (–2 mm fraction from dumps, unsieved if from tailings) are placed in 2 liters of deionized water and stirred slightly. The pH and conductivity are measured after about 5 minutes and after 24 hours; a sample is taken at 24 hours using the same syringes and 0.45 um filter as used for field water samples. A few drops of 1:1 nitric acid are added to stabilize metals in solution. For both the tumble and passive leach tests, 60 ml of leachate were analyzed by an inductively coupled plasma-mass spectrometry (ICP-MS) method that measures metal concentrations of about 60 elements, generally with a lower limit of determination of about 1 part per billion. Precision and accuracy of ICP-MS are variable across the large range of concentrations of these samples, and by element, but are generally about ±20 percent (Appendix I). The final data and quality assurance information will be reported elsewhere. Samples of dump rock, tailings, and altered unmined rocks were also analyzed for total chemistry by standard methods; those results will also be reported elsewhere.

The framework for evaluating water quality in my reconnaissance studies of mines is that of aquatic life (class 1, cold water) from the Colorado Water Quality Control Division(CWQCD,1989, and website www.state.co.us/wqcc). In this report I will refer to them as aquatic life water standards (ALWS). These reference standards are generally similar to those of domestic drinking water supplies, but are more restrictive for elements such as Cu and Zn that affect aquatic life more than human health, and more stringent than for agricultural use. Standards for various reaches of streams in the Mineral Creek watershed have been set by CWQCD (1989) according to use of the water, which generally is that for aquatic life-cold waters. These values are referred to by some as chronic exposure. In detail, values for metals are corrected for the effect water hardness: increases in hardness reduce the toxicity of some metals (Cd, Cu, Pb, Zn) thus the concentration for the metal to cause chronic or acute toxicity is higher (300 ppb Zn at 400 mg/L hardness compared with 50 ppb Zn at 100 mg/L hardness). Hardness corrections are not made for my results because hardness has not been determined for most samples, but is known to be about 100 mg/L $CaCO_3$ equivalent for waters of pH 7 to 8, and low to nil at pH's below 5—the hardness of most samples is very low because most are acidic. The values in table 1 provide reasonable guidelines for evaluating the severity of degradation, consistent with the reconnaissance nature of my sampling. These values are useful for interpretation of processes operating at mine sites, but readers should consult results of other definitive studies (CWQCD, 1989; Owen, 1997; Herron and others, 1998; Wright and others, 1998a; Kimball and others, 1998; Wirt and others, 1999) for more specific data and regulatory concerns.

Table 1: Colorado Basic Stream Standards for Metals: Class 1 Aquatic Life

pH	6.5—9.0		
Al (sol)	100	Fe	1000
Cd	1	Mn	1000
Cu	10	Pb	25
		Zn	50

Note: These values are for chronic exposure; values are in µg/L (or parts per billion). The selected values shown are for 100-200 mg/L water hardness, which is appropriate for water Animas water samples with near-neutral pH; standards for Al, Fe, and Mn, do not vary with hardness. Taken from CWQCD (1989, table 5, which cites Colorado Department of Health, 1984, Basic Standards and Methodologies 3.1.0)

Geologic Framework and the Importance of Geology

The regional and local geology of the upper Animas watershed is well established from many excellent studies over the past century, especially those of Burbank and Luedke (e.g., Burbank and Luedke, 1964; Burbank and Luedke, 1969; Luedke, 1996), as well as studies of the mines by Ransome (1901), and by Casadevall and Ohmoto (1977). Regional geology and resource information is also provided by recent reports on the San Juan National Forest (Neubert and others, 1992; Van Loenen and Gibbons, 1997). Geologic studies are continuing in the AML program to better establish the relations between geology and water quality (Bove and others, 1998). The geology is too complex to review in any detail here; the abundant and excellent literature will serve readers well. In simple terms, the study area lies both inside and outside a major volcanic feature called a ‘caldera” which largely determined the distribution of rock units, structures, rock alteration, mines and prospects (fig. 2). The curving fault zone on the western margin of the caldera is the locus for a sequence of several stages of small intrusions, wallrock alteration, and mineral deposition in the Middle Tertiary (about 26 to 15 Ma)—and this is now the zone where many of the most degraded waters originate from both mined and unmined sources. Hydrothermal alteration produced by the intrusions and ore-forming processes differs greatly in mineralogic and chemical composition (Casadevall and Ohmoto, 1977), with important influences on waters today. Volcanic rocks that are altered to shades of green (introduced chlorite, epidote, and often calcite) tend to buffer acidic waters to near-neutral pH even if they are pyritic, whereas the white or red altered volcanic rocks (leached, introduced sericite, kaolinite, alunite, turn red on weathering of pyrite) tend to create or enhance acidic conditions (Smith and others, 1994; Nash, 1999). The divergent evolution of water pH and metal concentrations is largely a reflection of the acid-neutralizing capacity (ANC) of the rocks, often called ‘buffering capacity’. Pre-Tertiary sedimentary rocks are exposed in the southwestern part of the study area and underground in the deep mines west of the caldera (such as the Idarado mine)—the hydrogeochemical character of ores in these units today differs in important ways from those in volcanic rocks because of the high ANC of these units.

Mineral deposits of the upper Animas watershed can be considered to be of just a few types, or can be split apart into many subtypes for special purposes such as economic geology or mining engineering (Burbank and Luedke, 1969; Casadevall and Ohmoto, 1977). For the purposes of this study only four types need to be mentioned: 1). Polymetallic veins, rich in pyrite, and having variable proportions of chalcopyrite, galena, sphalerite, gold and silver-bearing sulf-arsenide minerals as in the Sunnyside mine and the majority of mines and prospects in the study area; these tend to be along major faults inside and outside the caldera and have moderate argillic alteration haloes of pyrite and clay minerals tens of feet wide. Manganese minerals (rhodonite and rhodochrosite) are locally abundant in some veins, and tungsten (as wolframite, a Fe-W-oxide) and fluorine (fluorite) are abundant in some places. 2). Polymetallic breccia pipes, similar in composition to the veins but tending to be richer in sulfide and arsenide minerals, as at the Lark and National Belle mines; these deposits are restricted to the caldera fault zone, are highly localized as intense bodies of alteration and ore minerals, but have wide alteration haloes of the acid-sulfate type with disseminated pyrite-alunite-clay minerals as in the Red Mountain area; 3). Porphyry systems containing shattered zones filled by copper-molybdenum quartz-sulfide veinlets as at Moly Mountain and Anvil Mountain; these mineralization systems with large vertical and horizontal dimensions have been drilled but none have been mined in this area and it is the peripheral alteration halo containing pyrite that creates acidic drainage today (Bove and others, 1998). 4). Placer deposits of gold in alluvial gravel; these deposits were mined in a few places such as Arastra Gulch; placer deposits will not be mentioned further but they are a reminder that mineralized rocks and veins have been shedding metals into the streams of the area for thousands of years.

Polymetallic is an appropriate descriptor for virtually all of the mines and prospects of the upper Animas watershed because many base metals and metalloids (collectively called metals for simplicity) are concentrated in these rocks, even if miners may have emphasized silver, gold, or copper for economic reasons. We must remember that zinc, one of the toxic metals of prime concern here, was not deemed economic and therefore not recovered before 1912, thus is slighted in the early literature. Significant amounts of zinc are found in all of the ores and waste rock dumps, and zinc-rich rocks were intentionally left underground in many of the older workings. It is counter-productive to describe the mines in economic or commodity terms because the rocks remaining in the mine or in mine dumps and their environmental geochemistry bear no useful relation to that classification.

The scale of deposits and associated alteration haloes are important attributes to bear in mind. The porphyry systems have a surface expression of a square mile or more, whereas the breccia pipes can be as small as an acre, and the major polymetallic veins of the Eureka area can be traced for several miles in length. The volume of rock mined was determined by economic factors; in all cases one must assume that a much larger volume of mineralized rock existed but did not have sufficient thickness or grade to support mining. The scale of alteration is not proportional to the size of the mine or the mineralized orebody: the large polymetallic veins worked by the Sunnyside mine and the Mayflower (Shenandoah-Dives) mine have relatively narrow alteration haloes, whereas the small breccia pipe deposits have much larger alteration haloes of rocks that now are red and major sources of acid and metals.

Changes in mining and milling technology over the years have important influences on the materials left behind in the mines or placed on dumps and tailings piles. In this region at least two stages of technology can be highlighted: 1) Early (1875-1918), small volume mining of high grade zones, with small associated milling infrastructure. The miners lacked powerful equipment, created very narrow stopes, and generally brought only hand picked high grade ores to the surface. Mine dumps were small relative to the amount of ore removed. 2) Later (post 1918), increasingly large-scale mining of lower-grade ores made possible by consolidation of workings, electric-powered machines, and new milling technology such as selective flotation to recover specific sulfide minerals. The change in style was first made at the Sunnyside mine and an associated new mill built in 1917. In this stage mine tunnels became many miles in length (some crossing under natural drainage divides), tramways were the norm to carry distant ores to centralized mills, and large mine dumps and mill tailings piles were made. Tailings technology changed in 1935 when regulations required that mill tailings be confined to so-called ‘tailings ponds’ rather than allowed to go into surface streams. The very large (millions of cubic yards) mill tailings piles of some of the large mills in the region are physically stable today (some older ones as at Eureka were breached during storm events), but their contents remain a matter of study because they were not built on an impermeable pad (thus infiltrating waters can escape through the base into alluvium). This simplistic review of technology is a reminder that individual site evaluations must consider the mode of mining and milling used at the site before a remediation technology is chosen.

Rating Scale

In this report I will use a qualitative rating scale with four levels: H, high, M, medium, L, low, and N, no priority (no work recommended). A similar scale for rating environmental degradation (EDR) was used by Lovekin and others (1997) with appropriate descriptors: 1, extreme; 2, significant; 3, potentially significant; 4, slight; and 5, none. This is a good system, and my observations and results generally lead me to agree with the EDR ratings of Lovekin and others (1997), but at this stage of the upper Animas watershed investigations a bit more emphasis on amenability to reclamation seems needed, and in this context I have benefited from the studies of Herron and others (1997) on what they term ‘feasibility.’ Some of my rankings differ from those of Lovekin and others (1997) because I included more consideration of amenability to reclamation and place more weight on geologic parameters in ranking the sources or remediation of toxic substances.

Description of Priority Sites

Mines and prospects in the Mineral Creek watershed have been described by Neubert and others (1992), Lovekin and others (1997), and Van Loenen and Gibbons (1997) as part of work undertaken for the San Juan National Forest. Lovekin and others (1997) describe 25 priority sites, and provide geochemical data and an 'environmental degradation rating' for those sites. This good work utilized appropriate methods and reached sound interpretations. My work generally supports the findings of Lovekin and others (1997), but some of my comments emphasize different aspects of the geology or geochemistry in rating priority for restoration. Locations and names of mines studied in this watershed are listed in Table 2.

Brooklyn mine area: Rank H. An area of about 100 acres in Browns Gulch in the vicinity of the Brooklyn mine (approx. 3,000 ft E-W x 1,500 N-S; fig. 3) is one of the most highly disturbed areas in the Mineral Creek watershed and clearly is degrading the water quality of the creek. This mined area is of mixed ownership (private and public), and has evidently been worked by several operators over the years, with more activity in the past 20-40 years than most of the upper Animas watershed because most of the roads and workings are not shown on the topographic map (1955). There are numerous specific problem sites in need of reclamation, and despite their bad appearance these sites appear to be more readily reclaimed at reasonable cost than many other sites. My observations and data are similar to those of Lovekin and others (1997), but my comments here differ as points of emphasis. Because the land status is complicated, and I am not certain of property lines on the ground, my comments here will be somewhat generalized. Identified problems relate to scattered mine dumps, a small mill and tailings pond, and drainage from at least the major mine adit and possibly others.

A mine adit, gated and locked, has been used in recent years and in 1998 was being used for exploration drilling by a lessee (George Munzing, oral commun., 1998). Water drains from the adit at about 10-20 gpm, and was well described by Lovekin and others (1997) as being acidic (pH 3.15) and rich in many metals (4x to 26x CWQCD water quality standards). When I examined the site on August 13, 1998, the flow was about 10 gpm, pH higher (4.8) and water quality much better than just described: metal concentrations were elevated but approximately at ALWS. The bigger problem, in my view, is what happens to this water after it leaves the adit and reacts with sulfidic waste rocks on large mine dumps.

Waste dumps of several types are present, apparently from several kinds or stages of activity. Trenches or bulldozer cuts northwest of the main adit have created substantial waste piles of mineralized rock. Southeast of Browns creek, along FS-825 jeep road, are ragged piles of mixed alluvium and mine waste, possibly left from stockpiles because no mine openings are nearby. The volume of rock in these two areas is moderate, but amenable to reclamation. The highest priority solid waste site is the large waste dump (actually a series of dumps from several mining elevations), comprising more than 10,000 cubic yards (Lovekin and others, 1997) of sulfide rich rock. These rocks are wetted by acidic mine drainage. My tests on August 13, 1998 showed that the waters clearly react with the waste to become more acidic and metalliferous. The mine drainage becomes more acidic (from pH 4.8 to 2.9), conductivity increases from 606 to 884 µs, and metals rise dramatically to more than 10X ALWS. Iron, copper, and zinc are most significant—zinc is possibly most problematic at 130 X ALWS. Another symptom of problems at this waste dump is shown by the composition of puddles, which I infer are a suggestion of what water runoff might be in a storm event. The puddles are extremely acidic (pH 2.1), and metal concentrations are extremely high (Fe, Cu, Zn are >100X ALWS. Runoff presumably would be a diluted version of this composition.

One sample from the Brooklyn mine dump, visibly rich in sulfide minerals, was put through the 24 hr. passive leach test. The leachate reached a pH of 2.6, and contained high concentrations of base metals. Concentrations of Cu, Zn, and As are above the median for Animas dump samples, and concentrations of Fe and Pb are much higher than the median.

A simple mill was erected below the adit not many years ago; processing of about 50-100 tons/day may have been possible. Remains of six-inch diameter plastic pipe and wire cable suggest that the tailings were carried eastward across the creek to a series of two or three ponds constructed from local alluvium (no lining material is apparent). Ocher tailings are in two ponds, partly covered by water in August of 1998. The pond water had a pH of 4.8 and a conductivity of 126 µs, suggesting the surface water is not highly degraded chemically. However, pore water in the tailings has much more dissolved metals, including substantial amounts of Mn, Fe, and Zn. These metalliferous waters may be seeping into alluvium, but I could not verify this to be so. These small ponds, about an acre in size, could be reclaimed easily.

Water quality of Browns Gulch is significantly degraded at pH 3.8, several metals >2X ALWS and zinc most problematic at about 42X ALWS in my one reconnaissance sample. Reclamation of several problem sites in the Brooklyn mine area by standard techniques that control surface water flow and runoff seems workable and would substantially improve the water quality in Browns Gulch. There are other substantial contributions to Browns Gulch over its length of more than 1.5 miles, including numerous small prospects and large areas of highly altered rocks. As in many sub-basins in the upper Animas watershed, pre-mining water quality surely was not pristine. Reclamation planning in this area would benefit from more closely spaced sampling of surface waters and dump materials referenced to a reliable land survey.

Bandora mine area: Rank H. This mine complex of three or more west-trending adits worked a vein in pre-Tertiary sedimentary host rocks, and is the largest mine of this type in the upper Animas watershed. According to USFS maps, the mine area is mixed private and public land, and it was not possible for me to be certain where the property lines were located relative to mine adits and dumps or to estimate the amount of dump or mine drainage on public land. I presume that the mining claims (patents) were positioned over the vein(s), as confirmed in some recent cadastral surveys, and were not concerned, as we are now, with surface disturbance and dumps. There are ruins of a cement foundation with the multiple level geometry of a small mill, but no tailings could be identified and informal reports in the Colorado Mining Yearbooks for the late 1940's-1950's state that Bandora ore was trucked to the Mayflower mill; thus mill tailings do not appear to be a concern at this site. Several dumps are prominent (fig. 4) because the mine waste slid down the steep hillside as a relatively thin veneer; the volume is moderate but not as great as it appears. Most of the waste rock is fine grained quartzite or siltstone with low content of sulfide minerals; analyses are not yet available but my preliminary estimate is that the dumps are not a major problem. The main concern at this mine complex is the relatively large flow of water, especially from the lowest adit, and the bright red iron oxide materials that precipitate from the drainage (plate 1A). In the mid-1990's the mine adit was closed (not sealed) and a trench dug to divert the drainage east of the dump, but in 1997 and 1998 the ditch was breached and mine waters flowed overland and spread red precipitate that drew attention to the discharge.

The Bandora mine was described briefly by King and Allsman (1950) as working two parallel quartz veins in quartzite. The active workings in 1947 were on the fourth level and exceeded 1,200 feet in length. Average assays were reported as 0.5 percent lead, 10.6 percent copper, 54 oz./ton silver, and 0.42 oz./ton gold, but there was no report for zinc in those assays. However, a shipment of ore to the Shenandoah-Dives mill in 1947 contained 9.9 percent lead, 7.9 percent zinc, 1.25 percent copper, 13.7 oz/ton silver, and 0.12 oz./ton gold.

Mine drainage from Bandora is not highly acidic, but is carrying substantial amounts of many metals. The high metal concentrations in the large flow, about 20-40 gpm, indicate this is a significant source of loading to the South Fork of Mineral Creek. My observations and data are similar to those of Lovekin and others, 1997. The pH of the lower adit drainage was 5.6 and conductivity was 406 µs on 8-24-98; the upper adit with smaller discharge had pH 6.8 and conductivity 210 µs. Analysis of a reconnaissance water sample from the lower drainage shows high Fe, Mn, and Cu, and very high Zn and Cd (230X and 50X ALWS, respectively). Reclamation activities should focus on the Zn and Cd more than Mn and Fe, because the former may not respond to simple treatments that raise pH and flocculate Fe-Mn-oxides (Smith and others, 1994).

A sample from the lower Bandora mine dump was tested by the passive leach method for 24 hours. The final pH of the leachate was 4.2, higher than the median for the Upper Animas study area, and most base metals were much lower than the median dump leachate, but the concentration of Zn was very high relative to more than 100 other Animas dumps tested to date. The passive leach results are consistent with the chemistry of water from the Bandora adit.

Bonner Mine: Rank M. A series of south-trending adits, presumably on the same vein, were developed many years ago and left an inter-layered set of mine dumps on the south side of Middle Fork Mineral Creek (fig. 5; plate 1E). The canyon wall in this vicinity is steep, north-facing, dark, and probably retains snow longer than many areas. The lowest dump is less than 200 feet from the creek, thus this site poses more reclamation logistical problems than others. At least three collapsed adits appear to be draining water in modest amounts (about 5-10 gpm each in August, 1998) that percolates into the dump waste and reappears at the surface (plate 1F). I sampled two of the mine-related seeps, and my results are similar to those reported by Lovekin and others (1997). The seep at mid-dump level had a pH of 3.1 and that from the lowest adit had a pH of 2.9. Concentrations of Al, Mn, Fe, Cu, Pb, Zn and Cd are very high (3X to 52X ALWS), with that of Zn probably most problematic at 50X and 52X ALWS, respectively.

One sample from the lower Bonner mine dump was tested by the passive leach method, and other samples will be run in early 1999. The leachate reached a pH of 3.0, slightly more acidic than the median of Upper Animas dumps tested to date. The concentrations of base metals were below the median, but Zn was slightly below the median. The passive leach test suggests that zinc is the most mobile and problematic metal in the Bonner dump materials. A sample of red iron ‘floc’ from the lower adit drainage also was tested by the passive leach method, producing a pH of 2.9 but very low concentrations of all metals. The leach test suggests that the iron floc can be a source of acidity, but when it reacts with water it does not release much metal.

From what I was able to see at the site, and from available chemical data, I would rate the Bonner mining area as a moderate source problem. First, the volume of water flow is not very high—at least when observed in August of 1998. Second, visual examination of the dump rocks suggests that it is not especially rich in sulfide minerals. Excavation to expose the collapsed adits would be required to measure the effects of dump rocks vs. mine workings. One would expect some improvement in water quality if mine drainage was piped away from the dumps. However, the dump rocks do not appear to be a major source of acid or metals. Mitigation of the mine waters will be a challenge because of the limited space and setting on the steep slope. Because the flow of water appears to be quite low, the magnitude of metal loading from these mine drainages may not merit expensive reclamation efforts.

Ruby Trust mine: Rank M. There was substantial mining at this site, but the moderately large waste dumps are mostly out of sight because they are immediately below the Ophir Pass road. A collapsed wooden building and machinery appear to be partial remains of a former mill, but only a small amount of tailings could be found (other tailings may have been washed away down the creek, as at other old mill sites). The most remarkable feature of this site is the very large flow of water from the collapsed adit that bears north, probably to intercept veins that outcrop east of Clear Lake (Luedke, 1996). The dump contains altered volcanic rock with abundant pyrite, but no vein material and no ore sulfides such as galena or sphalerite were recognized; chemical analyses are not yet available.

The large flow of water, possibly 50-100 gpm, had a pH of 6.4 and conductivity of 363 µs. A reconnaissance water sample contained elevated concentrations of toxic metals, but only that of iron exceeded ALWS. The concentrations of Fe and Zn, combined with the high flow volume, make the metal loading substantial. The values for Fe and Zn are 2.4X and 1.4X ALWS, respectively. Thus this is one of several near-neutral, high flow discharges that must be evaluated. Treatment of this water probably would be difficult unless the pH could be raised substantially to cause Zn to precipitate

(Smith and others, 1994). The mine drainage flows across the dump for about 100 feet, but does not appear to react much with the dump rocks. Diversion of surface water would be easy to do and would minimize leaching reactions and runoff from the dump.

Burbank mine area: Rank M. Several mines of modest size were excavated in the past 40 years or so (they are not shown on the 1955 topographic map) in the valley of Clear Creek, north of the South Mineral Creek Campground, to work veins in weakly altered volcanic agglomerate and breccia, and some veins are in pre-volcanic clastic rocks. The Burbank mine is the largest of these, and noteworthy for the large flow of water from the gated adit. The water seems to resemble that from the Bandora mine in its chemistry and tendency to form bright red precipitate of Fe-oxides. The flow of about 150 gpm (measured at 164 gpm by Lovekin and others (1997) has a pH of 5.7 and conductivity of 527 μs. This water looks worse than it is chemically. Among the toxic metals, Mn is 1.4X and Fe is 6X ALWS, but others are not in excess of ALWS.

Reclamation at this site is a medium priority. The high content of Fe in the mine drainage and reactions of mine waters with waste dumps are the items of major concern. Other nearby sites appear to create fewer problems and may not require mitigation of geochemical effects. The Ensle adit, hundreds of feet higher on the same structure, has mine drainage with higher concentrations of toxic metals (Lovekin and others, 1977), but the flow is only a few gpm and the waters probably would be mitigated by reactions with rocks and alluvium having high buffering capacity; also those waters are not visible from the jeep road.

Imogene mine: Rank M. The Imogene mine is located on the west side of Mineral Creek and is visible from US 550; a popular Forest Service jeep trail crosses the mine dump. The most notable features of the site are the high flow of water from the collapsed mine adit and the erosion of dump material and transport out onto the valley floor below (plate 1B). Ferricrete-cemented talus occurs above the adit. Water from the adit, possibly 100 gpm, flows through a culvert under the jeep road, and then over dump rocks for several hundred feet. The drainage had a pH of 5.4 and conductivity of 256 μs on 8-14-98; a reconnaissance sample showed very high iron (6X ALWS) and high concentrations of Mn and Zn. The high concentration of Zn, 2.6X ALWS, combined with the high flow, indicate a substantial loading of Zn.

The mine dump is comprised of silicified volcanic rock with moderate amounts of disseminated pyrite and interstitial clay; no vein material or base-metal sulfide minerals were noted. Because the mine drainage is allowed to contact the sulfidic waste rock, water quality is further degraded. No analytical results are yet available for my sample, but Lovekin and others, 1997 provide information from an EPA Method 1312 leach test.

The Imogene mine should be given moderate priority for reclamation because it is easily accessible, has high visibility, and should be amenable to mitigation. This site is one of many characterized by significant water flow, near-neutral pH, and high iron and zinc content. Water mitigation is the first priority, and reclamation of the dump should require only simple methods.

Southside Chattanooga Curve: Rank M. This obscure site, hidden in thick brush just a few hundred feet south of the horseshoe curve, produces water with substantial amounts of toxic metals. The mine dump is small, about 200-400 cubic yards, suggesting small extent of workings, but the red water and iron floc at the adit are signs of bad water quality. The mine drainage, about 30-50 gpm, has a pH of 4.9 and conductivity of 282 µs. A chemical analysis shows that Fe, Mn, and Zn exceed ALWS. The concentrations of Fe and Zn at 2.5X and 8X ALWS are of most concern. Results reported by Lovekin and others (1997) are similar, but higher for Mn and lower for Zn.

This site is given a ranking of medium to suggest that it should be considered for reclamation, chiefly with the intent of improving water quality prior to discharge into nearby Mill Creek. The site is close to a major road, but not easily accessible. Other sites in the upper Animas watershed have similar water chemistry and are under study for effective mitigation methods (Herron and others, 1997), thus those methods should be applicable here.

North of Imogene mine: Rank L. An area of ferricrete about 2,000 feet north of the Imogene mine was trenched during prospecting, and a small adit and shaft made to explore west of the ferricrete. The adit has a small associated dump and drains water at the rate of about 100-200 gpm. After leaving the gated adit the water creates notable amounts of red iron flocculate and flows into the wetland of beaver ponds in the main valley of Mineral Creek south of Chattanooga. The dump is so small that there could be only minor underground workings; the volume of water seems much larger than expected from a small excavation, thus I infer that the mine drift intersected a watercourse or spring system. Another inference is that this watercourse is part of the relatively recent (thousands of years) system that deposited ferricrete and the iron bog to the east. Water emerging from the adit had a pH of 5.1 and conductivity of 377 µs on 8-14-98. Chemical analysis of a sample shows that Fe, Mn, and Zn concentrations are substantially in excess of ALWS. Results reported by Lovekin and others (1997) are similar, but do not include the high value of Zn (7.4X ALWS) determined here. The site is given a low priority ranking because I suspect that reclamation will not be cost-effective.

The water problems at this site appear to be only partly related to past mining. As for others considered here, this poses questions as to the extent of reclamation that is appropriate on public lands. Quite clearly, mitigation of Fe and Zn at this site would have a beneficial effect on water quality in the Mineral Creek watershed. If the flow of water reflects a natural watercourse, plugging of the adit might have limited beneficial results because the waters would tend to escape on other fracture zones. Further studies of water chemistry and fracture-flow hydrology, and their implications for restoration are suggested.

West Burro Bridge: Rank L. This site about 1,000 feet west of Burro Bridge is but one of many small mines south of the Imogene mine, but this one has a noteworthy amount of water flowing from the sealed adit. The mine is not visible in the dense trees, but the drainage and associate red-brown iron floc can be seen from the jeep trail that runs north from the Ophir Pass Road to the Imogene mine. The mine drainage was described by Lovekin and others, (1997). The water leaving the sealed mine adit has a pH of 5.3 and conductivity of 201 µs; the flow on 8-19-98 was about 20-30 gpm. A chemical analysis showed high concentrations of Mn (2.3X), Fe (6.4X), and Zn (8X) ALWS. The dump contains altered volcanic rock with moderate content of clays, iron oxides, and pyrite. The water flows across part of the modest sized dump and presumably leaches more metals.

The lack of access to this site poses problems for many kinds of reclamation, but it is only a short hike for small-scale activities that may be appropriate.

Paradise mine: Rank L. Two small adits in the upper canyon of Middle Fork Mineral Creek produce very high flows of water that deposit an unusual white material that is highly visible from the Ophir Pass road (fig. 6; plate 1C-D). The mine dumps are relatively small (a few hundred cubic yards). The unusual composition of the waters, such as the high concentration of aluminum and rare earth elements (P. Verplank, USGS, oral commun., 1997) has attracted substantial academic interest. My interim conclusion is that this site should not be a priority in reclamation. I believe that reclamation would be very difficult, expensive, and probably ineffective because the high flow of water seems to be mostly natural and would escape elsewhere.

Abundant geochemical information is available elsewhere for this remarkable site. The adits with high flow of water are described well by Lovekin and others, (1997), and their water analysis shows extremely high concentrations of Al, Mn, and Fe (to which my sample results are similar). In August of 1998 the canyon was mostly clear of snow and the collapsed adits, dumps, and flowing waters were well exposed. The larger eastern workings created a small dump that is now covered with white and red microgranular precipitate from the gushing flow of water (plate 1D). Flow was very high, possibly 200-400 gpm, and upwelling through the collapsed material. Conductivity values varied substantially, from about 800 to 1,300 µs, suggesting incomplete mixing of waters of different composition. A typical pH was 4.5. The western working had much lower flow, about 10-20 gpm, but very similar pH and conductivity. The prospector drove the mine adit into outcropping ferricrete, which was fairly common exploration practice in the early years of the district. The small size of the dumps, combined with the observed ferricrete, suggest that the high flow of water is from a natural fracture system and is not produced by mine workings. The old prospector probably dug into a flowing spring (water course) and did not pursue the structure for very many feet.

The dump rocks are unremarkable to the eye, but thick crusts of white and red materials precipitated from the mine waters are highly visible from a distance. The original dump rocks contained moderate amounts of disseminated pyrite and soft clay minerals, but no visible ore minerals. No chemical analyses are yet available. Water is the question at these adits. My two reconnaissance water samples contain very high concentrations of Al, Mn, Fe, and Zn, but low Cu and Pb. Because of the very high flow volume, the loadings of Al, Mn, Fe, and Zn must be very high or extreme and a major input to the creek a few feet away.

I suggest caution in making plans to reclaim this site. I view these waters as originating in the large mountain of red-altered, pyritic volcanic rock above and to the south of the site (Luedke, 1996). Generally similar waters also flow down the next tributary to the east, the so-called “Red Trib” of the Middle Fork of Mineral Creek (Bove and others, 1998). My sense is that these water compositions are not related to mining. If one were to attempt to ‘plug’ the adits, I suspect that the highly fractured rocks and hydraulic head would cause the waters to flow out elsewhere with little improvement in quality. I suspect that reclamation will not be effective at this site, and therefore give it a low priority ranking.

Silver Crown mine: Rank L. Just west of the horseshoe curve at Chattanooga is this moderate sized mine that technically is somewhat different in character from most of the mines in the area in that it probably is related to an intrusive complex and a molybdenum porphyry system (Van Loenen and Gibbons, 1997; Neubert and others, 1992). The mine adit drains about 20-30 gpm, with a pH of 5.5 and conductivity of 360 μs, and no deposition of red iron floc. These suggestions of benign conditions are supported by a chemical analysis that shows that only Fe and Zn are above standards at about 2X ALWS. The mine drainage flows through the dump, which normally is a bad condition, but here the pH and conductivity do not change significantly, suggesting little reaction. Similar results are reported by Lovekin and others, (1997), but they found only Mn to be in excess. The water compositions suggest that the chemistry is moderated by green propylitic rock alteration.

This site is given a low ranking. Some reclamation work can be done, easily and with some beneficial results, but no major improvements to the watershed should be expected. The flow of water is substantial, and the site does contribute Zn to the Mineral Creek watershed, but this is not a major source.

Bullion King mine, Rank L. The Bullion King mine in Porphyry Basin is a popular destination on jeep trail FR-822, west of Red Mountain Pass (fig. 7). The mine dumps are prominent in the alpine basin and their ocher color suggests they are the type that produces AMD. The site was described by Lovekin and others (1997) as private, but of interest for acquisition by the Forest Service. It was given an EDR of 3 (potentially significant). The large dumps are rich in pyrite, which one would assume should produce acid; the dumps also are rich in clay. The water at the closed adit has a pH of 5.1 and a flow of about 10 gpm; below the dumps the pH is 4.6. Conductivities at both sites are very low, 130-140 μs, which indicates low content of dissolved solids. The Bullion King mine and dumps do not appear to generate much acid, and this will be examined further in lab leach tests. A chemical analysis of the pH 4.6 sample contains surprisingly high metal concentrations of Mn, Zn, Cu, Cd, and Pb for the low conductivity. The concentrations of Zn (3X), Cu (3X), and Cd (10X ALWS) are sufficiently high to merit further study.

Reclamation planning for the Bullion King mine area requires further study. The dumps are visibly rich in sulfide minerals, and this sulfidic waste is reacting with mine drainage. Although data are limited at this time, there are numerous indications that even simple reclamation measures would have a beneficial effect on the mine drainage. These are the headwaters of the creek in Porphyry Gulch, which mixes with the highly degraded waters of Mineral Creek that drain the Longfellow, Koehler, and Carbon Lakes mining areas. Further study may show that the drainage from the Bullion King complex is attenuated naturally by mixing with other waters and reaction with green-altered volcanic rocks with high buffering capacity.

Upper Brown's Gulch: Rank L. Scattered mines and prospects about ½ mile northeast of the Brooklyn mine (fig. 3) are on mixed private and public lands that are difficult to evaluate because of uncertainties in location. Several of the larger mines had shafts, and these do not drain water. A few of the adits do drain water and these are the sites of concern, as discussed by Lovekin and others, 1997. Their site 102, just east of the jeep trail and described as patented, had a small flow of water, less than 5 gpm, with a pH of 2.6 and conductivity of 520 µs on 8-13-98. A small vegetation kill zone occurs below the mine, but this does not seem to be a substantial contributor of metals or acid. Southeast of this site, at lower elevations, are several other small mines with dumps of about 50-200 cubic yards of sulfidic rock. Kill zones below some of these dumps suggest episodic flow of acidic waters, but there was very low flow in August, 1998. One drainage, a few gpm, had a pH of 2.8 and conductivity of 675 µs, indicating degraded water quality. However, this adit entered an area of pyrite-clay altered volcanic rocks, thus some of the degradation is likely related to the rock alteration. Pending results of a cadastral survey, some modest reclamation might be attempted at one or more of these small mines. These mines presumably contribute to upper Browns Gulch, which has a pH of about 4.3 northeast of the Brooklyn mine complex, but this upper basin also drains altered, unmined rocks on the flank of Ohio Peak that probably contribute metals and acid to the headwaters.

Chattanooga: Rank N. A cluster of three adits on the hillside about 2,000 ft southeast of the abandoned townsite of Chattanooga was identified as a "potentially significant" site by Lovekin and others (1997) because of mine drainage at the time of inspection (2 gpm of pH 6.2 water with high Mn), and the kill zone extending several hundred feet down the hillside. When I visited the site in August of 1998 there was no mine drainage. The mine dumps are small, about 50-150 cubic yards each, and composed chiefly of pyrite-sericite altered volcanic rocks that are common in the region.

There are hundreds of small mines of this type in the upper Animas watershed that generate small amounts of mine drainage for a few months of the year, and the chemistry of that water often does not meet State water quality standards. Because the flow is seasonal and infiltrates alluvium within a short distance, it is difficult to sample and evaluate the full impact of these waters. A generalized point can be made that the geologic setting of most of these waters is favorable for natural attenuation by reaction with green propylitic-altered rocks and that these are probably only small contributors to the upper Animas watershed. It is clear that numerous sites demand priority attention before these. Perhaps these sites will not require much if any reclamation work.

U.S. Basin: Rank N. Scattered small mines and prospects occur in this broad sub-alpine basin in the northeast corner of the Mineral Creek watershed. There are no roads or trails to these mines, an indication that they were not very productive. The U. S. Basin site #1 was identified by Lovekin and others(1997) as category 4, causing ‘slight’ degradation. My observations lead me to agree. The mine workings are small, and most of the dump material is similar to that in outcrop—pyrite-altered volcanic rock. Water seeping from mine openings tends to be very similar to that of natural seeps or springs in unmined, altered rocks, with pH of about 5.0-5.5. Chemical analysis of water from U.S. Basin site #2 is highly degraded, with Mn (8X), Fe (3.8X), Cu (30X), and Zn (10X ALWS).

U S Basin is an excellent example of an area with patches of sulfidic alteration and veining, but generally having green propylitic alteration of volcanic rocks. Mines and unmined sites can be shown to produce degraded, acidic water. But samples of flowing surface waters a few thousand feet away show the results of natural attenuation by dilution and buffering with green-altered rocks that raises pH values to near-neutral, and reduces metal concentrations.

Lower Ice Lake area: Rank N. This lovely sub-alpine area was the locale for several relatively small mining operations prior to 1900, supported by a small mill below tree line on Ice Lake Creek. One site was given an environmental rating of 3 (potentially significant, Lovekin and others, 1997), which probably is correct in detail. However, if one steps back from the adits and dumps, there is abundant evidence that the geology of this upland basin provides good natural attenuation of local sources of AMD. The pH of the stream below the problem site, close to Lower Ice Lake, is 7.6, and conductivity 95 µs. Likewise, the water of Upper Ice Lake has a pH of 7.3 and a conductivity of 37 µs. These values alone suggest that dilution by uncontaminated surface waters, and buffering by the prevailing green alteration in volcanic rocks, mitigates the relatively small inflow of degraded waters. The chemistry of two water samples supports this inference. The pH 5.6 creek water contains elevated concentrations of Fe, Zn, and Cu, but the values are below the ALWS.

The water quality at some small point sources in this area may be marginal, and the water in Lower Ice Lake may not be optimum for fisheries, but in general this sub-basin has relatively good water. The pre-volcanic sedimentary rocks at lower elevations can be assumed to further mitigate any problems that exist there, well above the South Fork of Mineral Creek.

Red Mountain Pass—Headwaters of Mineral Creek: Rank H. An area of about one sq. mile east of US 550 on Red Mountain Pass (fig. 7) contains numerous mines and dumps that produce highly degraded waters that are well known (Herron and others, 1997). Most of the land is private, but there are small slivers of public land. Reconnaissance studies of creeks south of Longfellow-Koehler mines, and southwest of Carbon Lakes, on public lands, indicate that the water is far more degraded than at any of the mine sites described above. My work is not definitive, but it shows quite clearly that waters on public lands are severely impacted by mine sites above them. Qualitatively, waters have pH’s below 3, and conductivities of 460 to >2000 µs, with little indication of improvement below those mines until the headwater tributaries mix with larger flows coming from west of US550 (the area of green alteration). Mixing with Mineral Creek and Porphyry Gulch Creek, which have pH’s above 5, raises the pH of the mixed streamwaters to about 3.0 and decreases the conductivity to about 280, causing precipitation of abundant orange-brown floc (plate 1G) that is identical in appearance to the floc in Cement Creek. Research on the Cement Creek floc (Desborough and others, 1999) shows it to be the crypto-crystalline material schwertmanite, an iron-oxyhydroxide-sulfate mineral. Schwertmanite is very reactive: at times it is a sink for Fe and numerous base metals, and at other times it dissolves, releasing large amounts of acid and base metals. Farther south, below the Silver Ledge mine, and after there has been much dilution and deposition of schwertmanite (and presumably entrained Cu-Zn), Mineral Creek is still very acidic (pH 3.0), and carries very large concentrations of Al, Mn, Fe, Cu and Zn into the Chattanooga wetlands and iron bogs.

My reconnaissance water data suggest that the northeastern headwaters of Mineral Creek are an order of magnitude or more degraded than others waters in the Mineral Creek watershed, as described well by Herron and others (1998) and Walton-Day and others (1998).. A geologic-geochemical framework may be helpful for understanding the chemistry of these waters in the Mineral Creek watershed: 1). The waters are extremely acidic, and those acids overwhelm any buffering in the local rocks. Thus these waters generally flow substantial distances, more than ½ mile, with little change in composition, whereas waters in other parts of the Mineral Creek watershed tend to be partly mitigated by natural processes in shorter distances; 2). Mixing with waters sourced in western, green-altered volcanic rocks improves the quality of northern Mineral Creek, but the pH remains very acidic and high concentrations of key toxic metals (Al, Fe, Cu, Zn) remain in solution. The situation is well summarized by Herron and others, 1997: “The Longfellow-Koehler site is the largest single source of zinc and iron related to mining in the Mineral Creek watershed. Zinc loads are greater than the combined zinc loads from all other mining source sites.” The Carbon Lakes area mines are also an important contributor. The importance of this area was recognized by the Animas River Stakeholders Group when they chose the Longfellow-Koehler as the highest priority in the Mineral Creek watershed. Restoration of the Mineral Creek watershed seems to require a balance of reclamation activities on private sites, such as Longfellow-Koehler, major sites on mixed-ownership sites such as Bandora, and some activity on smaller loaders such as Imogene or Burbank on public lands.

Other Concerns: Smelter Slag and Mill Tailings

Mill tailings are a substantial source of toxic metals in many mining districts, and are recognized as a problem in the Upper Animas River where they are present in several kinds of fluvial deposits (overbank and bedload; Vincent and others, 1999). Mill tailings can be a source of metals either in their sites of original placement (tailings dams or ‘ponds’) or dispersed in streambeds after a tailings pond has been breached during a storm event. During my reconnaissance of the upper Animas watershed, I have located more than 50 mills or mill ruins, and less than half of them have confined tailings—the majority of the older (prior to about 1920) mills have few or no tailings at the site, implying that the tailings were not impounded or that they were eroded during storm events. Tailings at a few sites have been reprocessed or moved for reprocessing. Tailings appear to be a problem chiefly in the Upper Animas River between Eureka and Silverton (Vincent and others, 1999).

There appear to have been only a few mills in the Mineral Creek watershed, possibly because the mines were generally small producers and had access to mills near Silverton (or in the case of Koehler-Longfellow, mills to the north of Red Mountain Pass). From the literature and my reconnaissance studies I have been able to locate seven sites, but only a few cubic yards of impounded tailings. The largest mill was at the North Star mine, across from the smelter, south of Silverton. Because of access issues, I could not investigate for tailings, but none are visible from US550. Also on the lower part of Mineral Creek was a mill for the Lodore Mine, southeast of Silverton. A small area of tailings remains in the floodplain. A mill dating to about 1905 is reported to have been at Chattanooga to support the Silver Ledge mine; the ruins of the mill structure are in place, but I could find no tailings. I suspect that the tailings are now in the wetlands south of Chattanooga. Small stamp mills have been identified below Ice Lake (a popular site for hikers), and at the Ruby Trust mine. A very small mill operated near the Brooklyn mine within the past 40 years, piping tailings across Brown’s Gulch to small ponds (fig. 3) that retain a small amount of tailings. A few burned beams, of the type used in stamp mills, were located above Mineral Creek about 200 yards south of the new Burro Bridge; only a trace of tailings are retained in the foundation and no others could be located. A cement foundation at the Bandura mine site has the stepped geometry of a small mill. No tailings could be found in the structure or below it. Reports in the Colorado Mining Yearbook stated that ore from Bandura was trucked to the Mayflower mill, thus this may not be a mill or perhaps it never operated.

Mill tailings do not appear to be a significant factor in water quality of the Mineral Creek watershed. Only the tailings at two sites, Lodore and Brooklyn, are sufficient in size and proximity to streams to merit consideration for reclamation. Those two tailings sites could be reclaimed very easily if an appropriate site could be found for a stable impound.

Smelter slag from the Walsh smelter in the 1890’s (Ransome, 1901) can be seen just north of US550 on the south side of Silverton. Most of the slag has been crushed and sieved to medium sand size. The slag is not chemically reactive in leach tests (Nash and others, 1998), but has very high concentrations of base metals (notably Pb, Cu, Zn, Cd) and probably poses a threat only if ingested. The slag does not appear to contribute metals to the watershed.

Discussion:
Multiple sources of degraded waters and implications for reclamation

Reclamation activities at abandoned mining sites need to be planned with an understanding of sources of contaminants and pathways to surface waters or aquatic receptors. This report has described the composition of mine dumps and the probable mobility of metals as determined by lab leach tests, which is one indication of the magnitude of a source. However, mines and dumps are not the only sources of metals or acid: natural sources in unmined rocks have been mentioned in several places. As a geologist, I see mines and dumps in a larger, three-dimensional geologic framework, whereas engineers and regulators tend to view discharges from mining areas as ‘point sources’ with no consideration beyond the pipe or adit. The concept of natural sources of acidic and metalliferous waters may be only academic interest for some, but I believe it must be considered when estimating reclamation or restoration feasibility. One of the difficulties is that there are no objective and quantitative measures of source, although research by the USGS AMLI group is developing chemical and isotopic criteria (e.g., Wright and others, 1998b). The following discussion, which is more descriptive than quantitative, and is speculative in places, is offered to promote inquiry into the role of natural sources of acidic, metalliferous waters. Two or three classes of waters can be considered as important examples.

The most notorious type of degraded water is highly acidic (pH <3) with extremely high metal content (Smith and others, 1994; Plumlee and others, 1995b ??) well known at the Longfellow-Koehler and some other mining areas in the upper Animas watershed. These mine drainages are high loaders in Fe-Cu-Zn because of the extreme metal concentrations at low to moderate flow volume. A significant attribute, beyond the adit, is the fact that in the worst cases the buffering or neutralizing capacity of the local rocks is inadequate to attenuate the acidic conditions. This is true at Longfellow-Koehler in Mineral Creek, but also at many other drainages on Red Mountain No. 1 and No. 3—into both the upper Uncompahgre watershed (Red Mountain Creek) and into the Cement Creek watershed. Geologic studies by Bove and others (1998) show that the alteration assemblages are such that there is little or no ANC in the Red Mountain rocks, and this is confirmed by anyone who walks the creeks and measures pH downstream for a mile or more. Conditions in the Red Mountain Creek watershed, just to the north of the study area, are pertinent analog for the Mineral Creek watershed. During my reconnaissance geochemical studies for the Uncompahgre National Forest in 1997 and 1998, it was clear that the water downstream from deposits similar to Longfellow-Koehler (National Belle, Guston, and others) remained very acidic and Red Mountain Creek is visibly contaminated for several miles to the north. These extreme water compositions are predictably related to breccia-pipe type deposits with associated ‘acid-sulfate’ alteration of the Red Mountain type (Plumlee and others, 1995a). Similar extremely toxic waters are found in other vein-type settings in the upper Animas watershed. The vein-type deposits tend to create local and small flows of extremely acidic water, but these drainages tend to be attenuated by nearby green-altered rocks as the in Cunningham Creek drainage of the Upper Animas River northeast of Silverton, in the headwaters of Henson Creek, and in the headwaters of Unconpahgre River.

It also is apparent that some of the extremely acidic (pH 2-3) waters with extremely high metal content are coming from mine workings driven into structures that can be argued on geologic grounds must be major watercourses independent of any effects of mining: these appear to be chiefly naturally acidic waters. The Guston mine was located on a spectacular ferricrete outcrop and was notorious for acidic waters that corroded mining equipment in the early years of mining (Ransome, 1901). A small adit (about 5,000 cubic yard dump) at the head of Corkscrew Gulch, south of Red Mountain No. 1 (and only a thousand feet northwest of the Cement Creek watershed), is the source of a substantial flow of pH 2.2 waters that carry very high concentrations of metals; the small size of the mine workings suggest that these waters are only partly related to mining. The composition of some springs and surface waters also attest to natural sources of acidic, metal-rich waters in highly altered rocks (Bove and others, 1998; Nash, unpub. data, 1998). These are warnings that plugging of the adits may be ineffective because these natural waters have substantial head and will find alternate routes to the surface.

A second type of problem water has near-neutral pH, elevated to moderate concentrations of Fe-Cu-Zn, and is a ‘high loader’ because of the very high flow volume. Some of these waters have sources in large volumes of pyritic-altered volcanic rocks, as at Moly Mountain and Bonner mine, but others are associated with vein deposits as at Bandora and Imogene mines. These near-neutral waters may have multiple origins and mixing histories, that may be of more academic than practical interest. A key aspect of these waters is that natural attenuation of zinc may not be effective if it is not removed during flocculation of iron at pH 4-6 (Smith and others, 1994). There are many examples of near-neutral, high-volume flows of this kind in the upper Animas watershed, mostly in the Mineral Creek watershed, but also several in the Cement Creek watershed. Because these waters tend to make prominent deposits of red iron floc, they are easily seen by the public and some look far more ominous than their chemistry indicates. Some may be most significant for their part in the iron cycle in streambed deposits, as in Cement Creek and Mineral Creek. The iron deposits may form in response to mixing of two or more water compositions. The most damaging kind of deposit (flocculate) is that of schwertmanite that forms at about pH 3.5 and dissolves at low stream flow, thereby releasing sorbed metals and also copious amounts of acid (Desborough and others, 1999).

A possibly related type of water is that which forms iron bogs and ferricrete. Iron deposits, whether thousands of years old or forming today, are symptomatic of natural acidic drainage in the Upper Animas watershed. Some studies suggest that the iron bogs are major contributors to the metal loadings in Cement Creek and Mineral Creek watershed (Owen, 1997; Kimball and others, 1998). Terrace deposits of iron adjacent to streams in the Mineral Creek watershed are prominent at many places, and numerous exposures indicate complex gradation of textures from hard, banded goethite to soft, spongy iron bog. These iron deposits in the Mineral Creek watershed are, in my opinion, unrelated to mining and the largest volume of iron is most certainly older than mining. The best examples of this point are the deposits at 11,500 feet elevation on the east side of Ophir Pass, and the well known deposits on the west side of Ophir Pass at Iron Springs (Hanshaw, 1974). Waters in these deposits today are highly variable in pH and conductivity, indicative of incomplete local mixing; the lower pH’s range from 5.9 to 2.7 and conductivities are generally in the range of 385 to 1550 µs. Chemically, concentrations of Al and Fe are highly variable, from 900 to 15,000 ppb, concentrations of Cu are 3 to 630 ppb and Zn ranges from 75 to 430 ppb Geochemical processes in these iron deposits are under study by others in the AMLI group, in particular to determine if the iron deposits are either sources or sinks for metals. Several of the problem mine sites in the Mineral Creek watershed described earlier are adjacent to old or modern iron deposits, and in some there is sufficient structural information to postulate a likely commonality of groundwater flows. Federal Land managers and regulators will have to decide if these commonalities are solely academic, or if they represent conditions that are important factors for defining reclamation or restoration goals.

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Appendix I: Description of Precision and Accuracy of water analyses

Water samples collected from mines and streams in the field, and also water samples generated in the lab in our leach tests were analyzed by a commercial laboratory using a relatively new method called ICP-MS (inductively coupled plasma—mass spectrometry) in which 65 elements (technically an isotope of each) were determined for masses from lithium to uranium. Experience with the laboratory over three years, plus analysis of replicate samples (repeat analyses of water from the same bottle or duplicate bottles collected at the same time) and of reference standards allows the following generalized comments on precision (reproducibility) and accuracy (approximation of the correct value).

1. The sampling methods, described elsewhere, and the ICP-MS analytical method are not those of the EPA and other technical protocols used for high precision, certified analyses of waters (see CWQCD, 1989).

2. Results are reported for five or six orders of magnitude for most elements of interest in these natural and experimental waters, from less than 0.1 ppb (part per billion or microgram per liter) to 100,000 or more than 1,000,000 ppb in some unusual waters. This is a difficult challenge for any method or chemist. These samples often required dilution by amounts of 1:10 to 1:100 to keep the analyte within the calibration range.

3. It is clear that precision and accuracy are complex issues and are not the same for all elements and all concentration levels. I assume that analytical error is greater at the very high concentration levels of some of my unusual mine or experimental waters, but documentation of that error is difficult and is incomplete at this date. Replicate samples suggest that precision is not much worse than at normal concentrations. Because reliable standards do not exist for waters with very high “trace” metal concentrations (>10,000 ppb), it is not possible to evaluate accuracy at high levels the way it is done at more normal levels. For reasons that I can not explain, the precision and accuracy for “major” elements (Al, Ca, Mg, etc) are much lower than for trace metals. The user of these results should consider them semi-quantitative with errors of about 50 percent in some cases (but less in others).

4. Based on standards and replicate samples, the precision for trace metals (such as As, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, Se, V, and Zn) appears to be about 10 percent (1 standard deviation) for normal water concentrations, and possibly 20 percent at very high concentrations. The accuracy of determinations on these trace metals seems to be about 10 percent for normal concentrations. The precision and accuracy for Fe, which generally is not a trace metal in these waters, is not as good as most others, and possibly is about 20 percent.

5. Some trace metals pose special problems. Mercury is analyzed, but it is well known that Hg is not stable unless preserved by special methods, thus for my samples the Hg originally in the water was not present in the analyte (the analysis is valid, but the sample

is not). Silver, a potentially toxic trace metal, should be high in many of my samples, but analytical results are erratic and nearly always very low (despite good results for neighboring atomic masses); results for Ag are not considered reliable. Results for Se, Te, and Tl appear to be reasonable, but no standards contained these elements; precision is about the same as for other trace elements.

6. These ICP-MS results are deemed satisfactory for the objectives of this study: classification or ranking of water compositions. The protocol used for four years in Arizona, Nevada, and Colorado AML studies (sampling, storage, analysis, and quality control) is reproducible from day to day, year to year, at a total error of about 20 percent for most trace elements. Many replicate samples have an error of about 10 percent, and a few have a higher error. These error numbers are best understood by examination of figure 8. The error bars show that an analysis for a metal with a concentration of about 10,000 ppb is reliably different from one having 1,000 ppb or 100 ppb. This is the real goal of these studies, characterization of sites with high to very high metal concentrations, not making a test for Zn at 220 vs 240 ppb to determine compliance with regulatory standards. For sample compositions within the error bar of 20 percent, relative to a standard of concern, further sampling and analysis is of course recommended.

Fig. 8: Diagram of analytical error for various metal concentrations.
This diagram shows graphically the magnitude of 5, 10, 20, and 30 percent error bars over an wide range of hypothetical metal compositions. Many of the trace metal determinations (e.g. Cu, Pb, Zn) have error bars like those shown for 10 percent, a few (Cd) may be closer to the 5 percent example, and some (e.g. Fe) are like the 20 percent example. This plot shows that even with high analytical error (20 or 30 percent) the reported values for about 10,000 ppb do not overlap those of a sample with 1,000 or 100,000. Thus the ICP-MS results are appropriate for ranking of water compositions spanning 4 to 6 orders of magnitude (1 to 1,000,000 ppb).

Table 2: Interim Ranking of Priority mining areas, USFS lands, Mineral Creek watershed, San Juan County, Colorado

Site name	**Nash** site	**CGS** site*	**Location (GPS)** N-dms	W-dms	**Rating**
Brooklyn	N588	261/4193-1.104, 204	37-51-40	107-42-55	High
Bandora mine	N648	253/4185-1.104	37-47-12	107-48-04	High
Bonner mine	N516	258/4191-2.100-200	37-50-35	107-44-18	Med
Ruby Trust	N524	257/4192-1.100	37-50-45	107-45-10	Med
Burbank mine	N603	255/4189-1.103	37-49-08	107-46-19	Med
Imogene mine	N511	259/4193-1.101	37-51-44	107-43-45	Med
S Chatt. Curve	N579	260/4194-2.104	37-52-26	107-43-58	Med
N Imogene mine	N512	260/4194-1.104	37-52-18	107-43-32	Low
W. Burro Bridge	N598	259/4192-3.103	37-51-03	107-43-45	Low
Paradise mine	N520	256/4191-1.100-102	37-50-33	107-45-52	Low
Up. Browns Gul.	N586	261/4193-2.102	37-51-48	107-42-24	Low
Bullion King	N594	258/4195-2.200	37-53-17	10744-32	Low
Silver Crown	N577	258/4194-1.100	37-52-18	107-48-40	Low
U S Basin	N582	263/4195-1.201	37-52-25	107-42-03	No
E. Burro Bridge	N596	260/4192-1.100	37-50-59	107-43-33	No
Low. Ice Lake	N611	253/4188-1.101	37-48-43	107-47-58	No
Chattanooga	N590	260/4194-2.104	37-52-22	107-43-11	No

* CGS site in Lovekin and others, 1997.

Plate 1: Color photographs of mines and mine drainage in Mineral Creek watershed, San Juan County, Colorado (next page).

A. Mine drainage below lower adit, Bandora mine, that is precipitating iron floc. The ditch was constructed in recent years to divert the drainage.

B. Eroded mine dump and mine drainage at Imogene mine. Storm events have eroded the dump and carried it onto the valley floor below.

C. View of the two adits and dumps at Paradise mine as seen midway between County Road and the mines.

D. Closer view of the Paradise mine dump and major flow of water that deposits white material. The white material is brighter than ice and highly visible from the County Road.

E. View of the Bonner mine dumps from the access road. The West Fork of Mineral Creek is in trees at bottom of photograph.

F. Mine drainage and orange-red iron floc on dump, lower adit, Bonner mine.

G. Orange-brown iron minerals precipitate in North Fork of Mineral Creek below junction with Porphyry Gulch creek. The iron mineral resembles the schwertmanite that is abundant in Cement Creek.