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Geochemical Investigations and Interim Recommendations for Priority Abandoned Mine Sites, BLM Lands, Upper Animas River 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 U. S. Bureau of Land Management (BLM) in the Upper Animas River watershed. Results of chemical analyses of dump materials, leachates of those materials, and surface waters draining mines or dumps provide indications of where acid is generated or consumed, and metal concentrations below mines or dumps. Information on sites previously identified as needing reclamation is reviewed and available geochemical information is used to rank 26 sites into four classes of priority for reclamation.

Although there are more than a thousand mining sites (productive mines and prospects) on BLM lands in the Upper Animas River watershed study area, the majority are very small (less than about 70 cubic yards of dump material), are more than 2 miles from a major stream, or so inaccessible as to prohibit reclamation. In the summers of 1997 and 1998 approximately 200 sites were observed and more than 100 of these that appeared to have the potential to geochemically impact the watershed were examined more carefully and sampled. Building upon the prior work of the BLM and associated agencies, this work attempted to identify the most significant sources of mine-related contamination and to rank those sites as to priority for reclamation. These most significant mining areas have been examined within a geologic framework and were evaluated by multiple criteria, including tendency to generate acid and release toxic metals, observed damage to vegetation, potential to release metals based on leach tests, and likelihood of transport into streams of the watershed. No single measurable parameter, such as metal concentration, can be used to rank the sites. Rather, subjective estimates are required to evaluate combinations or interactions among several parameters. The most subjective estimate, while ranking feasibility of reclamation, is the relative amounts of naturally occurring metals and acidity and mine-related contamination at each mining area. Mitigation of natural contributions at mines or unmined areas is beyond the scope of my studies, but should be considered when planning reclamation. Available information for the 26 priority sites is adequate for ranking, but at some sites additional information on groundwater conditions is needed for a more complete site evaluation.

Introduction

Mining at small and large mines, and countless prospect excavations, has disturbed millions of tons of mineralized rock in the Silverton area and has created chemical and physical conditions that may have degraded aquatic life in the watershed. The U.S. Geological Survey (USGS) has a program of integrated geological-hydrological-biological-chemical studies underway in the Upper Animas River watershed as part of the Abandoned Mine Lands Initiative (AMLI)to provide Federal land managers a scientific rationale for cost-effective restoration of public lands affected by historic mining (Buxton and others, 1997; Nimick and von Guerard, 1998). Information and interpretations reported here are part of the mine site, or metal source, component of the project. Others on the AMLI team are investigating diverse aspects of geology, geochemistry, hydrology, and biology that are pertinent to establishing pre-mining and existing conditions, as well as attainable reclamation goals.

Field studies by the author in the summers of 1997 and 1998 focussed chiefly on historic mines and prospects identified by others as being entirely or partly on public lands administered by the U.S. Bureau of Land Management (BLM); 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 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 nor change the interpretations.

This report will consider only sites on public lands administered by the BLM, which is the eastern half of the Upper Animas River watershed (fig. 1). My work in the field was guided by the maps and information generated by Hite and others in work done by the U.S. Bureau of Mines 1994-1995 (Hite, 1995), with updated information from the BLM (Hite, written commun.,1997). I attempted to start my work with an open, unbiased perspective, thus did not review the work by Herron and others (1998) until after reaching many of my own interim conclusions. Comments made here on specific sites are more descriptive interpretations than quantitative assessments. Ranking of magnitude of environmental degradation or priority for reclamation is complex. In my opinion, the geologic and chemical data that are available for these mine 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 (1998) and Wright and others (1998a), but there is no comparable measurement to quantify aspects of toxic metals in solids in mines or on mine waste dumps.

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 flowing through mined materials. 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 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.

Methods

Field and laboratory studies for this investigation utilized methods that were developed for the AMLI program and efforts have been made to maintain consistency among the 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 contract, information provided by B. Hite, currently with BLM and part of the Bureau of Mines study) or U.S. Forest Service (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 reasonably accessible sites within 2 mile of major streams that had dumps larger than about 70 cubic yards (Nash and others, 1998). Of the more than 500 sites identified by previous investigations, the majority are smaller than 70 cubic yards, and are unlikely to be significant contributors to the watershed and 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 $\pm$ 200 feet (based on real tests). On-site work included brief description of rock types, rock alteration and ore mineralogy, an estimate of size, and collection of a representative sample of the entire dump surface. 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 material. The composite sample, split from the total sieved material, amounted to about 2 kg. The -2mm fraction is deemed most likely to be involved in short-term reactions and contributing to runoff. Water draining portals and dumps was noted at 48 sites; pH and

conductivity were measured at these sites and at some a single reconnaissance water sample was collected from mine portals or below dumps for chemical analysis and comparison with leach tests described below. The field water samples were filtered through a disposable 0.45 µm cellulose filter and 1:1 ultrapure nitric acid was added to stabilize cations.

Lab studies were conducted to describe the bulk mineralogy and chemistry of the -2 mm samples, and their reactions in water. A suite of 120 samples was collected in 1997, including some dump samples from privately-owned sites, and some representative samples of mill tailings and unmined mineralized rocks, for comparison with the dump samples. X-ray diffraction (XRD) studies by George Desborough, USGS, have been made to determine the major minerals in the -2 mm dump samples; the limit of determination by routine methods is about 2 percent, but special methods were used to detect importance trace minerals such as anglesite ($PbSO_4$). 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 (K-Fe-Al-SO_4), 10% contain anglesite, 3% contain alunite (K-Al-SO_4), and 3% contain gypsum ($CaSO_4$). 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 designed by G. Desborough (Deaborough and Fey, 1997; Nash and others, 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 hrs; a sample is taken at 24 hrs using the same kind of syringe and 0.45 µm filter as used for field water samples. A few drops of 1:1 ultrapure nitric acid are added to stabilize cations. For both the tumble and passive leach tests, 60 ml of leachate is analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) that measures concentrations of about 60 elements, generally with a lower limit of determination of about 0.1 part per billion. Precision and accuracy of ICP-MS is variable across the large range of concentration of these samples, and by element, but generally is about ± 20 percent (Appendix I). Samples of dump rock, tailings, and altered unmined rocks were also analyzed for total chemistry by standard methods. The chemical results for leachates and dump samples are being evaluated for quality assurance and will be released as soon as the data are shown to be reliable or new results obtained.

Geochemical framework for evaluation

This report relies on the chemical analyses of mine dump materials, leachates, and surface water samples. Median and maximum values for leachate and surface water analyses are summarized in Table 1. Concentrations of metals in surface waters and in

leachates span a large range (figs. 2, 3); high concentrations at problem sites stand out by one to three orders of magnitude, as shown on the log scales. Because water quality standards for this area are currently being evaluated and revised, there are no clear and simple reference standards for evaluation of geochemical information at sampled sites. Also, the goal of this study is identification of significant sources of mining-related pollution that contribute to the watershed, not sites that exceed regulatory standards. Geochemical results will be described and ranked in the following ways: 1). Compositions of mined waste rocks and tailings, determined by total chemical analysis, are reported in parts per million, with the understanding that only part of the amount measured may actually be reactive and soluble under the conditions that exist. Because only 100 ppm of 1,000 ppm Zn in a dump sample may be soluble, this information on total chemistry is difficult to apply and is not emphasized in this report. 2). Compositions of water samples, determined by ICP-MS analysis that is not as precise and accurate (Appendix I) as methods used by regulatory agencies, are related to water quality standards for aquatic life (class 1, cold water) because that is the standard for the predominant use of the streams (fisheries). The analyses are reported by magnitude relative to the aquatic life water standard (ALWS) to emphasize the order of magnitude of the value, not the details and the complexities, and to avoid fixation on numbers in ppb that may not be appropriate or easily grasped. 3). Compositions of leachate solutions, determined in the same manner as surface water samples by ICP-MS, are described relative to the median for this study (78 samples), because there are no reference water quality standards for these analyses. The analytical values are similar to those for surface waters, and the ALWS might be invoked but this would be misleading. The emphasis is on high values relative to the study median, with the understanding that such high values are indications of high *potential* to release metals and acid.

Table 1. Statistical summary of selected results of leachate and mine drainage analyses, Animas River watershed, San Juan County, Colorado
[Chemical data from ICP-MS analyses, reported in parts per billion; pH in standard units; number of samples, dump samples, n=78; tailing samples, n=7; surface water samples, n=112; *, for pH the 'maximum' is the most acidic (minimum) pH]

	Dump sample leach		Tailing sample leach		Surface waters	
	median	maximum	median	maximum	median	maximum
pH	3.5	2.4*	4.5	3.8*	4.6	2.1*
As	1.8	3,575	0.3	1.2	0.9	>5,000
Cd	6.2	165	10.0	82.1	2.1	454
Cu	70.1	6,990	85.4	1,360	25.0	38,000
Fe	910	144,110	103	312	3,760	>999,999
Mn	241	37,370	83.0	7,990	817	87,200
Pb	137	11,710	--	23,150	3.6	2,520
Zn	423	30,870	642	25,180	649	117,300

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 Commission (1988 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 for 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 Animas River watershed have been set by CWQCD according to use of the water, which generally is that for aquatic life-cold waters; these values are the same as for 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 for these mine-related waters are highly variable, with extreme examples at 14 and 1,280 mg/L $CaCO_3$, and a median of 195 mg/L. Hardness corrections were not made for my results because to do so would imply more precision than appropriate in these hydrogeochemical studies. The values in table 2 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; Owens, 1997; Herron and others, 1998a; and others, 1998; Kimball and others, 1998; and work in progress in 1998) for more specific data and regulatory concerns.

Table 2: 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; 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 River watershed is well established from many excellent studies over the past century, especially those of Burbank and Luedke (eg. Burbank and Luedke, 1964; Burbank and Luedke, 1969; Luedke, 1996), and from mine studies as by Ransome (1901), and by Casadevall and Ohmoto (1977). 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' (or circular volcanic subsidence structure) which largely determined the distribution of rock units, structures, rock alteration, mines and prospects (fig. 4). 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 some of the most degraded waters in the study area (or on the Western Slope of Colorado) 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, Bove and others, 1998), with important influence on waters today. In simple terms, volcanic rocks that are altered to shades of green (introduced chlorite, epidote, and often calcite) tend to buffer waters to near-neutral pH even if pyrite is present, whereas the white or red altered volcanic rocks (rocks that were leached, altered to sericite, kaolinite, or alunite millions of years ago, and turn red as pyrite weathers) tend to create or enhance acidic conditions (Smith and others, 1994; Bove, and others, 1998; 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 River 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 kinds 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. Manganese minerals (rhodonite and rhodochrosite) are locally abundant in some veins (Plate 2, fig. B), and tungsten (as wolframite, a Fe-W-oxide) and fluorine (fluorite) are abundant in some places.   These deposits tend to occur along major faults, either inside or outside the caldera, and have argillic alteration haloes of pyrite and clay minerals tens of feet wide. There are significant differences in wallrock composition and mineralogy, especially for deposits outside of the Silverton caldera that tend to be either sedimentary or green propylitic-altered volcanic rocks—either of which have moderate buffering capacity that provides important natural mitigation of acidic waters. 2). Polymetallic breccias, 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. It is the peripheral alteration halo of pyrite (unmined rocks) that creates natural acidic drainage today and thus is of concern for environmental impact (Bove and others, 1998). 4). Placer deposits of gold in alluvial gravel; these deposits were mined in a few places such as Arastra Gulch but will not be mentioned further. The placer deposits are a reminder that mineralized rocks 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 River 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 And we must remember that zinc, one of the potentially 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 in many of the older workings zinc-rich rocks were intentionally left underground. It is counter-productive to describe the mines by economic or commodity terms because the rocks remaining in the mines or in mine dumps and their environmental geochemistry bear no useful relation to that classification.

Structural geology is important for the flow of ground waters in this watershed of high relief. Just as structural geology was emphasized for exploration (Burbank and Luedke, 1968) and for ore genesis (Casadevall and Ohmoto, 1977) because structures controlled the flow of ore fluids, many of these structures also are important controls on groundwater flow. Details of fracture-flow hydrology are complex. For example, major structures that would seem to be prime for flow, may be clogged by fault gauge and clay, and thus allow no flow or even serve as a barrier. Younger, post-mineralization, fractures and cross-fractures often are major carriers of water. More attention needs to be given to the description and role of fracture systems in groundwater regimes in the Upper Animas River watershed.

Scale of deposits and associated alteration is an important attribute to bear in mind. As mentioned above, 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 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 to the mine or the mineralized orebody: the large polymetallic veins worked by the Sunnyside mine or the Mayflower (Shenandoah Dives) mine have relatively narrow alteration haloes, whereas the small breccia pipe deposits can have much larger alteration haloes of rocks that now are red.

Changes in mining and milling technology over the years have had 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 broken out: 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 floatation to recover separate kinds of sulfide minerals. The change in style was first made at the Sunnyside mine and associated new mill built in 1917. In this stage mine tunnels reached 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 created. 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 are potentially reactive and contributing metals to groundwater because they were not placed on an impermeable base. 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 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). Building on the studies of Herron and others (1998), I offer general comments on amenability to reclamation. My interim recommendations have more of a base in geology than the other investigations, and my estimates of geologic parameters lead me to different ratings for some of the mines or mining areas than some previous studies.

Description of Priority Sites

An interim list of priority sites on BLM lands (Table 3) was developed after my field studies, interpretation of chemical analyses, and discussions with BLM staff. The sites listed are generally consistent with the evolving list of priorities developed by Hite and others of BLM, with some additional sites that I consider significant. Localities are shown on figure 5. Land ownership status of some sites has changed as the result of careful cadastral surveys by BLM in 1997 and 1998. The complex mosaic of land ownership in the study area greatly complicates objective study, especially on sites that are of mixed private (patent) and public ownership. The mixed ownership generally develops in places where the vein or lode is covered by a patent, but mine dumps or other mine-related waste has been placed on public lands. At some sites it was not possible for me to reliably determine property lines and to know if I was sampling on private or

public portions: my studies were designed to improve the understanding of the sites and potential sources of contaminants and the impacts they might have on water quality, not to determine ownership or responsibility. Most of the sites have no formal names, or names have changed over the years, thus will be referred to by site numbers assigned by the Bureau of Mines (Hite, 1995) , such as B060 (the B to distinguish from the N series of site identifiers for my work.

Site B001 [N225] priority H: This site in the middle portion of Cement Creek, west side near Georgia Gulch, was originally believed to be on BLM lands, but a survey in 1997 suggested that it is private. It is called the Mammoth Tunnel by Herron and others (1998) and described as a crosscut intended to intersect the lower part of the vein system worked by the Henrietta mine, but it probably did not reach the target. Some implications of this history are: a). the mining did not encounter ore, and b). it is a deep tunnel under the mountain and collects water from a large volume in the same manner as a mine drainage tunnel. The jeep trail to the Kansas City mine crosses the dump. The dump of moderate size is mostly covered with fine-grained red iron oxide materials deposited from mine drainage (Pl. 1, figs. A and B). The chief concern here is the flow of water from the collapsed mine adit, about 30 gpm with a pH of 4.8 and conductivity of 990 µS/cm, but the water evolves to a pH of 3.2 and 1,300 µS/cm conductivity after reacting with the dump materials. Water at the collapsed adit is very rich in Fe and Zn (26X and 14X ALWS) and rich in Cd, Cu, and Mn (1.7X, 1X, and 3.2X ALWS); a second sample in 1998 had a pH of 4.5, and the analysis showed similar high metal concentrations (but Fe and Zn were even higher at 50X and 20X ALWS). A 1997 water sample from the toe of the dump has approximately the same levels of Cd, Cu, Mn, and Zn as at the adit, but Fe has decreased to 17X. The passive leachate solution carries very high concentrations of zinc (above the median for this study), and high concentrations of Pb and Cd (near the median). The leachate analysis suggests that the dump has the potential to release more base metals than are seen in the water samples. Reactions in this mine dump are complex and merit further study.

There are several lines of evidence that site B001 is a significant source of Fe, Zn, and Cd, which are metals of major concern in Cement Creek. Because the new cadastral survey suggests the adit and dump are not BLM land, it is not clear who might do reclamation that should focus on the mine drainage. The waste rocks also are a source of metals and would be a smaller factor if the mine waters could be diverted around the dump.

Site B009 [N311] rank H: This small mine on the west side of Cement Creek, south of Fairview Gulch, is well known for the huge flow of water from its collapsed portal. The mine is called the Elk Tunnel by Herron and others (1998) who estimated the flow at about 170 gpm. As of 1998 the water flowed down the hillside, across the jeep trail (Pl. 2, fig. E),and into Cement Creek. The drainage has a pH of 6.4, which normally suggests that it should carry small amounts of metals. At this site the water carries high concentrations of Fe , Mn, and Zn (4X, 1.4X, and 3X ALWS) , thus this is a significant loader. Other metals such as Cu and Pb are very low, as expected of near-neutral pH waters. Analyses of tumble and passive leachates of dump rocks show that the dump

contributes moderate amounts of Cu, Cd, Fe, Pb, and Zn, close to the median for dumps in this study. This dump does not appear to be a significant source, and would be even less of a metal contamination factor if mine waters did not wet the dump.

The high flow of water from the tunnel, combined with high concentrations of Fe, Mn, and Zn, makes this a significant source and a high priority for reclamation. The short distance to Cement Creek means that there is little opportunity for natural processes to attenuate the metal concentrations. The high flow and relatively high pH of this mine drainage may be more complex to treat than at most sites (Herron and others, 1998).

Site B014[N307]: rank L: This mining area in lower Minnesota Gulch comprises at least six adits and a shaft, on both sides of the steep canyon. There is no vehicle access to this part of the canyon. Several of the dumps appear to be smaller than 70 cubic yards. An adit on the south side produced a small dump, a few hundred cubic yards, of very sulfidic rock, but there are no indications of acid generation or significant flow of water. The easternmost adit, my site 307, bears southwest and appears to be the largest and most significant mining activity, creating a dump of possibly 700 cubic yards. Water drains from the adit part of the year, but was dry in August of 1997, thus no water sample could be collected. A trail of tell-tale bright orange-red Fe-oxide materials on the dump testifies to intermittent acidic waters. The dump contains pyrite-rich rock, as at the dump a few hundred feet to the west. No leach tests were made on this dump material.

This mining area is given a ranking of low for the following reasons. The individual dumps are relatively small and either dry or only seasonally subject to flow of surface waters. There is evidence for acid mine drainage (AMD) in the red oxide coatings, but the acidic waters do not appear to move much beyond the dumps. Seasonal surface waters in Minnesota Gulch appear to infiltrate the alluvial fan before reaching Cement Creek, and any mine drainage probably would do the same, with greater possibilities of natural attenuation of pH and elevated metal concentrations. There is no road access to these sites, which obviously complicates reclamation activities. The dumps are not visible from a road. Minor amounts of reclamation could be done using hand tools, with some beneficial results. A major effort does not appear to be warranted or cost-effective.

Site B021 [N192]Rank N: This mining area is in an area of red-weathering pyritic alteration, on the flank of a ridge between Red Mountain Number 1 and 3, where there are about 8 adits and 5 shafts that tested pyritic veins. The closest access is a drill road along the ridge spine, originating at Corkscrew Pass. This is one of the larger of the small dumps, about 1500 cubic yards, produced from a shallow shaft. The dump is very rich in pyrite (> 10 percent) and is scattered down the steep slope. There is a small kill zone in the alpine tundra below the dump. Leach tests produced one of the most acidic pH's of those we tested, and the acidic leachate carries very high concentrations of Fe (highest among those tested), Cu, Pb, and Zn. The shaft is filled with water that does not drain to the surface. The mine water has a pH of 2.9, and carries very high concentrations of Cu and Fe (28X and 36X, respectively, relative to ALWS), but low concentrations of Cd, Pb, and Zn (well below ALWS).

It is suggested that little or no reclamation is appropriate at this dump. Access is very difficult. Water does not flow from the shaft (but presumably seeps into the subsurface). This small mining operation, like many others in this alpine basin, tested one of the many pyritic alteration zones and a case can be made that this is mostly natural material—simply brought to the surface in the dump. Because there is so much more of this material (mined and unmined) in this basin, it seems that reclamation of this dump would have a miniscule effect on the waters in Dry Gulch creek and Cement Creek to the south.

Site B022 [N235]Rank L: This mining area is known as the Kitti-Mack mine, one of the more famous old-time mines in the north-eastern part of the Upper Animas River watershed. One or more tramways carried ore to mills lower on the mountain: an early one at middle elevation (probably water powered), and a newer one at the base (and which created the fairly large tailings impound near Middleton). The dump is larger than most on BLM lands, about 9,000 cubic yards. The dump is more gray than the usual red-brown hues of most dumps in the area, possibly from manganese staining, and contains prominent white quartz fragments. Leach tests of the dump material yielded higher than median amounts of acid, Cu, Fe, Pb, and Zn. The source of the acid and metals is not obvious—but may be in the fine-grained matrix of the dump.

Water flows from the collapsed lower adit at a rate of about 30 gpm, and is crudely channeled across the dump. The pH of 6.3 is much higher than most mine drainages in the study area. Testing the mine drainage in 1998 showed a pH of 5.5 and somewhat higher conductivity than measured in 1997. Despite the near-neutral pH, the water carries substantial amounts of some metals of concern: Cd, 6X, Cu, 11X, and Zn, 20X (relative to ALWS). The 1998 sample composition was very similar to that of the 1997 sample for most metals, but Cu and Zn were a bit higher (25X for Cu, 30X for Zn, relative to ALWS). This water flows over dump material and infiltrates alluvium and talus just below the dump. The pH of the water at the base of the dump is slightly more alkaline and the conductivity is slightly higher, suggesting that reactions with the dump rocks do not change the mine water composition much (but no sample was collected to determine actual concentrations). There are no indications of the usual red iron coatings indicative of AMD, and the lack of these precipitates may indicate that the base metals will not be removed by adsorption reactions. In other words, copper and zinc may be more mobile and travel farther in these near-neutral, low-iron waters, as explained by Smith and others (1994). The predominant green-altered volcanic rocks in the mine area may have mitigated mine drainage prior to discharge, and may or may not further reduce metal concentrations because the pH is near-neutral at the portal. More specific studies of this atypical mine drainage are suggested. Drilling of a well to monitor water below the surface would allow sampling of shallow groundwater to better understand water compositions after the mine waters react with rocks and mix with normal waters.

Site B049 [N260] rank L: Highland Mary mine dump. This large dump (>50,000 cubic yards) has been partly reclaimed in recent years, obscuring former mine workings (Pl. 2, fig. C). This site is part of a much larger infrastructure of interconnected mine workings

at depth and to the northwest, possibly including the Shenandoah-Dives-Mayflower mine complex (Ransome, 1901; King and Allsman, 1950) which reportedly are on the same vein. Mining in the period 1947-1955 was in close proximity, but it is not clear if the workings actually were connected. Considering the structural control and the short distances between mine workings, it is possible that drainage from the Highland Mary mine actually flows to the northwest and into the lower levels of the Shenandoah-Dives-Mayflower mine. Also, an adit near the Highland Mary mill trends south and could be draining parts of the Highland Mary mining area. According to Ransome (1901), several tunnels were driven southwestward to intersect veins in the Silver Lake area. These many tunnels could explain why the dump appears to be dry and shows no signs of mine drainage.

The dump rocks contain more vein-filling calcite than any other site I have seen in the study area.   One of the structures in the mine is called the spar fault, presumably after calcite on the structure. Although no dump material has yet been examined in leach tests, I am confident that it would not produce acid and most metal cations would be immobile. Tests will be made in the future to measure the mobility of As, Cd, and Zn, which are known to be somewhat soluble under neutral to alkaline pH. Much of the early mining at Highland Mary (Ransome, 1901) was in Precambrian schist; minerals such as hornblende in the schist probably would have substantial ANC, to supplement that of calcite. This dump sits high above the valley and does not appear to be a significant source of metals to Cunningham Creek basin. The dump is accessible, so additional grading or covering of mineralized materials could be done relatively easily.

Site B052 [N218] rank H: This mining area is in Prospect Gulch, a tributary of Cement Creek, on the flank of Red Mountain No. 3 (Pl. 1, fig. E). There are several adits and shafts on this north side of the gulch, and exploration activity reported in Colorado Mining Yearbook (1953) indicated that several of the workings were operated by the same company. The Lark mine is a short distance to the west. This area is commonly referred to as the Joe and Johns mine (Herron and others, 1998). Work in the 1950's apparently connected the Joe and Johns to the Lark in an effort to dewater the Lark, but there has been no confirmation that the work reported by the mining company actually reached its target (Bruce Stover, oral commun., 1999). A substantial amount of water flows from the Joe and Johns adit, and much of it may relate to the Lark mine workings.

The dump is a complex mixture of mine waste, avalanche debris, and alluvium (road base) spread from the bed of the County road 35; the material at the surface appears to be roughly one-third mine waste. Passive leach tests on an average sample of these materials (mine rocks diluted by alluvium) produces more acid than the median, and higher than median concentrations of base metals. The concentrations of Cd, Cu, Pb, and Zn are notably high.

Water flowing from the collapsed portal at about 10 gpm is a major concern. My sample of water from August, 1997, yields high acidity and metal concentrations, similar to those obtained by many other scientists. The pH of 2.7, is very low and a warning of likely high metal content. My chemical results by the ICP-MS method indicate some of

the very highest values of any mine waters sampled in the area. The noteworthy concentrations, relative to ALWS, include: As, 2X; Cd, 55X, Cu, 40X, Fe, 29X, Pb, 46X; and Zn, 140X. Although the flow from the adit is not large, these high concentrations indicate that this site is a high loader of metals; details of metal loading are under study by others.

Site B060 [N303] rank M: This mining area is on the west side of Cement Creek, and west of the road; it is commonly known as the Culvert or Mayday mine (Herron and others, 1998). Because this dump is being studied in detail by others, my work here was limited. The dump is large, amounting to more than 35,000 cubic yards, and visual inspection reveals high amounts of pyrite, galena, and sphalerite in local piles, but there is only moderate sulfide in most of the dump. This dump possibly contains more clay than others, but the lack of puddles after summer thunderstorms suggests that permeability (infiltration) is good. Several leach tests have been made by G. Desborough and others of the USGS to understand in some detail the processes of acid generation and metal mobilization. Two representative samples from the Mayday dump, collected in the same manner as others in this study and tested by the same passive and tumble leach procedures, yielded pH's of 3.2 and 3.4 (more acidic than the median). The leachates contained high concentrations of base metals, with notably very high concentrations of Pb from one sample. Concentrations of Cu were near the median for this study area (table 1), for Zn were near the median in one and higher in another, and for Pb were at the median in one and much higher in a second sample. The large difference in results for the two samples is consistent with visual estimates of different material at the surface, and perhaps indicates that additional samples and tests are needed if these indications of high metal mobilities is not sufficient.

The mine portal (protected by a large diameter steel culvert generally used for roads) is open and was dry in August of 1997, and the dump was 'dry' (technically, it was damp from summer rains). There are no indications of substantial amounts of mine or dump drainage, but runoff may occur at times. The greatest problem may be percolation of snowmelt or summer rainfall into the dump, generation of acid, and mobilization of metals into alluvium and shallow groundwater below the dump, and then lateral flow into the nearby Cement Creek.

Comments added after first writing: Discussions with several people at a meeting with BLM-USFS-AMLI staff in Durango, Feb. 2-4, 1999, demonstrated that some of my perceptions, above, underestimate the impact of the Mayday dump. Two lines of new evidence indicate that there is significant mobility of metals into shallow groundwater and then into Cement Creek: a). sampling of wells drilled into the eastern side of the dump, and b). sampling of Cement Creek as part of a tracer study undertaken by Kimball and others in 1997 (Kimball and others, 1998; Walton-Day and others, 1998). Both of these water studies document high concentrations of metals that must be coming from the Mayday dump. Because the dump is dry for most of the year, the water is probably related chiefly to surface and subsurface flows to the west and above the mining area, and probably augmented by snowmelt or rainfall that infiltrates the dump. Details of the

chemistry and flows of water will be described and interpreted by others on the AMLI project.

These additional findings are significant for more than the Mayday mining area: these results and inferences for shallow groundwater are a warning that we may be underestimating the importance of groundwater as a pathway for metals from dumps to streams in many other parts of the Upper Animas River watershed. The unconventional writing style, above, is used to show the reader how different the interpretations are, before and after the supplementary studies and data. Our studies of mining areas in the Upper Animas River watershed clearly are not able to sample all sources and pathways, and we must make the best interpretations we can with limited information. In the specific case of the Mayday dump, we need to acknowledge the important role of groundwater transport of metals and to raise the ranking from medium to high priority. Identification of the role of groundwater also has important implications for reclamation at Mayday and elsewhere. The use of wells to sample and monitor shallow groundwater clearly is effective and is recommended for other mining areas.

Site B070 [N430] rank L : This mining area is at the base of Kendall Mountain, immediately east of Silverton, and the toe of the dump is about ten feet above the floodplain of the Animas River. The dump is fairly large, about 3,000 cubic yards. The dump appears to have low sulfide content and is lighter in color (less iron?) than the adjacent unmined ferricrete on the hillside. The adit is caved and there were no signs of mine water or AMD in September of 1997. The dump is visible from the town of Silverton. No sample of dump material has yet been tested for leachable metals and acid generation.

This adit and dump appear to pose few problems chemically, but the location of the site may be sufficient to justify reclamation work to minimize potential for erosion into the Animas River.

Site B072 [N204] rank H: This site in the upper part of Prospect Gulch (Pl. 1, fig. E), above Cement Creek, is known as the Lark mine, or Lark #3 level (the lowest level of the Lark workings). The site is described in detail by Herron and others (1998). The Henrietta mine to the south may have worked the same vein system, and the Joe and Johns mine to the east worked a parallel vein. In the 1950's a crosscut was made to connect the Lark with the Joe and Johns adit and allow water to drain to the lower elevation, but this report has not been confirmed. If water does drain to the Joe and Johns tunnel, this would explain the relatively small flow from the lowest level of the Lark mine. In addition, water from the Lark could flow along a fracture zone into alluvium or bedrock before reaching the portal.

The dump has been graded into two levels, with roughly 35,000 cubic yards of rock on each level. The upper dump contains large amounts of rusty colored rock that is alluvium from the hillside, not mined rock. Two samples were collected in an effort to obtain average material from the upper and lower dump levels. Leach tests confirm what is expected of the visibly sulfide-rich dump rocks: both samples generated more acid

than the median, and Cd. Cu, Fe, Pb, and Zn concentrations in leachate were higher than median values. The sample from the lower dump level, generated a lower pH and nearly twice the metal concentrations of the upper level sample. The upper sample includes alluvial material, thus is somewhat diluted; the lower sample probably is most representative of the inner, unexposed part of the dump. It clearly is reactive and a potential source of both acid and metals.

A small seep of water comes from the collapse adit. The water has a pH of 3.1 and it infiltrates the dump within about 20 yards of the adit. Chemical analysis shows very high metal concentrations relative to ALWS: Cd, 20X; Cu, 42X, Pb, 12X, and Zn 64X. The small, seasonal flow suggests a relative low loading for these metals. However, larger flows may exist in the subsurface. A spring south of County road 35 is located on a logical (but unproven) continuation of the Lark structural system (Burbank and Luedke, 1964), has extremely low pH, high conductivity, and even higher metal concentrations than those described above. Also, if the reports are correct, water is diverted into the Joe and Johns tunnel, so that site would have to be included in any reclamation plan for the Lark mine. The hydrology and chemistry of waters in this area are described in detail by Wirt and others (1999).

The Lark mine and dump are given a high priority for reclamation because the dump materials are potential sources of highly mobile metals, and there is evidence for mine waters at the surface carrying metals. Geologic and geochemical evidence at the Lark mine are consistent with the model for ore deposits associated with acid-sulfate alteration (Plumlee and others, 1995) in which both the mines and the unmined rocks have tendencies to produce very acidic, metal-rich waters; these systems are problematic for both their sources of metals and acid, and for the lack of buffering capacity to naturally mitigate acidic drainage from mined or unmined sources. The hydrology may have similarities to the Mayday mining area, previously described, including the potential for possible sub-surface flow of acidic, metal-rich waters into Prospect Gulch. As at the Mayday dump, drilling of wells would allow specific measurements of subsurface water quality and flow. Another complicating factor is the likely contribution of acidic, metalliferous waters from unmined, sulfidic rocks of Red Mountain #3 along the same structures that host the Lark ores (Burbank and Luedke, 1964). Reclamation at Lark will be complicated but feasible and a significant improvement to water quality in Prospect Gulch.

Site B101 [N335] rank L : This mining area is in the vicinity of the Kansas City mine in the upper part of Georgia Gulch. There are two very small adits in a narrow alteration zone. The dumps have been disturbed by avalanches or episodic flow of water in the narrow gulch. The dumps remaining are smaller than 70 cubic yards. Water was not flowing from the mine workings when visited in September, 1997. There are indications of iron-oxide minerals deposited from surface waters—which could be either natural drainage from altered rocks in the gulch, or mine drainage. The sample of dump material has not yet been put through leach tests.

This site is given a low priority ranking because the dumps are very small, and there is little if any mine drainage. Also, it is difficult to distinguish contributions from the small mining operations from the adjoining unmined, altered rocks. Depending upon final restoration standards for the study area, this site may not merit any reclamation work.

Site B105 [N201] rank L : This is a small adit and dump above Dry Gulch, about 100 yards north of the Prospect Gulch Road (County Road 35); it is called the Margaret mine by Herron and others (1998). The adit was excavated into an outcrop of ferricrete. The water flowing at about 10 gpm from the adit has a pH of 3.1 and carries elevated amounts of many metals. Concentrations of Cu, Fe, and Zn are 6 to 9X the ALWS, whereas the concentrations of As, Cd, and Pb are high but close to the ALWS.

Leach tests suggests average to below average metal mobility. The dump is small and not highly reactive, but very close to an intermittent creek that feeds into Cement Creek. Reclamation should be done to divert mine and surface waters from the dump materials.

Site B116 [N309] Rank M: This small dump (about 1,000 cubic yards) and adit are located east of Cement Creek within an unnamed gully, across from Fairview Gulch (Pl. 1, fig. H). The adit is partly open and drains water at about 10-20 gpm, which flows without constraint across the dump. The mine drainage infiltrates dump and alluvium before reaching the gully and its seasonal creek. The chief concern here is the mine drainage.

The mine drainage has a pH of 3.8, close to the median. The waters carry very high concentrations of Fe (22 X) and Cu (7X), while Zn is slightly elevated (3X) relative to ALWS. It is not known if the drainage picks up more metals while infiltrating the dump, but the leach tests suggest this should not be a major factor.

The dump is lighter in color than most, possibly from a high content of clays. Pyrite is abundant in places, but overall is lower than most dumps in the watershed. The leachate pH of 3.38 is slightly more acidic than the median of 3.50. The leachate carries low concentrations of base metals.

This site has no vehicle access, but is a short walk from the Cement Creek road. One option for reclamation would be to use simple equipment to divert the mine drainage away from the dump. This dump is small and not highly reactive, thus does not appear to be a significant contributor.

Site B123 [N175] rank H: This mining area is in Ross Basin, high in the headwaters of Cement Creek (Pl. 1, figs. C and D). It is called the Grand Mogul-East Adit mine by Herron and others (1998; site #26). The lode is probably patented and the dumps probably are on BLM lands and would represent one of the larger waste dumps on BLM lands (estimated at about 35,000 cubic yards). The adit is collapsed. There is no visible drainage at the former opening of the adit, but water seeps from beneath the dump and

probably is related at least in part to the mine workings. The mine workings, mine wastes, and other features are described in fair detail by Herron and others (1998). Because of uncertainties in property boundaries, this site was not included in the early studies by the Bureau of Mines (Hite, 1995) and was not included on the early list of priority sites. I was impressed by the site when I visited it in 1997 and on two subsequent visits. The dump contains unusually high amounts of visible pyrite, sphalerite, and galena, and the seep from the toe of the dump is distinctly red—the first such waters in the northern reach of Cement Creek. Alpine vegetation is killed for several hundred feet to the southwest, along the dump seep. Because alluvium fills the valley at this site, much of the drainage from the collapsed adit, and from the dump, probably flows below the surface (as groundwater), yet 20-40 gpm is evident at the surface in August.

The water draining through the dump is badly degraded. The pH of 3.3 is low, and the concentrations of Cu and Zn are very high (100X and 110X ALWS), and concentrations of Cd, Fe, and Mn are high (40X, 2.8X, and 2.2X, respectively). The concentration of Pb is close to ALWS, despite suggestions from the leach tests (see below) that it should be higher. The source of this water, and of the metals, is not tightly defined—the water clearly flows through the dump (and probably extracts metals), but the source is probably to the northeast in the collapsed mine adit. The surface water evident at the toe of the dump is certainly a minimum estimate of the water impacted by the mine workings and dump. Further work is needed to quantify the water discharge, such as opening the adit to permit sampling of water inside the tunnel, or drilling monitor wells into alluvium near the dump to test the composition of water flowing in alluvium or possibly in structures in bedrock.

The dump is visibly rich in pyrite, sphalerite, and galena. Leach tests show these materials are highly reactive and produce some of the highest metal concentrations in this study. The leachate pH of 3.3 is not much more acidic than the median, but the metal concentrations are in the upper quartile. Relative to ALWS, the metal concentrations in leachate include: Cd, 60X; Cu, 25X; Fe, 2.8X, Mn, 2.2X, Pb, 460X, and Zn, 164X. The lead concentration is extremely high, only four other samples yielding higher amounts. Considering the large tonnage, this dump would appear to be among the largest potential or active sources of metals from mine dumps on public lands, and thus is given a high priority for reclamation.

Site B152 [N298] rank L : This mining area is south of Silverton, near the switchback on US550 called "Dead Man's Curve", and one of the few mines on BLM lands that occurs in Tertiary granitic rocks. The dump is quite large, possibly 15,000 cubic yards, and a substantial amount of water flows from the closed adit.

Water flows around the edge of the large dump in a fairly well constructed ditch at a rate of about 20-30 gpm. The pH is 6.9, one of the highest (meaning good) of the mine drainages sampled, and the concentrations of metals are very low for a mine drainage, all below the ALWS. The pH of the mine drainage would suggest buffering by alteration minerals in the granitic rocks. The mine water pH is distinctly higher than the

pH of the leachate at 3.7, indicating that acid generation by sulfide minerals exceeds the buffering capacity of the dump rocks. This is one of the few examples where the leachate pH differs significantly from the measured pH of the mine drainage. The leach tests suggest that the dump has the potential to liberate more metal and acid than the mine workings. The metal concentrations in the leachate are moderate, but higher than the mine water. These observations suggest that the mine drainage is not a problem now, and if it is diverted from the sulfidic dump rocks, the mine (adit drainage plus dump) will not contribute much to the watershed. The leach tests suggest that the dump is a potential source of acid and metals, and therefore reclamation work to minimize this release should be considered. The dump probably releases metals by way of infiltrating waters, and these can only be monitored by wells.

Site B156 [N231] rank M: This small mine and dump are east of the Animas River, about a mile north of Middleton; the mine is commonly known as the Forest Queen. The site is the subject of several detailed studies because of concerns that the mine drainage may be impacting the nearby wetlands. My examination in 1997 was done in the same manner as others, but I collected two water samples to test for changes in water composition between the portal and the wetlands due to reactions in the waste dump. My water sample 231, collected at the collapsed adit, had a pH of 5.1 and conductivity of 830 μS/cm, whereas sample 232, collected at the outflow from catch pond, had a pH of 5.3 and conductivity of 1150 μS/cm. These simple tests suggest that the dump materials, or possible reactions in the pond, raised the pH slightly and added dissolved solids. Chemical analyses by ICP-MS are more informative: the concentrations of most toxic metals decreased 10-30 percent, whereas Ca and Sr from rock-forming minerals increased in the pond outflow. Relative to other mine drainage samples and the ALWS, the adit water (231) is less acidic than most, and only Fe, Cd, and Zn are highly enriched. The concentrations of Cd, Fe, and Zn exceed ALWS (8X, 12X, 7X). This adit seems to be like quite a few others that have moderate acidity (pH 4.5-6), and very high iron content, but moderate to low content of other metals. It is likely that the mine waters were initially more acidic, perhaps akin to the leach pH of 3.3, but have been partly neutralized—and in the process perhaps Cu and Pb have precipitated inside the adit, but Fe-Cd-Zn remain soluble in the evolved water.

The dump is relatively small, about 1,500 cubic yards, and has been reworked to create a settling pond. The mined rocks are heavily coated by iron oxides deposited over many years from the mine drainage, but are not obviously rich in sulfide minerals. The dump sample collected for leach studies was intended to be an average of the dump, including the iron oxides. In the leach tests, the leachate pH of 3.3 was slightly more acidic than the mean, and suggests the materials have the potential to generate acid. Of the base metals, only Pb was higher than the median concentration. In the actual waters, the concentration of Pb is lower than the Pb concentration of the leach test, probably because the pH is higher.

There are several lines of geochemical evidence to suggest that the Forest Queen adit drainage and dump are close to the median of this study for acidity and metal mobility. The physical situation of the mine next to a wetland suggests that it may have a

higher impact on the biological environment than at other drier localities, and this concern warrants further work. Discharge of mine waters into alluvium below the adit and dump is quite likely here, but can not be tested without a monitoring well. Based on interim information, including considerations for the physical situation, I would rank this mining area as a medium priority for reclamation. This is not to say that reclamation is not needed, rather, that others sites appear to be contributing higher metal loadings and are in greater need of reclamation to improve the overall watershed.

Site B169 [N144] rank L : This mining area is a cluster of small prospects (x's on topographic map) and adits in the canyon of the North Fork of Animas River, about a mile north of Animas Forks. The entity B169 was defined by Hite and others (1995) as a 'site' and covers more than ten excavations. Here I will refer to only one mining site, a small adit, east of the river and in the middle of the cluster. A short jeep road, east of the main road to Engineer Pass, angles southeast across the edge of the small mine dump (possibly 2,000 cubic yards). The dump is fairly typical of mines in this area, containing abundant course-grained pyrite, but no visible galena or sphalerite. A chemical analysis of a dump sample reveals high concentrations of base metals relative to unmined rocks, but values very close to the median for more than 100 dump samples in this study. The leach tests show the dump material generates a pH of 3.4, near the median for dump materials, and the metal concentrations in the leachate are below the median.

A small amount of water flows from the collapsed adit, well under 10 gpm. The pH of 5.7 is above the median for mine waters, and the conductivity of 80 μS/cm is very low (indicative of low dissolved solids). Concentrations determined by ICP-MS are consistent with the low conductivity; specifically, base metals are much lower than most mine waters, and only Zn is above the ALWS (2.7X).

This site appears to be contributing very little to the North Fork. The dump is typical of thousands in the study area, and because it is dry for most of the year and not very large, it probably contributes only a small amount to the load in the North Fork. The mine drainage has very low volume and the metals in solution are less concentrated than in most mine drainages. Because the adit and dump are adjacent to a side jeep road that is used by the public, this site is highly visible and this might be a factor when considering reclamation options.

Site B219 [N713] Rank N : This area of several small adits and dumps on the east side of California Gulch has prominent black coloration produced by manganese oxides. Large quartz-sulfide-rhodonite ($MnSiO_3$) veins are exposed and shed fragments down the hillside; the veins and clasts are presumably the source of the Mn staining. The dumps are small, about 100 cubic yards each. A small amount of water, less than 10 gpm, seeps from one of the collapsed adits. The mine drainage has a pH of 3.2, and chemical analysis shows very high metal concentrations. Relative to ALWS, the values are: Cd, 56X; Cu, 35X, Fe, 20X, Mn, 87X, Pb, 1X, and Zn, 54X. These high metal concentrations were previously determined by the Bureau of Mines (Hite, 1995) and their ranking system flagged these waters as a high priority for reclamation. No leach tests have yet

been made for materials collected in 1998, but that will probably not change the geochemical story significantly.

This mining area is a good example of choices in the ranking and decision-making process. If one looks solely at chemical results, one reaches the conclusion that the drainage and dumps demand reclamation. If one acknowledges that several large veins outcrop here, and that the mining created only small openings along the veins, one then may come to the conclusion that much of the chemistry of the degraded water is essentially a natural background produced by the unmined veins. I favor the latter point of view. Finally, because the dumps are small and the flow of water is small, I conclude that this mining area merits little or no reclamation effort. At present it probably contributes a relatively small amount to the total watershed, and I suspect that normal reclamation activities would result in barely detectable improvement in water quality.

Site B233 [N160]Rank M: This mining area is about ¼ mile north of Denver Lake, close to the headwaters of the Animas River and in sight of the road to Engineer Pass. There are several excavations (prospects), but the chief concern is a west-trending adit along a quartz-sulfide vein and the sulfidic dump associated with it (possibly 4,000 cubic yards). Water is ponded inside the open adit and in August of 1997 and 1998 a small flow (<10 gpm) ran over the southwest corner of the dump. The dump rocks are rich in vein material and contain unusual amounts of visible galena and sphalerite, as well as pyrite. The vein here is very similar to others in this northern part of the study area (Mineral Point district) in that the sulfide minerals are very coarse-grained and abundant within the veins. The total analysis of a dump sample confirms the high Pb and Zn concentrations, and the low content of Cu. The leach tests show that the dump materials generate a pH of 3.6, near the median, and that the concentrations of metals in the leachate are near the median. The kill zone in alpine tundra for about 100 feet east of the dump (Pl. 1, fig. G) probably is a reflection of seasonal releases from the dump.

The mine drainage is possibly the major concern for this site that is about 300 feet west of an alpine wetland. Although the grassy vegetation appears to my untrained eye to be healthy, is there an impact from AMD? The mine drainage has a pH of 3.5, near median for my samples of mine waters, but the base metal concentrations are high to very high. Iron is only a bit above the ALWS, but other more toxic metals are much higher relative to the ALWS: Cd 25X, Cu 5X, Pb 38X, and Zn 54X. The Pb concentration is unusually high for this study area, and the Zn and Cd concentrations also are very high.

This mining area is given a ranking of medium because reclamation seems feasible and should improve the health of the nearby alpine wetland. The metal concentrations in the mine drainage are high and a threat to the local environment. Because the flow of mine drainage is small, the loads of base metals are not high compared to numerous other sites in the study area and thus might be interpreted as meaning low impact on the overall watershed.

Site B234 [N155] Rank M :   This mining area is high on the ridge above the London mine, north of Animas Forks. Over a broad area of Houghton Mountain and Denver Hill, large quartz-sulfide veins can be traced for several miles (some continue to the northeast, over Engineer Pass, into the headwaters of Henson Creek). This part of the vein system was prospected by several small shafts, and later by trenches along the veins cut by the shafts. Rocks excavated from both the shafts and the trenches are very rich in pyrite and spread as a veneer only a few feet thick over a relatively large area, about half an acre (Pl. 1, fig. F). The total amount of sulfidic waste may be about 2,000 cubic yards. Water fills the trenches and presumably drains along the structures, but not along the surface. Alpine vegetation is killed across nearly an acre.

Water in the trenches, with a pH of 3.0, probably flows at <10 gpm into the subsurface. Chemical analysis shows very high metal concentrations (relative to ALWS): Cd, 105X; Cu, 110X, Fe, 3.2X, Pb, 100X, and Zn, 168X. Leach tests on the sulfidic waste are consistent with the surface water chemistry just summarized. The leachate pH is 2.8, and concentrations of Cd, Cu, Fe, Pb, and Zn are very high relative to the median for dump leachates in this study (table 1).

This mining area is given a ranking of medium because at least some of the reclamation should be feasible at low cost. The mine drainage is highly degraded, but reclamation may be difficult as much of it may be a natural expression of a large sulfide-rich vein, exposed at the surface for hundreds of feet.

Site B238 [N150] Rank L: This mining area worked a large sulfide vein on the northeast corner of Houghton Mountain, south of the London mine. The vein was mined at several levels by adits that produced dumps of modest size (but which are quite visible because the rusty rocks slide down the steep hillslope). The middle adit contains ponded water that barely flows out onto the dump. The mine water has pH 3.2 and high metal concentrations: Cd, 25X; Cu, 26X; Fe, 1.4X; Mn, 3.8X, Pb, 2.6X, and Zn 28X ALWS. The dump of about 7,500 cubic yards is moderately rich in sulfide minerals. The passive leachate has a pH of 3.2, slightly more acidic than the median, and lower than median concentrations of base metals (table 1). A kill zone on the hillside below the dump suggests episodic flow of degraded waters, perhaps during spring runoff.

This mining area is given a low priority for reclamation with the following considerations: the large vein is well exposed and is presumed to be a contributor to degraded water quality and the kill zone; there is little to no surface drainage during most of the year; and, the mining is on a steep hillside with poor access. Despite the high chemical concentrations, the indications of low flow suggest that this area is not a significant loader of metals to the watershed. Reclamation may improve the appearance, but probably would not substantially improve the quality of Burrows Creek and the Animas River.

Site B248 [N300] Rank L: This mining area about 1 mile west of Silverton, on the north side of US550, very close to the BLM-Forest boundary, is highly visible (pl. 2, fig. F), and poses fundamental questions regarding reclamation of public lands. The area is

characterized by steep slope at the base of Anvil Mountain, and abundant talus derived from highly altered sulfidic zones that are bright red on weathered surfaces. The small mining excavations are difficult to identify in the talus scree, but my best estimate is that only a few hundred cubic yards of rock were mined. Recent quarrying operations by San Juan County for road-building materials complicates the situation. No drainage is evident from the collapsed adits, but ponded water along the highway is in contact with rocks of uncertain source, mining or natural. Several square miles of red, altered, and sulfidic rocks on the flank of Anvil Mountain occur above this disturbed area. This is a classic area of Red Mountain type alteration, and the type locality for the aluminosilicate mineral zunyite is here at the old Zuny mine; zunyite is characteristic of severe hydrothermal alteration of the acid-sulfate type (Plumlee and others, 1995).

The red rocks of the mining and talus area are visibly rich in pyrite, which is disseminated through the volcanic rock, and bright red iron oxide minerals that paint the surfaces. Leach tests on the –2mm fraction of the dump and talus scree, as made for conventional dumps, yield pH 3.2 waters, more acidic than the median, but the leachate carries low concentrations of base metals.

The chief problem here seems to be the ponded water, which appears to be connected to Mineral Creek. The pH of the ponded water is 3.2, and the concentrations of Fe and Zn are high (19X and 4X, respectively), but concentrations of Cd, Cu. Mn, and Pb are below ALWS. From my visits to this site I am impressed by the large volume of unmined altered, pyritic rock relative to what appears to be a small amount of mined rock. The rocks in the ponded water appear to be more talus than mine waste. In my estimate, this situation is related more to natural weathering processes than to mining. Reclamation of the mining waste does not appear to be either feasible or appropriate. Reclamation could be done on the ponded water to minimize contact with the altered rocks (talus or mined), such as filling the low areas with clean rocks. This area is given a low priority based on my estimate of the predominance of natural processes, and the low feasibility of effective reclamation.

Site B249 [N396]Rank L: This mining area is on the west side of the Animas River, west of Middleton. There are two adits, and two modest-sized dumps (about 1,000 cubic yards in upper dump). The lower adit is not far above the Animas River floodplain, and drainage from the adit infiltrates alluvium along the river.

The pH of the drainage is 7.0, consistent with waters in contact with weakly altered volcanic rocks. Chemical analysis of the mine water shows low metal concentrations (some of the lowest in the study), except for Zn which is about 4X ALWS. The dump sample has not yet been tested.

This mining area does not appear to be a significant source of metals, but because it is so close to the Animas River, some reclamation should be considered. Mitigation of the zinc from neutral-pH waters may not be an easy matter, and may be deemed insignificant considering the low flow (hence very low loading).

Site B262 [N320] Rank N :   This mining area comprises several adits and dumps (Pl. 1, fig. I) at the end of a long jeep road, starting at Ohio Gulch on the Cement Creek road and winding into Porcupine Gulch. This was considered BLM land through 1997, but a cadastral survey showed it to be a private site. My work was done before learning of the new survey results.

The two main adits explore a vein and alteration zone. The dumps are possibly 2,000 cubic yards each. Water drains from the lower adit at about 5 gpm. The dumps contain bleached volcanic rock that appears to contain only small amounts of sulfide minerals. The leach test yielded a pH of 3.2, somewhat more acidic than the median, and leachate concentrations of Al, Cd, Cu, Fe, and Zn are higher than the median for this study (table 1). The mine water, at pH 4.1, is less acidic than most mine drainage, but the concentrations of metals are nevertheless very high: Cd, 5X, Cu, 35X, Fe, 3.6X, and Zn 38X ALWS.

Considering the small flow of water, and the distance from Cement Creek, this mining area probably does not contribute significant metal loads to the watershed. If the area is indeed private, the property owner could be encouraged to divert the mine waters away from the dump materials, and stabilize the dumps that are eroding into the creek.

Site B271 [N211] Rank H: This number is shown on the original Bureau of Mines maps as two mining sites, one midway between the Lark and Henrietta mines, and the other an adit in Prospect Gulch about 1,200 feet to the east. My estimate is that these localities are mining activities related to the Henrietta mine complex that were conducted as part of exploration in the 1970's; they are called the 800 and 1000 levels of the Henrietta mine by Herron and others (1998). The eastern site, my site 221, is a relatively new mine adit with prominent green-painted steel beams, a modest sized dump, and (surprisingly) no mine drainage. According to Herron and others (1998), this was a bold but unsuccessful exploration effort, intended to reach the lowest part of the Henrietta deposit (1000 level). Regardless, the eastern adit is dry and seems to pose no problems. The dump is dry, but is slowly eroding into Prospect Gulch. That condition could be improved, but other aspects of the eastern adit (1000 level) will not be considered further.

Site 271 is hereby assigned to a long, narrow dump of highly sulfidic rock, northeast of Prospect Gulch and the Henrietta mine, and just southwest of County Road 35. This dump is midway between the Lark and Henrietta mines. In 1997 I estimated that the dumped rocks probably are on a sliver of public lands between patents, and the rocks probably originated from 1970's exploratory mining on a deeper level of the Henrietta mine. The dump terminates at an eroded bridge and is headed for the base of the older Henrietta mine dump; the postulated mine adit is caved and covered by dump rocks. This mining scenario is explained by Herron and others (1998) who provide other important information for this complex mining area. Two aspects of dump 271 bear discussion: the composition of the rocks, and their role in some highly acidic, metal-rich surfaces waters that flow into Prospect Gulch creek.

The dump has unusual physical features: it is long (400 ft), narrow, and averages about 15 feet thick as the broken rock was placed like a roadbed along a contour. I estimate roughly 10,000 cubic yards of material. The dump is close to Prospect Creek, and two surface drainages intercept the long dump, at least one related to a ditch along County road 35. Water periodically collects on the dump, and two surface drainages run down the steep slope to Prospect Creek.

Rocks on this dump are less weathered and larger in size than on most dumps in the watershed, reflecting the more recent age of the materials. The volcanic rocks are very rich in pyrite, sphalerite, and galena. Total chemical analysis of a sample shows lower concentrations of base metals relative to other dumps in this study, but Pb and Zn concentrations of 3,800 and 2,000 ppm are not insignificant. But I noted when collecting the sample, that most of the sulfide minerals were in the coarser material that did not pass through the 2 mm sieve—so the sample I collected may not be a fair representation of this dump. Leach tests yielded a pH of 3.3, slightly more acidic than the median of all dumps in this study, but the leachate contained smaller than median amounts of base metals. This also may not be a fair measure if the sulfides were not represented in the –2 mm sample. Also, the unweathered, coarse-grained nature of the sulfides here may have minimized their reactions in the 24 hr tests. Additional tests are needed to evaluate the mobility of metals from this dump.

Some very acidic waters have been observed near this dump. In 1997 I assumed that runoff with a pH of 2.6 and high conductivity of 1,080 µS/cm was produced by reactions in the dump. My 1997 sample 213, collected midway between the dump and Prospect creek, contained extremely high concentrations of metals: Cd, 6X, Cu, 83X, Fe, 21X, Pb, 1.7X, and Zn 86X ALWS. A sample of dump runoff collected in 1998 had pH of 2.3, conductivity of >2,000 µS/cm, and even higher metal concentrations: As, 4X, Cd, 26X, Cu, >1,000X, Fe, >200X, and Zn >400X ALWS. This is close to locality PG-14 of Herron and others (1998), marked by a numbered stake. The source of the water seemed to be a ditch along the county road, until I noted a small spring or seep emerging from the gully created by the road runoff. That spring had the same pH and conductivity as water on the dump. A puddle of water on the dump in 1998 had a pH of 2.3, conductivity >2000 µS/cm, and extremely high metal concentrations. There are at least two interpretations of these observations: 1). Surface waters react with the dump, generate acid and mobilize metals, and flow into Prospect Creek just east of the Henrietta mine dump. 2). Most of the metals are from the spring, not from the new dump. The spring appears to be along a N-trending fracture system that projects toward the Lark adit and Lark dump. Further work is needed to substantiate these scenarios and to guide reclamation. If scenario 1 holds, the obvious work would be to divert surface runoff from the County road and elsewhere above the dump, and to isolate the dump from water as well as possible. If scenario 2 is correct, the dump would not be a major factor, but instead the source of the metals would be to the north in the vicinity of the Lark mine. Most likely, both scenarios operate to release degraded water to Prospect Gulch.

This area is given a high priority for reclamation because the loadings are high, and reclamation appears to be highly feasible, but further work is needed to provide

detailed information on the source or sources of water and metals. Studies by Wirt and others (1999) and other work in progress may clarify this complex geology and hydrology.

Site B318 [N380] Rank L: Mining was active in this area many years ago, and was renewed in the past 30 years (judging by two kinds of waste and newer plastic materials). It is on the side of Tuttle Mountain, about 600 feet above California Gulch. This is an area of large quartz-sulfide veins worked by many small adits and small cuts or stopes. The mining described here is not shown on the published topographic map. There are two concerns here: water draining from the lower workings, and stockpiled ores that are extremely rich in sphalerite and galena (Pl. 2, fig. A). The stockpile is clearly not 'waste' as at most dumps: it was carefully and selectively placed in one area, presumably in preparation for shipment to a mill. The stockpile may merit consideration by a hazardous materials specialist as it probably contains more than 10 percent each of Zn and Pb.

Water from the lower adit is piped under the mine road and allowed to flow over the dump and down the hillside. The water, with an unusually high pH of 7.3, flows at about 5 gpm. Most metal concentrations are low, but some exceed ALWS: Cu, 3X; Pb, 1X; and Zn, 15X.

Leach tests on a composite sample of typical dump material (not stockpile) yields a leachate that is more acidic than the median in this study, and the concentrations of Cu, Fe, Pb, and Zn are higher than median (table 1). This is one of the few examples in this study of leach waters being more acidic and metal-rich than the flowing mine waters; perhaps there is not much sulfide ore left in the small adit to create the acidic waters predicted by the lab test.

This mining area is ranked low on the reclamation list for the following reasons: the amount of water flowing is quite small, and the metal loads are very small; the dumps are small and not highly reactive; the exposed veins contribute to the problems and would continue to do so after mine reclamation. Because the mining area is easily accessible, simple reclamation methods to consolidate dump materials, cover the stockpile of ore, and divert water, could be done at low cost.

Discussion and Summary

The descriptions and interpretations in this report are an interim estimate of what is known about these priority mining sites and which ones are probably the most significant contributors of acid and toxic metals to the Upper Animas River watershed. Field observations, by myself and many others, and sampling of waters and solids are considered adequate for the ranking of priority. Available information in this and other studies is best for characterizing surface runoff or the potential for runoff in storm events. Information is limited or lacking on geochemical processes operating within dumps and the magnitude of dispersal of metals and acid into shallow ground water. A next stage of this work will be to integrate results from the mining areas with information on streams nearby (eg., Kimball and others, 1998) that appear to be reflecting ground water input

from mines and dumps. Also, there are some questions of dump composition and reactivity in the subsurface that can only be addressed by three-dimensional sampling that requires drilling or trenching and is beyond the scope of my work.

The environmental-geochemical literature often refers to mines and mine drainage as 'point sources', an image that may be misleading for those attempting reclamation. Although drainage in some mines comes out of a single pipe, reclamation is not so simple as turning off a valve on that pipe. Mine workings and mine dumps clearly are three dimensional and complex in the details that must be considered in reclamation. Several examples can be outlined: 1) geology, that tends to introduce compositional variables in space (ore, alteration, buffering capacity, etc); and 2). physical features such as faults and fractures that focus and conduct water are non-uniform in space. Some of this variability in space is known, but because nearly all of the mines are closed it will be difficult to know these spatial details when planning reclamation work.

Many of the mines and dumps studied here show evidence of natural as well as mining-related processes that result in degraded water quality. Geologic and geochemical guides used for mineral prospecting are useful for evaluating pre-mining attributes. For example, many of the mine adits in this region were excavated based on the presence of iron-rich materials including gossan and ferricrete; these and other features are indications that the surface was not pristine when mining started (Church and others, 1999). Also, the processes that created some of these features, such as flow of acidic, iron-rich spring waters a century ago are likely to be operating today— reclamation of the mine may not mitigate such natural processes, nor should it be expected to. Inputs from natural processes are difficult to quantify, but work by the USGS AMLI team is attempting to develop methods for this such as the use of isotopic tracers (Wright and others, 1998b) to fingerprint natural and anthropogenic (mining) sources. The other approach is to use 'best professional judgement' of experienced geologists and geochemists. I have offered my judgements for several mining areas that, based on my experience, appear to reflect chiefly contributions from natural processes. Others will have to evaluate the relevance of that subjective information relative to objective, quantifiable scientific data.

Many other mined and unmined areas of the Upper Animas River watershed are being investigated by one or more scientific organizations to better understand the many sources of metals and their fate in the watershed. Although this report considers only mining areas on public lands administered by the BLM, I have inevitably observed many mining areas on private property while driving on public thoroughfares. Consistent with the emphasis in this study on waters that transport toxic materials from mining sites, it is my general impression that there are many mining sites on private lands or on mixed private and public lands, that appear to release degraded water that flows in high volumes (highly visible iron precipitates form from flows more than a foot wide) (Pl. 2, figs. H and I). My limited information supports the detailed information and interpretations of Herron and others (1998). One substantial flow of water, the North Fork of Cement Creek, is so acidic (pH 2.4) that the tell-tale iron precipitates are not produced until the North Fork mixes with the main stem and produces red or orange deposits similar to

those in Plate 2 (figs. D and G) which are major problems because they dissolve during high flow conditions (spring runoff) with the release of acid and adsorbed metals (G. Desborough, USGS, written commun., 1999).

Reclamation is recommended and appears to be feasible at about 10 to 15 mining sites on BLM lands, and about the same number on USFS lands to the west (Nash, 1999). A much larger number of mining sites on private property that are significant sources of metal loads have been or should be reclaimed. The reclamation work is discussed by others (Herron and others, 1998). Common geochemical principles indicate that a first step on any mining site is to minimize reactions of water and sulfidic rock. Much reclamation work directed at this has been done northwest of the drainage divide in the Uncompahgre watershed (Ironton area); the geology, ore deposits, and climate are essentially identical to that of the Upper Animas River watershed and the Ironton experience should be directly applicable. Techniques to improve the quality of mine and dump drainage waters are being evaluated and should help improve the quality of surface waters in the Upper Animas River watershed, but engineers face a daunting task. Much work by scientists from many agencies will help focus and direct reclamation effort, but only time and monitoring will tell how much improvement toward biologically-defined restoration goals will be possible.

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Table 3: Interim Rankings of Priority Mining Sites on BLM lands,
Upper Animas Watershed, San Juan County, CO
[BLM site numbers are from Hite, 1995]

BLM site	Nash site	Mine name	Rank	Location by GPS N decdeg	W decdeg
B001	N225	Mammoth	High	37.8792	107.6728
B009	N311	Elk Tunnel	High	37.8700	107.6678
B014	N307		Low	37.8647	107.6797
B021	N192		No	37.9014	107.6700
B022	N235	Kitti-Mack	Low	37.8653	107.5381
B049	N260	High. Mary	Low	37.8531	107.5656
B052	N218	Joe&Johns	High	37.8914	107.6789
B060	N303	Mayday	High	37.8472	107.6817
B070	N430		Low	37.8531	107.5675
B072	N204	Lark	High	37.8944	107.6806
B101	N335		Low	37.8800	107.6706
B105	N201		Low	37.8881	107.6650
B116	N309		Medium	37.8722	107.6806
B123	N175	E Mogul adit	High	37.9103	107.6306
B152	N298		Low	37.8044	107.5850
B156	N231	Forest Queen	Medium	37.8658	107.5667
B169	N144		Low	37.9400	107.5722
B219	N713		No	37.9233	107.6081
B233	N160		Medium	37.9550	107.5783
B234	N155		Medium	37.9519	107.5833
B238	N150		Low	37.9450	107.5828
B248	N300		Low	37.8108	107.6858
B249	N396		Low	37.9319	107.6089
B262	N320		No	37.8594	107.6875
B271	N216	Mid-HL	High	37.8914	107.6828
B318	N380		Low	37.9078	107.5517

Appendix I: 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 ICP-MS (inductively coupled plasma—mass spectrometry) in which 60 elements (technically an isotope of each) were determined for masses from lithium to uranium. Experience with the laboratory over three years, 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 (eg, see CWQCD).

2. Results are reported for five or six orders of magnitude for most elements of interest in these natural waters and leachates, 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 because there are no standards at this level, 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 present 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 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. Replicate analyses show that the composition of these acidified water samples change by less than a few per cent after a year of storage at room temperature (D. Fey, USGS, oral commun., 1999). 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 6. 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 recommended.

Figure 6: Diagram of analytical error for various metal concentrations (next page).

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 (eg. 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 (eg. 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).

Explanations for Plates 1 and 2

Plate 1: Color photographs of mines and mine drainage (page 44).
A. Mammoth mine (site B001), collapsed portal with mound of iron-rich materials precipitated from mine drainage. B. Mammoth mine, looking east, showing iron-rich materials precipitated on mine dump; Cement Creek is on far side of dirt road. C. East Mogul mine (site B123), looking east toward Ross Basin. D. East Mogul mine dump (B123), showing seeps of water that precipitated red iron floc along headwaters of Cement Creek. E. Lark mine area (site B072) at the base of Red Mountain #3; Joe and Johns mine is to the right (east), and the dumps in foreground are from the upper levels of the Henrietta mine. View is north along the structural zone that contains the Henrietta and Lark deposits. F. Site B234, north of London mine, showing widespread sulfidic waste and vegetation kill; to southwest are the large mines on Houghton Mountain . G. Site B233, north of Denver Lake, showing sulfidic mine dump and zone of dead vegetation; mine drainage is diverted to the left side of dump. H. Site B116, showing lighter than normal color of mined waste and mine drainage on right side. I. Site B262, showing mine workings in bleached volcanic rocks; a small creek and small flow of mine drainage is on right side of lower mine dump.

Plate 2: Color photographs of mine features and iron precipitates from mine waters (p. 44).
A. Site B318, stockpile of mined rocks containing abundant sphalerite and galena; the concentrations of base metals are sufficient to be ore and were placed here on waste rocks in preparation for shipment to a mill. B. Site B219, manganese-rich materials turn black when weathered. This area of California Gulch has unusually high amounts of manganese minerals, which more typically are minor ore constituents. C. Site B49, Highland Mary mine, reclaimed in recent years. This mine waste has unusually high amounts of calcite from non-ore veins. Fault blocks of limestone occur a short distance east (lower elevation) of this site, a unique geologic situation in the study area. D. Cement Creek, about 3 miles northwest of Silverton, with abundant orange crusts of the iron-sulfate mineral schwertmanite that formed during low-flow conditions (August, 1998). These crusts will dissolve during spring runoff, releasing acid and metals. E. Site B009, high flow of water from mine flows down hillside to Cement Creek, precipitating iron-oxide minerals. F. Site B248, adjacent to US 550, that is predominantly red-weathering pyritic rock, with a small amount of disturbance by mining. G. North fork Mineral Creek, showing iron-rich precipitates formed by mixing of very acidic mine drainage and near-neutral waters; schwertmanite probably is present. H. Mine drainage west of Eureka townsite, showing iron-rich floc precipitated when the mine drainage becomes oxygenated; the lower embankment is the edge of a road gravel quarry made by San Juan County. I. Mine drainage from Silver Ledge mine at the County Road along South Fork of Cement Creek; flow of about 700 gpm carries high concentrations of iron that precipitates outside of the portal. This is an example of mixed ownership: the mine is patented (private) and the dump and water course are probably on BLM lands.