Summary and Conclusions from Investigation of the Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado

By U.S. Geological Survey

Chapter A of

Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado

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Professional Paper 1651

U.S. Department of the Interior
U.S. Geological Survey

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Introduction

The Animas River watershed is one of many watersheds in the western United States where historical mining has left a legacy of acid mine drainage and elevated concentrations of potentially toxic trace elements. Many abandoned mine lands are located on or directly affect Federal land. Cleaning up these Federal lands and restoring these watersheds will require a substantial investment of resources and many years of work. As part of a cooperative effort with Federal land-management agencies, the U.S. Geological Survey implemented an Abandoned Mine Lands Initiative in 1997. The two watersheds studied under the initiative are the Animas River watershed in Colorado and the Boulder River watershed in Montana (fig. 1). The goal of the initiative was to use the watershed approach to develop a strategy for gathering and communicating the scientific information needed to formulate effective and cost-efficient remediation of affected lands in a watershed. The major premise of the watershed approach is that contaminated sites having the most profound effect on water and ecosystem quality within an entire watershed should be identified, characterized, and ranked for remediation (Buxton and others, 1997). Remediation of watersheds affected by historical mining should be done in phases and should be followed by sufficient monitoring to document the improvement of the aquatic and riparian habitat.

The watershed approach provides an effective means to evaluate the overall status of the Nation's natural resources and to communicate these results to the public. Land- and resource-management agencies are faced with evaluating risks associated with thousands of historical mine sites in many watersheds on Federal lands, particularly in the western United States. The level of scientific study conducted for the Animas River watershed will not be feasible for every watershed affected by historical mining; however, the detailed scientific studies described herein can help Federal land-management agencies decide which characterization efforts would be most useful in evaluating other such watersheds. The watershed approach helps to focus remediation activities at sites where restoration will have the most overall benefit. We implemented the following in this investigation:

- During this study, the watershed approach resulted in the collection of extensive information on the geology and geochemistry of rock and sediment, the hydrology and water chemistry of streams and ground water, and the diversity and health of aquatic and terrestrial organisms.
- We inventoried historical mines and characterized draining adits and mine and mill wastes.
- We defined geologic conditions that control acidity and release of potentially toxic trace elements.
- We collected and chemically analyzed hundreds of water, rock, sediment, and mine- and mill-waste samples.
- We conducted toxicity tests, assessed fish distribution and habitat, and analyzed fish tissue and biofilm.
- We examined benthic macroinvertebrates and mapped their distribution to evaluate ecosystem health.
- We defined hydrological regimes, measured chemical and physical parameters to define conditions of streamflow, and evaluated plausible sources of trace elements to streams.
- We provide these data, along with the GIS coverages developed during the study, in the database on the enclosed CD-ROM (Sole and others, this volume, Chapter G).

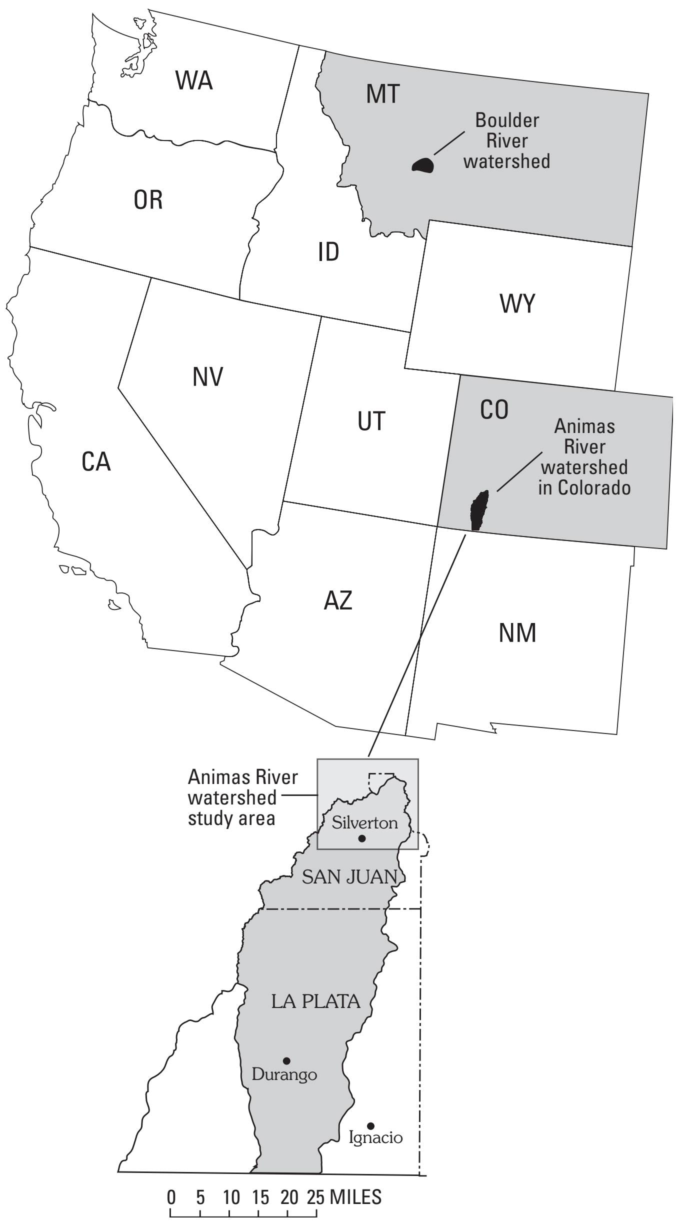

Figure 1. Index map of the western United States showing the two watersheds studied during the U.S. Geological Survey Abandoned Mine Lands Initiative. Enlarged view shows Animas River watershed in southwestern Colorado.

Study Area

The Animas River watershed study area is the northernmost headwaters of the Animas River watershed in San Juan County, Colo. (fig. 1). It encompasses the drainage basins of the Animas River at and upstream from Silverton, Colo., its two main tributaries, Cement and Mineral Creeks, and a short reach of the Animas River downstream from the confluence with Mineral Creek (fig. 2). Gold was first discovered in the study area at the site of the Little Giant mine in Arrastra Creek in 1871, although the presence of an arrastre in Arrastra Creek indicates that Spanish explorers found some free-milling gold at this site more than a century earlier. Mineral exploration did not begin until after the signing of the Bernot Treaty with the Ute Tribe in 1873. Franklin Rhonda, a topographer with the 1874 Hayden Survey, worked in the study area within a year after the establishment of the town of Silverton and described the water in both Cement and Mineral Creeks as iron sulfate waters that were undrinkable (Rhonda, 1876). Large quartz veins containing sulfide minerals are exposed at the surface in the study area. Studies of the complex geology and subsequent mineralization have been conducted in the area for more than a century (for example, Ransome, 1901; Burbank, 1933; Varnes, 1963; Burbank and Luedke, 1968, 1969; Lipman, 1976; Lipman and others, 1976; Casadevall and Ohmoto, 1977; Bove and others, 2001). The terrain is rugged: the elevation of the town of Silverton is 9,305 ft, and some of the mountain peaks in the headwaters rise to more than 13,800 ft (fig. 2). Elevations of the three Red Mountains shown on the cover photograph range between 12,219 and 12,747 ft and form the northwest boundary of the study area at the headwaters of Mineral Creek.

The findings from studies that characterized the geologic setting, defined the structural, mineralogical, and hydrothermal characteristics of the mineral deposits, and summarized the mining history of the watershed are as follows:

- Much of the study area is in a late Oligocene volcanic center that erupted many cubic miles of lava and volcanic tuff and formed the Silverton caldera. The study area was subsequently extensively mineralized (Lipman, 1976; Lipman and others, 1976; Bove and others, 2001; Yager and Bove, this volume, Chapter E1, pl. 1).

- Multiple episodes of hydrothermal activity produced widespread areas of alteration and caused extensive mineralization following the formation of the Silverton caldera (Bove and others, 2001). Previous geologic mapping of the study area, compiled by Yager and Bove (this volume, pl. 1), provides a geologic framework for subsequent interpretation of study results.

- Bove and others (this volume, Chapter E3) mapped zones of hydrothermal alteration using the data acquired by the Airborne Visible and Infrared Imaging Spectrometry (AVIRIS) instrument (Dalton and others, this volume, Chapter E2). Field testing of AVIRIS results and verification of the hydrothermal alteration suites by detailed field mapping and X-ray defraction results were used to develop the final maps. These field tests were used to refine the identification of hydrothermal mineral suites identified using the computer algorithms developed for AVIRIS data reduction (Clark and others, 2003; Dalton and others, 2004). As a result, AVIRIS spectroscopy has been shown to be a cost-effective tool for mapping hydrothermal mineral assemblages at the watershed scale.

Figure 2. Animas River downstream of Silverton taken from U.S. Highway 550 looking north-northeast, Sept. 26, 1997. Confluence of Mineral Creek (left foreground) with Animas River (far right) is in foreground. Town of Silverton sits on flood plain area known as Bakers Park downstream from Cement Creek, which flows through Silverton from left background and enters Animas River upstream of Mineral Creek confluence. Rugged mountainous terrain in background typifies majority of the Animas River watershed study area.

- Five different hydrothermal alteration assemblages were identified and the different water chemistry from each was characterized (Bove and others, this volume). A substantial component of the elevated metal concentrations and acidity in water can be attributed to weathering of hydrothermally altered rock. For example, the Red Mountains area (cover photograph) was heavily altered and mineralized, and the soil and surface water are so acidic that vegetation in the hydrothermally altered zones is sparse below tree line (Dalton and others, this volume; Mast and others, this volume, Chapter E7).

- Airborne magnetic and electromagnetic surveys show the crustal structure at three different depths (Smith and others, this volume, Chapter E4, pls. 3 and 4). Buried plutons, mineralized structures, and fractures carrying conductive ground water were identified in the subsurface by use of geophysical data. These fractured aquifers have important implications for future remediation activities in the Animas River watershed.

- Magnetic boundaries and changes in electrical conductivity are associated with faults, veins, and buried plutons. Detailed analysis of the geophysical signatures of geologic structures by McDougal and others (this volume, Chapter E13) shows that a significant number of the veins and structures identified by the geophysical data (36 percent) have not been evaluated for mineral resources.

- Predictive models (McDougal and others, this volume) utilize the geophysical data to infer plausible ground-water flow paths or barriers that need to be incorporated into any proposed remediation plans.

- Silver, lead, free-milling gold, and later zinc and copper were produced from more than 300 mines in the study area (Church, Mast, and others, this volume, Chapter E5). Beginning about 1890, mineral production in the study area averaged about 200,000 short tons of ore per year for a century (Jones, this volume, Chapter C). The Sunnyside mine, the last operating mine in San Juan County, closed in 1991. Total production of mines in the Animas River watershed study area between 1871 and 1991 is estimated at 18.1 million short tons of ore.

Many of these historical mines are on public land, administered by both the U.S. Bureau of Land Management (BLM) in the Department of the Interior and the U.S. Department of Agriculture (USDA) Forest Service, and they have been abandoned by those who originally worked the properties. Others are on patented claims and are owned by private citizens or are orphaned properties held by San Juan County for delinquent taxes. Remediation objectives for the watershed face a number of difficult challenges: issues of land ownership and financial liability, technical approaches needed to mitigate acid mine drainage without resorting to costly treatment facilities, and the need for adequate space to build new repositories to move those mine wastes that cannot be mitigated in place are but a few. These issues must be successfully addressed by consensus in the Silverton community, where much of the local economy for decades has been built around tourism in a historical mining district.

Environmental Effects

Historical mining began in an era of little concern for or understanding of the effects of mining on the environment. Development of our abundant mineral resources was one of the public policies used by Federal Government to populate the West following the Civil War. The lure of adventure and the promise of wealth were the motivating factors to entice people to emigrate west and settle the frontier. Following the initial phase of development and the completion of the Silverton narrow-gauge railroad in July 1882, mining in the basin progressively became more mechanized as milling technology rapidly improved. Mill waste was dumped in the lakes, rivers, and streams until about 1935, when the waste from the Mayflower Mill was retained. Once milled, most sulfide concentrates were shipped to Durango, Colo., for smelting (Sloan and Skowronski, 1975). Of the 18.1 million short tons of ore produced in the basin, an estimated 8.6 million short tons of mill waste (about 48 percent) was discharged directly into surface streams prior to about 1935 (Jones, this volume).

Determining the effects of historical mining in the Animas River watershed study area necessarily involved many detailed and specific scientific studies to quantify aspects of the environmental effects attributable to historical mining and milling. Individual chapters in this volume are briefly summarized in von Guerard and others (this volume, Chapter B) so that the reader may select those studies that address the problem of concern or specific area of interest. The basic findings in this report are listed under four broad headings.

Sources of Trace Elements

Several sources of trace elements and acidity affect surface streams in the watershed study area. Of the greatest concern are those that can be attributed directly to historical mining and that can and perhaps should be addressed through some remedial action.

- Studies of various aspects of water quality in the watershed (1996–2000) showed that historical mining has resulted in water-quality degradation (Kimball and others, this volume, Chapter E9; Wright, Simon, and others, this volume, Chapter E10; Walton-Day and others, this volume, Chapter E24).
- Sources of contaminants, both anthropogenic and natural or undisturbed, were detected by the numerous tracer studies completed along many of the reaches of the major surface streams and some tributaries. Much of the metal loading, which is summarized in Kimball and others (this volume), can be attributed to 24 specific areas in the watershed, although numerous other sources were identified. Major structures, hydrothermally altered areas, and major draining adits are among these sources.
- Numerous mine sites, both on public and on private land, have been identified as sources of metals and acidity from these tracer studies (Kimball and others, this volume). Metal loading from mine sites is summarized by Mast and others (this volume).
- Mine sites and mill-tailings piles are obvious candidates for sources of potentially toxic trace elements and acidity. Nash and Fey (this volume, Chapter E6) studied and ranked more than 100 mine and mill sites located on public lands. Of these, about 40 mine and mill sites were found to be of sufficient size, to have enough adit discharge, and (or) to have sufficient mine waste to be considered significant sources of trace elements and acidity at the watershed scale. Mines located on private land were not considered or ranked in the study by Nash and Fey (this volume) because access to these sites generally was not granted by the property owners.
- Most large mine sites in the study area are located on private land or on land with mixed private/Federal ownership. Data from mine and mill sites located on private land were provided by State agencies and a local citizens group, the Animas River Stakeholders Group, and are discussed and separately ranked in Wright, Simon, and others (this volume).
- Water-quality measurements from 75 inactive historical mines indicated that most mine water was dominated by calcium sulfate, had variable pH ranging from 2.35 to 7.8, and had highly variable chemistry (Mast and others, this volume; Nash and Fey, this volume).
- The fact that water chemistry from flowing adits has an essentially constant chemical makeup throughout the years of our study demonstrated that adit-water chemistry is not diluted by ground water coming into a mine pool during spring runoff, but rather that a large supply of water-soluble salts exists in the mines, and that these salts dissolve and saturate the fresh water added by infiltration by snowmelt each year. Thus, mine-adit flow is a constant source of contaminants and acidity to surface streams (Church, Mast, and others, this volume).
- Isotopic studies of sulfate in adit water demonstrated that both oxidation of pyrite and dissolution of gypsum, anhydrite, and calcite control the sulfur and oxygen systematics of mine water (Nordstrom and others, this volume, Chapter E8).

- Accelerated weathering of the large volumes of freshly crushed rock present in mine-waste and mill-tailings sites (Church, Mast, and others, this volume; Fey and others, 2000) has resulted in the release of elevated concentrations of cadmium, copper, and zinc into surface streams (Kimball and others, this volume; Wright, Simon, and others, this volume; Mast and others, this volume).

- Not all sources of metals and acidity in the study area are anthropogenic. Weathering of hydrothermally altered rock not associated with historical mine sites also results in the release of trace elements and acidity that degrade water quality (Bove and others, this volume). The annual freeze-thaw cycle each winter exposes fresh mineral surfaces to the weathering process. Weathering of pyrite, the ubiquitous iron sulfide present in hydrothermally altered and mineralized rock, results in the release of sulfuric acid and trace elements that potentially are toxic to aquatic life. This weathering process takes place whether or not a mineral deposit has been mined or the ground disturbed.

- Values of pH in surface streams today at low flow range from less than 3.5 to near neutral. Trace elements are in solution at low pH values, but as pH increases, different trace elements precipitate from solution and are sequestered by the iron-oxyhydroxide colloidal fraction. For example, a map of the concentrations of zinc in surface water at low flow (fig. 3) shows high dissolved zinc concentrations in some stream reaches.

- Trace elements are mobilized and acidity introduced into streams by water flowing through mine workings (Bove and others, this volume; Mast and others, this volume; Church, Mast, and others, this volume), across mine-waste dumps (Nash and Fey, this volume; Kimball and others, this volume), and over and through mill tailings disposed of on the flood plain (Vincent and Elliott, this volume, Chapter E22) and in stream reaches (Kimball and others, this volume; Wright, Simon, and others, this volume).

- Water most affected by historical mining will have a pH <3 with elevated concentrations of iron, aluminum, cadmium, copper, lead, zinc, arsenic, and nickel. Using the dissolved sum-of-metals as a measure of trace-element contamination from historical mining sites, Wirt and others (this volume, Chapter E17) showed that the dissolved sum-of-metals exceeded 1,200 µg/L in the Prospect Gulch subbasin on upper Cement Creek (fig. 3).

- Trace elements are partitioned between the dissolved and the colloidal phase in surface streams. Transport of colloids (fig. 4) results in variable concentrations of metals in the dissolved and suspended phases during different seasons of the year (Church and others, 1997; Fey and others, 2002). Settling of colloids onto the streambed is one mechanism of natural attenuation that caused changes in the distribution and bioavailability of some, but not all metals to aquatic biota (Kimball and others, this volume; Besser and Brumbaugh, this volume, Chapter E18, Besser and others, this volume, Chapter D).

Premining Geochemical Studies

One of the fundamental questions in the study of the effects of historical mines on the environment is always: What were conditions prior to mining? We specifically focused efforts on this question to provide data that could be used to establish reasonable remediation target concentrations for potentially toxic trace elements.

- Water quality in undisturbed background sites in the study area is controlled by the hydrothermal alteration assemblages (fig. 3; Bove and others, this volume; Mast and others, this volume; Kimball and others, this volume).

- Detailed statistical, mass-balance, and inverse modeling approaches were used to determine the percentage of potentially toxic trace-element loads that could be attributed to weathering of undisturbed areas within discrete subbasins (Bove and others, this volume). These studies had mixed results, and interpretation of the data was complicated by the geologic complexity of the area, density of historical mines and mills, distribution of mill tailings, and uncertainty about the ground-water contributions.

- Detailed studies of ferricrete distribution (Yager and Bove, this volume, pl. 2), classification, and age constraints (Verplanck and others, this volume, Chapter E15) show that ferricrete deposits mark areas of emergence of the paleo ground-water table (Wirt and others, this volume). Ferricrete deposits are spatially distributed down slope from areas of extensive pyrite-rich hydrothermal alteration. Active ferricrete deposition occurs down gradient of changes in slope that force low-pH ground water to the surface in sedge grass marshes and iron bogs (fig. 5).

- The presence of schwertmannite (a hydrous iron sulfate) in iron deposits in iron bogs and ferricrete deposits can be used to constrain the water chemistry of paleo ground water to a pH range of about 3.5 to >4 in acid-sulfate water (Wirt and others, this volume; Stanton, Yager, and others, this volume, Chapter E14). Ferricrete deposits therefore provide a record of the type and chemistry of ground water being supplied to the surface drainage basins prior to mining.

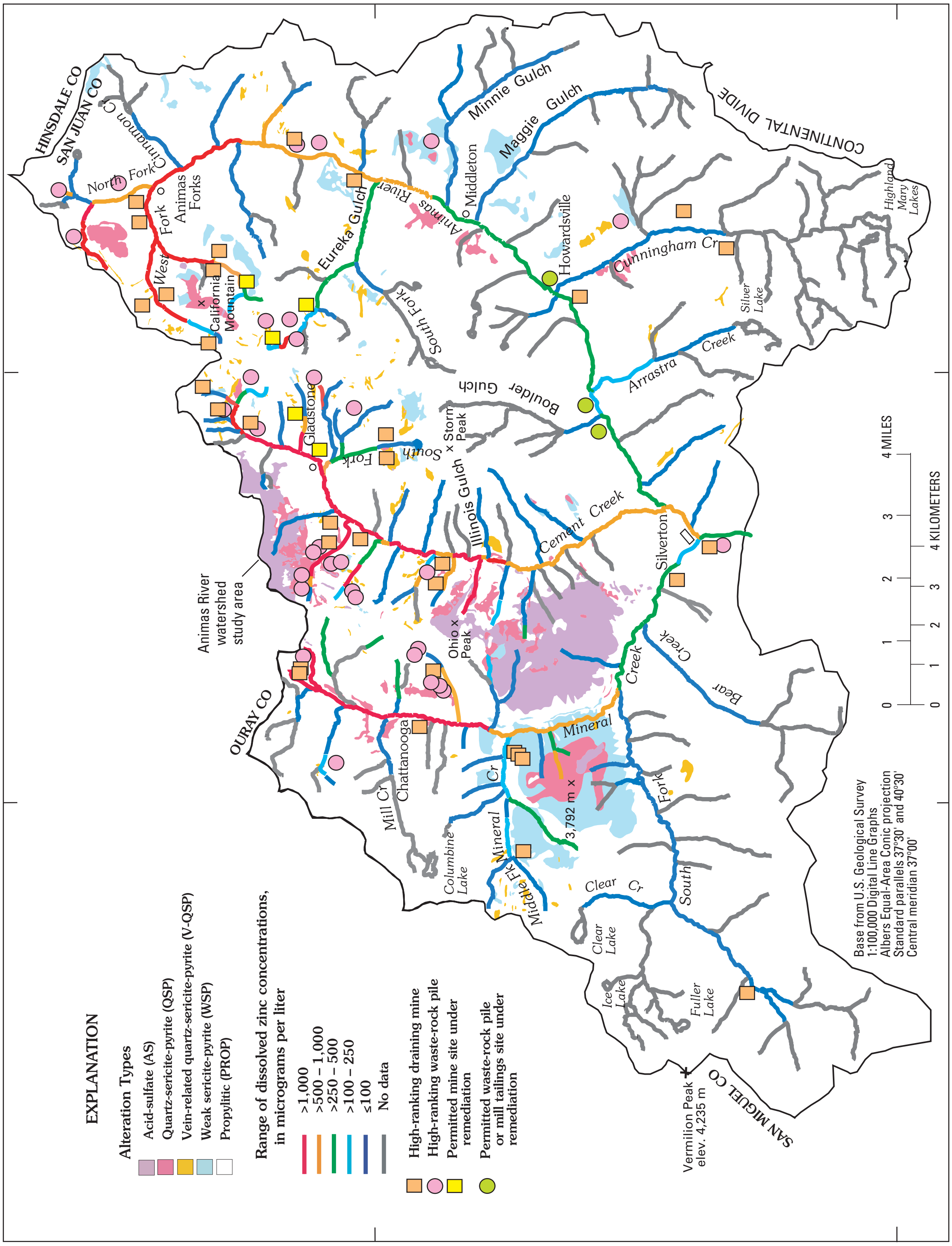

Figure 3. Distribution of zinc in surface water during low flow (Wright, Simon, and others, this volume, fig. 17).

Figure 4. View of mixing zone looking downstream (southwest) from confluence of Cement Creek (right) with Animas River (left). Iron colloids precipitate from more acidic surface water in Cement Creek (pH ≈3.5) upon mixing with more neutral water of Animas River. Photograph taken May 1998, by Briant A. Kimball.

- Oxidation of ferrous iron to ferric iron by atmospheric and biogenic molecular oxygen lowered pH and resulted in the precipitation of both amorphous iron oxyhydroxides and sulfates. The primary difference between these deposits and ferricrete deposits is largely the site of deposition. Both iron bogs and wetlands represent both a source of dissolved trace elements to surface streams and a transient sink for metals that were precipitated and trapped in these deposits. However, once these iron-rich deposits become inactive (that is, they become bog iron or ferricrete deposits), they are subject to erosion (fig. 5). They then become a source of trace-element-rich iron sediment that contributes to the active streambed sediment budget. Erosion rates of these ferricrete deposits are slow, as they also contain substantial amounts of amorphous silica (Wirt and others, this volume).
- Geomorphological studies of the Cement Creek valley (Vincent and others, this volume, Chapter E16, pl. 5) clearly showed how the last glacial retreat has significantly influenced landforms, how those landforms controlled surface and ground-water flow and stream gradient, and how they affected the distribution of sedge marshes and ferricrete deposits in the Cement Creek valley.
- Wood found in ferricrete deposits was always postglacial in age. Wood preserved in peat deposits and in stumps in growth position in ferricrete was dated using ^{14}C methods (Verplanck and others, this volume; Vincent and others, this volume), and these ages were used to calculate rates of accumulation of peat and estimate rates of erosion in the Cement Creek valley (Vincent and others, this volume).
- Geochemical studies of sediment from premining terrace deposits (Church, Fey, and Unruh, this volume, Chapter E12), constrained by the ^{14}C age data, indicate that premining geochemical conditions in Cement Creek were not very different than they are today. The observations of Rhonda (1876) indicating that, in 1874, the water in Cement Creek was “so strongly impregnated with mineral ingredients as to be quite unfit for drinking” confirm our conclusions.
- Studies of both paleo and active iron bogs (Stanton, Yager, and others, this volume) and of wetlands (Stanton, Fey, and others, this volume, Chapter E25) indicate that these sites are also sources of acidic water and elevated trace-element concentrations that affect water quality (fig. 5).
- Church, Fey, and Unruh (this volume) present data from both modern and premining terraces that clearly show that historical mining has had an effect on the distribution and concentration of trace elements in streambed sediment (for example, zinc, fig. 6). The source of these metal anomalies can be correlated directly to mining and milling through studies of the isotopic signature of the lead from mill waste and in sediment. Since water-quality data are not available from 1871 when mining began, the data from stream sediment preserved in premining terraces provide the best evidence of the state of the aquatic habitat when mining began. Anecdotal data indicate that native trout could be caught in the Animas River prior to mining (von Guerard and others, this volume), and the report by Rhonda (1876) indicates that water quality in the Animas River was good prior to mining.
- No newspaper accounts exist that document fish living in either Cement Creek or Mineral Creek upstream of the confluence with South Fork Mineral Creek. Data from springs in unmined areas (Mast and others, this volume), stream-sediment data from terraces (Church, Fey, and Unruh, this volume), and the absence of paleontological evidence for a viable aquatic ecosystem at the time the terrace deposits formed suggest that a viable macroinvertebrate community probably did not exist in either Mineral Creek upstream from the confluence with South Fork Mineral Creek or in Cement Creek prior to mining (Church and others, 1999).

Figure 5. Upper Cement Creek just south of Gladstone (fig. 3), showing iron colloids covering streambed; looking south across Cement Creek. Ferricrete deposits form the banks of the stream; older inactive deposits are dry and dark brown. Acidic water drains from the sedge grass marsh, through a small iron bog and into the creek. Note pronounced change in vegetation at break in slope in background. Shallow pools in the creek accumulate iron-rich colloidal sediment that sequesters trace elements.

Watershed Conditions (1996–2000)

The following is a summary of current conditions in the Animas River watershed study area as shown by our studies.

- Investigations of the aquatic habitat throughout the study area indicate that brook trout are surviving in some stream reaches of the Animas River (Besser and Brumbaugh, this volume; Besser and Leib, this volume, Chapter E19).

- Besser and others (this volume) provide an ecological risk assessment focused on fish and aquatic invertebrates of the Animas River watershed on the basis of their exposure to aluminum, cadmium, copper, and zinc. This study was based on water-quality measurements made during low flow in the years 1996–2000. For evaluating ecological risks, Besser and others focused on aquatic resources (that is, fish and benthic macroinvertebrates), and the effects of metals on the food web. In particular, they conclude:

  1. Dissolved and colloidal-bound metals pose the greatest risk to benthic macroinvertebrates and trout.

  2. The risk to stream biota associated with zinc toxicity in surface streams (fig. 7) and of the other trace elements studied occurred at potentially toxic levels in all acidic stream reaches (pH <4.5). However, risks to stream biota in near-neutral stream reaches (pH >6.5) varied widely.

  3. Copper posed the greatest risk to aquatic life, but that risk diminished downstream from the source in near-neutral stream reaches.

  4. Sources of risk to stream biota were ranked in terms of severity and indicate where remediation efforts would produce the most immediate and lasting results.

- Food-web studies indicate different risks of toxicity to stream biota. Concentrations of copper and cadmium remain constant or increase across trophic levels indicating dietary exposure of toxic trace elements. Copper concentrations in invertebrate diets and in trout liver suggested chronic copper toxicity in stream reaches where brook trout survived.

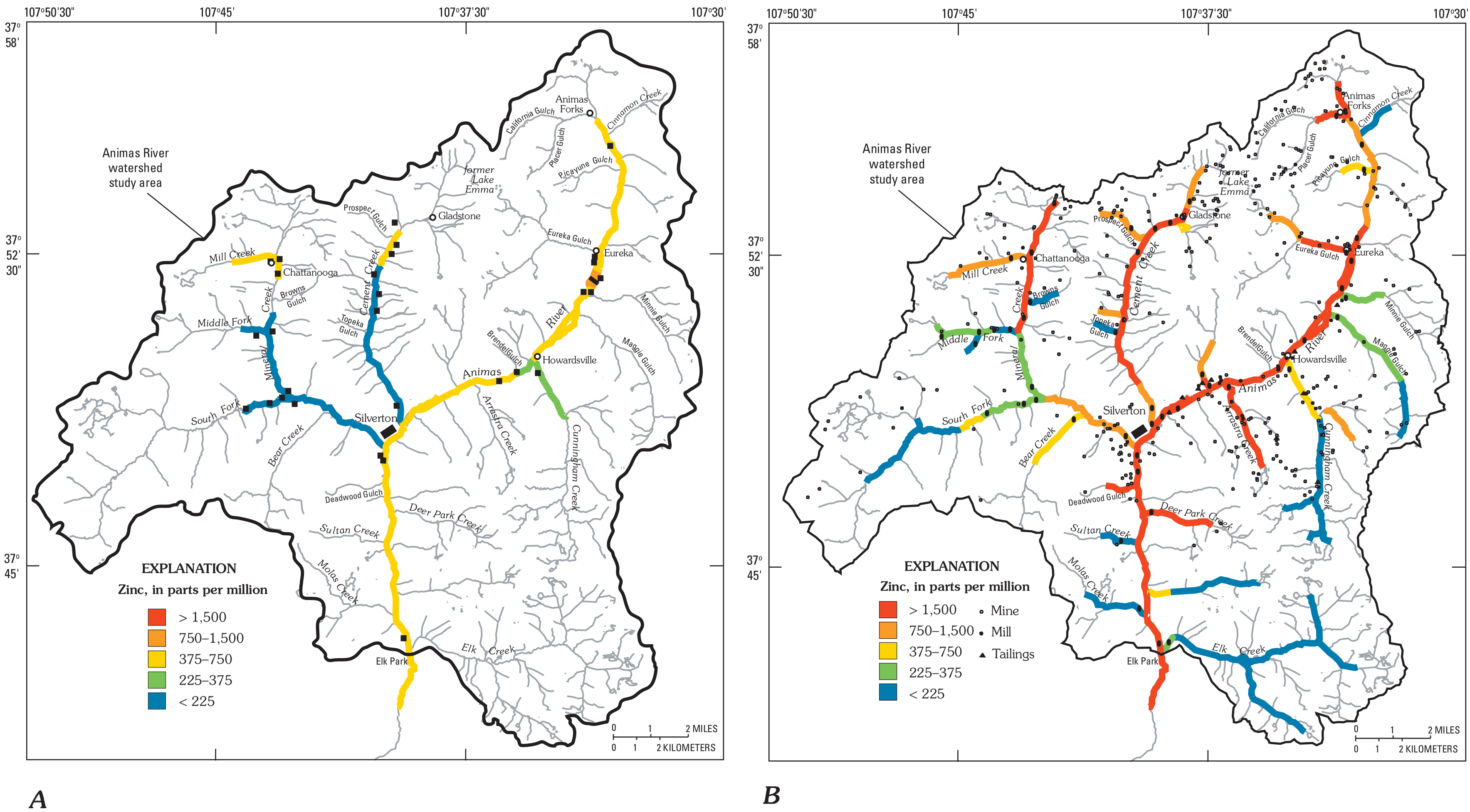

Figure 6. Zinc concentrations in *A*, premining sediment and *B*, modern sediment (from Church, Fey, and Unruh, this volume, fig. 28). Dots on stream segments show sample localities.

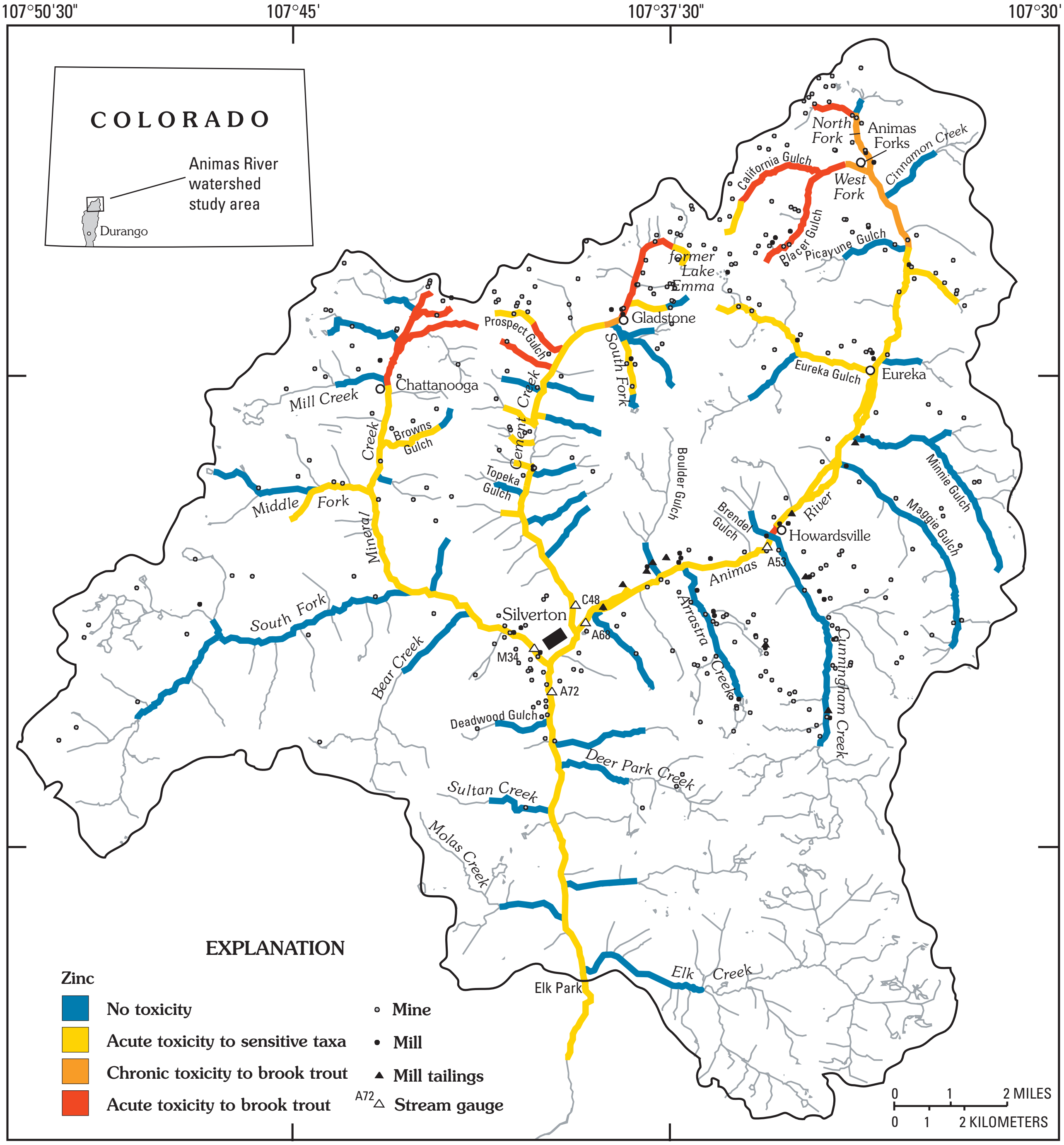

Figure 7. Zinc toxicity map showing categories of risk to aquatic life (Besser and others, this volume, fig. 4).

- Larison and others (2000) documented the toxic effects of cadmium accumulation in white-tailed ptarmigan (*Lagopus leucrus*) in the study area in conjunction with our work, showing that elevated cadmium levels in bone in the ptarmigan resulted in physiological effects.
- Studies of the variations in flow and surface-water chemistry measured at the gauging stations on each of the tributaries and downstream of the confluence of Mineral Creek on the Animas River indicate that the poorest water quality occurs during low flow in January and February. Toxicity tests of water and sediment using sensitive aquatic test organisms showed that this was the critical period for highest toxicity (Besser and Leib, this volume). Elevated concentrations of zinc during this period were highly toxic to amphipods and early life stages of brook trout, less toxic to fathead minnows, and least toxic to adult brook trout. Both fathead minnows and brook trout

showed significant toxicity effects due to the elevated concentrations of copper and toxicity, which approach the LC50 value for fathead minnows. These toxicity tests were used to establish the chronic toxicity thresholds for early life stages of brook trout.

- Documentation of changes of instream loads of cadmium, copper, and zinc throughout the year indicated that different stream reaches contributed different portions of the trace-element loads throughout the year (Besser and Leib, this volume; Leib and others, this volume, Chapter E11).
- The physical habitat in the streams also has been degraded as a result of historical mining. Those changes currently limit over-winter survival of trout because of the aggradation of sediment, infiltration of voids in gravel-bottomed streams by fine-grained iron-rich sediment, loss of willow thickets that stabilize the riverbanks, and subsequent loss of deep pools (Milhous, this volume, Chapter E21; Vincent and Elliott, this volume).
- As a direct result of milling at Eureka, sheets of gravel accumulated downstream in the braided reach at rates estimated to be 50 to several thousand times that prior to mining. Historical photographs of the riparian zone (Vincent and Elliott, this volume), along with analysis of the recovery of this braided reach downstream from the large Sunnyside Eureka Mill documented using aerial photographs of this reach taken in each decade since the 1950s, show that some recovery of the riparian habitat has resulted from natural erosion processes. Substantial amounts of the mill tailings originally disposed of in this reach (70–80 percent, Vincent and Elliott, this volume) have been transported downstream and dispersed in historical stream deposits (Church, Fey, and Unruh, this volume). An additional 10 percent of the mill tailings in this reach were removed by Sunnyside Gold, Inc., during remediation in 1996, and an estimated 10 percent of the mill tailings remain as discrete deposits in the braided reach downstream of Eureka.
- Studies of the premining geomorphology indicate that the Eureka reach was not a meandering single-thread channel prior to mining. Riparian zone recovery has taken place at the lower end of the braided reach immediately upstream of Minnie Gulch, and surface water quality is improved there (fig. 3). However, complete recovery of the riparian zone likely would take many centuries if no remediation were done (Vincent and Elliott, this volume).
- Studies of premining sediment quality in this reach clearly show elevated zinc concentrations prior to mining downstream from Eureka (fig. 6*A*), but the effects of milling at Eureka are very evident from the contrast of zinc concentrations in modern streambed sediment (fig. 6*B*).

Potential for Restoration of Functional Aquatic Habitat

Finger and others (this volume, Chapter F) address the effects of remediation and monitoring of recovery of stream biota in the streams as that process continues. A large number of remediation projects and activities have been undertaken, largely by Sunnyside Gold, Inc., at their own properties. Sunnyside Gold, Inc. also has done remediation at other sites in the watershed to reduce metal loading, under an agreement with the Colorado Department of Public Health and Environment. Additional remediation projects have been done by the U.S. Bureau of Land Management and the USDA Forest Service where they have clear ownership and liability under the Federal Water Pollution Control Act, revised by Congress in 1972 into the Clean Water Act (P.L. 92–500). The goals of the Clean Water Act include “the discharge of pollution into navigable waters be eliminated by 1985,***the discharge of toxic pollutants in toxic amounts be prohibited, and an interim goal of water quality, which provides for the protection and propagation of fish, shellfish, and wildlife, and***creation in and on the water***by July 1, 1983” [P.L. 92–500, §101(a), 33 U.S.C. §1251(a)]. The local community stakeholders group and individual property owners in Silverton, with funding from Non Point Source (NPS) 319 grants (EPA) and severance tax funds provided through the State of Colorado, have also completed remediation projects (Finger and others, this volume). Remediation projects completed through 2003 are summarized in figure 8. Remediation work done at the Silver Wing mine (fig. 9) is an excellent example of the public/private collaboration that will be required to achieve lasting success in reducing the metal loads to the watershed. The property owner has secured a 319 NPS grant from EPA for a passive treatment system to treat water draining from the mine, and he has diverted the adit flow away from the mine-waste pile in front of the mine adit. Similar types of activities have been conducted by Sunnyside Gold, Inc., and by the Federal land-management agencies in cooperation with the local stakeholders, to reduce and divert acid mine drainage away from mine-waste piles, remove highly reactive mine and mill wastes from the environment, and improve water quality in the Animas River watershed study area. Aspects of our work that provide a basis for evaluating the effectiveness of remediation efforts are listed following:

- Loading patterns for metals determined from the various tracer studies (Kimball and others, this volume) document loading of metals in surface streams and provide important constraints on remediation activities that need to be evaluated to improve water quality in the watershed.

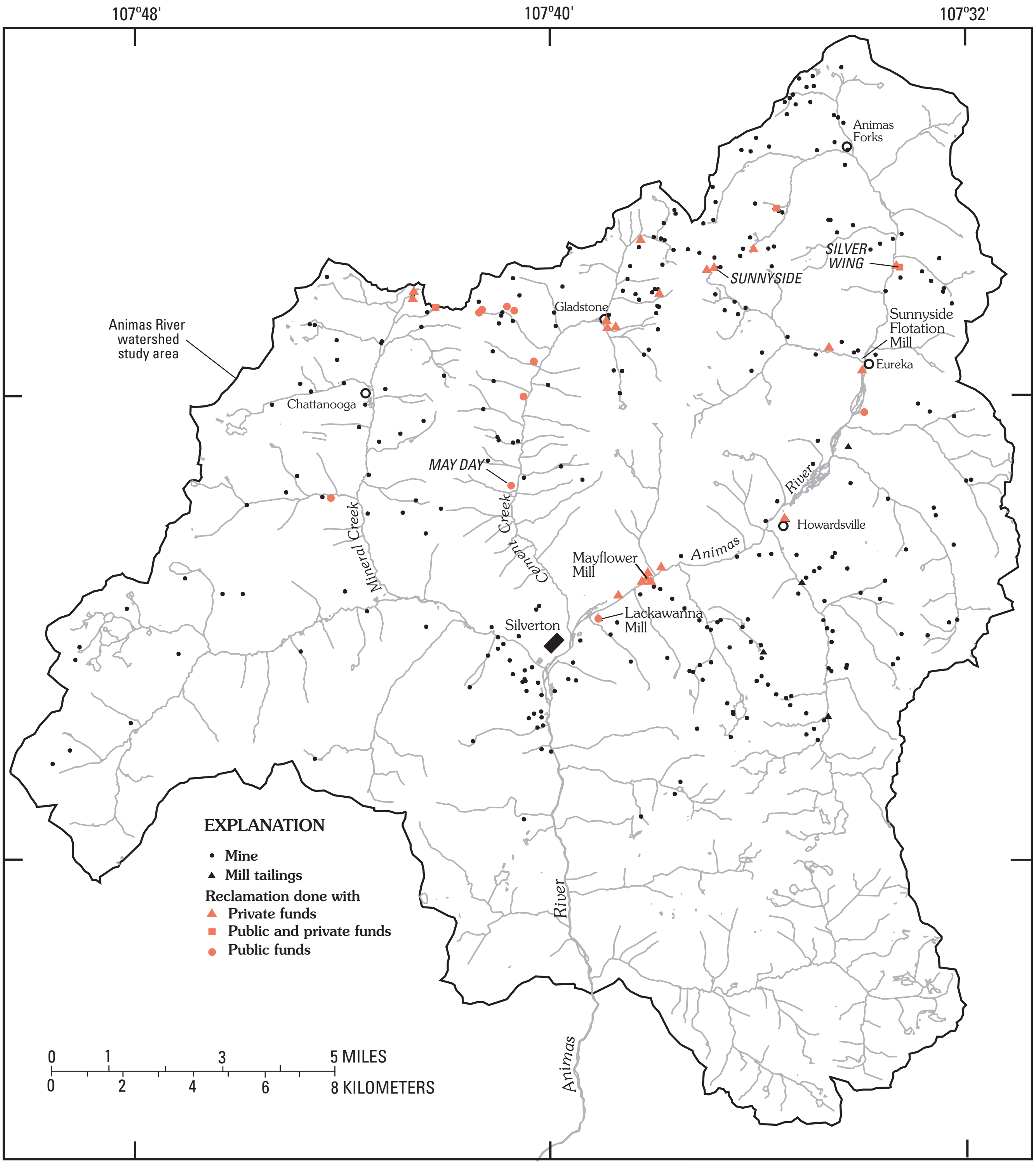

Figure 8. Sites where remediation work has been done (through 2003) in the study area (Finger and others, this volume, fig. 1). Sites are coded by types of funding used (private; public, that is NPS 319 grants through EPA, severance tax funds through the State of Colorado, and funding from the USDA Forest Service or U.S. BLM abandoned mine lands funds; and mixed private/public funding sources). Numerous mine adit closings have also been initiated by the State of Colorado using severance tax funds to reduce physical hazards. These adit closures do not affect water quality and are not included in this illustration. Data provided by William Simon (Animas River Stakeholders Group, written commun., 2004).

Figure 9. Silver Wing mine, a privately held, inactive mine site on east side of Animas River.

- Various remediation scenarios have been evaluated in four stream reaches using the tracer data in a chemical model (OTIS) that accounts for changes in chemistry by in-stream chemical processes (Walton-Day and others, this volume) in Cement Creek and the Animas River, and in Mineral Creek (Runkel and Kimball, 2002). The goal was to ascertain whether large anthropogenic sources of contamination could be effectively remediated.

- Although large amounts of metals and acidity could be removed by remediation of sources in the upper Cement Creek basin, changes in metal loads at the mouth of Cement Creek would be small because much of the metal loading comes from ground-water-fed iron bogs and sedge marshes (fig. 5).

- Remediation scenarios in the upper Animas River basin are promising, and reduction of dissolved zinc concentrations to below aquatic life standard for sensitive aquatic organisms may be possible.

- Prior to the remediation of the Lackawanna Mill site, the U.S. Bureau of Land Management in 2000 asked the U.S. Geological Survey (Wright, Kimball, and Runkel, this volume, Chapter E23) to assess the impact of the May Day mine site on water quality in Cement Creek. These data provide a geochemical baseline needed to evaluate the effect of the repository subsequently built at the May Day mine site for tailings from the Lackawanna Mill.

- Phased remediation of the most significant sources of metals and acidity in the watershed (as identified in Nash and Fey, this volume; Wright, Simon, and others this volume) is recommended and will allow real-time assessment of remediation efforts (Finger and others, this volume).

- Benchmark benthic macroinvertebrate data collected in the Animas River watershed provide a quantitative evaluation of the benthic community structure and health prior to remediation (Anderson, this volume, Chapter E20).

- Monitoring of the recovery of sensitive macroinvertebrates along with improvements of water quality as remediation proceeds is a proposed method for monitoring functional recovery of the aquatic communities (Anderson, this volume; Finger and others, this volume).

- Benthic macroinvertebrates are present in tributary streams and will reinhabit mainstem reaches upon restoration of water and sediment quality to levels where aquatic life can persist (Besser and Brumbaugh, this volume; Anderson, this volume).

References Cited

Bove, D.J., Hon, Ken, Buddington, K.E., Slack, J.F., Snee, L.W., and Yeoman, R.A., 2001, Geochronology and geology of late Oligocene through Miocene volcanism and mineralization in the Western San Juan Mountains, Colorado: U.S. Geological Professional Paper 1642, 30 p.

Burbank, W.S., 1933, Vein systems of Arrastre Basin and regional geologic structure in the Silverton and Telluride quadrangles, Colorado: Colorado Scientific Society Proceedings, v. 13, p. 135–214.

Burbank, W.S., and Luedke, R.G., 1968, Geology and ore deposits of the San Juan Mountains, Colorado, *in* Ridge, J.D., ed., Ore deposits of the United States, 1933–1967 (the Graton-Sales Volume): New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 714–733.

Burbank, W.S., and Luedke, R.G., 1969, Geology and ore deposits of the Eureka and adjoining districts, San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 535, 73 p.

Buxton, H.T., Nimick, D.A., von Guerard, Paul, Church, S.E., Frazier, Ann, Gray, J.R., Lipin, B.R., Marsh, S.P., Woodward, Daniel, Kimball, Briant, Finger, Susan, Ischinger, Lee, Fordham, J.C., Power, M.S., Bunck, Christine, and Jones, J.W., 1997, A science-based, watershed strategy to support effective remediation of abandoned mine lands: Proceedings of the Fourth International Conference on Acid Rock Drainage, Vancouver, B.C., May 31–June 6, 1997, p. 1869–1880.

Casadevall, Thomas, and Ohmoto, Hiroshi, 1977, Sunnyside mine, Eureka mining district, San Juan County, Colorado—Geochemistry of gold and base metal ore deposition in a volcanic environment: Economic Geology, v. 92, p. 1285–1320.

Church, S.E., Fey, D.L., Brouwers, E.M., Holmes, C.W., and Blair, Robert, 1999, Determination of pre-mining geochemical conditions and paleoecology in the Animas River watershed, Colorado, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Charleston, South Carolina, March 8–12, 1999, Volume 1, Contamination from hard-rock mining: U.S. Geological Survey Water-Resources Investigations Report 99–4018A, p. 19–30.

Church, S.E., Kimball, B.A., Fey, D.L., Ferderer, D.A., Yager, T.J., and Vaughn, R.B., 1997, Source, transport, and partitioning of metals between water, colloids, and bed sediments of the Animas River, Colorado: U.S. Geological Survey Open-File Report 97–151, 135 p.

Clark, R.N., Swayze, G.A., Livo, K.E., Sutley, S.J., Dalton, J.B., McDougal, R.R., and Gent, C.A., 2003, Imaging spectroscopy—Earth and planetary remote sensing with USGS Tetracorder and expert systems: Journal of Geophysical Research, v. 108(E12), no. 5,131, p. 5–1 to 5–44.

Dalton, J.B., Bove, D.J., Mladinich, C.S., and Rockwell, B.W., 2004, Identification of spectrally similar materials using the USGS Tetracorder algorithm; the calcite-epidote-chlorite problem: Remote Sensing of Environment, v. 89, p. 455–466.

Fey, D.L., Desborough, G.A., and Church, S.E., 2000, Comparison of two leach procedures applied to metal-mining related wastes in Colorado and Montana and a relative ranking method for mine wastes, *in* ICARD 2000; Proceedings of the Fifth International Conference on Acid Rock Drainage, Volume 2: Society for Mining, Metallurgy, and Exploration, Inc., p. 1477–1487.

Fey, D.L., Wirt, Laurie, Besser, J.M., and Wright, W.G., 2002, Water quality and aquatic toxicity data of 2002 spring thaw conditions in the upper Animas River watershed, Silverton, Colorado: U.S. Geological Survey Open-File Report 02–488, 31 p.

Larison, J.R., Likens, G.E., Fitzpatrick, J.W., and Crock, J.G., 2000, Cadmium toxicity among wildlife in the Colorado Rocky Mountains: Nature, v. 406, p. 181–183.

Lipman, P.W., 1976, Caldera-collapse breccias in the western San Juan Mountains, southwestern Colorado: Geological Society of America Bulletin, v. 87, p. 1397–1410.

Lipman, P.W., Fisher, F.S., Mehnert, H.N., Naeser, C.W., Luedke, R.G., and Steven, T.A., 1976, Multiple ages of mid-Tertiary mineralization and alteration in the western San Juan Mountains, Colorado: Economic Geology, v. 71, p. 571–588.

Ransome, F.L., 1901, A report on the economic geology of the Silverton quadrangle, Colorado: U.S. Geological Survey Bulletin 182, 265 p.

Rhonda, Franklin, 1876, Report on the topography of the San Juan Country, *in* Hayden, V.F., Annual Report of the United States Geological and Geographical Survey of Territories embracing Colorado and parts of adjacent territories; being a report of progress of the exploration for the year 1874: p. 451–496.

Runkel, R.L., and Kimball, B.A., 2002, Evaluating remedial alternatives for an acid mine drainage stream—Application of a reactive transport model: Environmental Science & Technology, v. 36, p. 1093–1101.

Sloan, R.E., and Skowronski, C.A., 1975, The Rainbow Route, an illustrated history of the Silverton Railroad, the Northern Silverton Railroad, and the Silverton, Gladstone, & Northerly Railroad: Denver, Colo., Sundance Publications Limited, 416 p.

Varnes, D.J., 1963, Geology and ore deposits of the South Silverton mining area, San Juan County, Colorado: U.S. Geological Survey Professional Paper 378–A, 56 p.