The Animas River Watershed, San Juan County, Colorado

By Paul von Guerard, Stanley E. Church, Douglas B. Yager, and John M. Besser

Chapter B of

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

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Introduction

Thousands of inactive hard-rock mines have left a legacy of acid drainage and toxic metals across mountain watersheds in the western United States. More than 40 percent of the watersheds in or west of the Rocky Mountains have headwater streams in which the effects of historical hard-rock mining are thought to represent a potential threat to human and ecosystem health. In many areas, unmined mineral deposits, waste rock, and mill tailings in abandoned mine lands (AML) may increase metal concentrations and lower pH, thereby affecting the surrounding watershed and ecosystem. Streams near abandoned inactive mines can be so acidic or metal laden that fish and aquatic insects cannot survive and some bird species are negatively affected by the uptake of metals through the food chain. Although estimates of the number of AML sites vary, observers agree that the scope of this problem is huge, particularly in the western United States where public lands contain thousands of inactive mines.

Numerous AML sites are located on or adjacent to public lands or affect aquatic or wildlife habitat on Federal land. In 1995, personnel from a U.S. Department of the Interior and U.S. Department of Agriculture interagency task force, including the Bureau of Land Management (BLM), National Park Service (NPS), U.S. Department of Agriculture (USDA) Forest Service, and U.S. Geological Survey (USGS) developed a coordinated strategy for the cleanup of environmental contamination from AML associated with Federal lands. As part of the interagency effort, the USGS implemented an Abandoned Mine Lands Initiative to develop a strategy for gathering and communicating the scientific information needed to formulate effective and cost-efficient remediation of abandoned mines on Federal land. Objectives of the AML Initiative included

- Characterize watersheds and individual sites
- Understand the effect and extent of natural sources
- Communicate these results to stakeholders, land managers, and the general public
- Transfer technologies developed within the AML Initiative into practical methods at the field scale and demonstrate their applicability to solve this national environmental problem in a timely manner within the framework of the watershed approach
- Develop working relationships with the private sector, local citizens, and State and Federal land-management and regulatory agencies, and
- Establish a scientific basis for consensus and an example for future investigations of watersheds affected by inactive historical mines.

The combined interagency effort has been conducted in two pilot watersheds, the Animas River watershed study area in Colorado (fig. 1) and the Boulder River watershed study area in Montana (Nimick and others, 2004). Comprehensive scientific investigations conducted in both watersheds clearly indicate that remediation of Federal lands affected by inactive mines will require substantial investment of resources.

Land-management and regulatory agencies face two fundamental questions when they approach a region or watershed affected by inactive or abandoned mines. First, with potentially hundreds of contaminated AML sites dispersed throughout a watershed, how should resources for prioritizing, characterizing, and restoring the watershed be invested to achieve cost-effective and efficient cleanup? Second, how can realistic remediation targets be identified, considering

- The potential for adverse effects from unmined mineralized deposits adjacent to existing inactive or abandoned mines (including any effects that may have been present before premining activity and that still may persist from unmined deposits)
- The possible impact of incomplete cleanup of specific inactive historical mine sites
- Other factors—some possibly as yet unidentified—that may limit sustainable development of desired ecosystems.

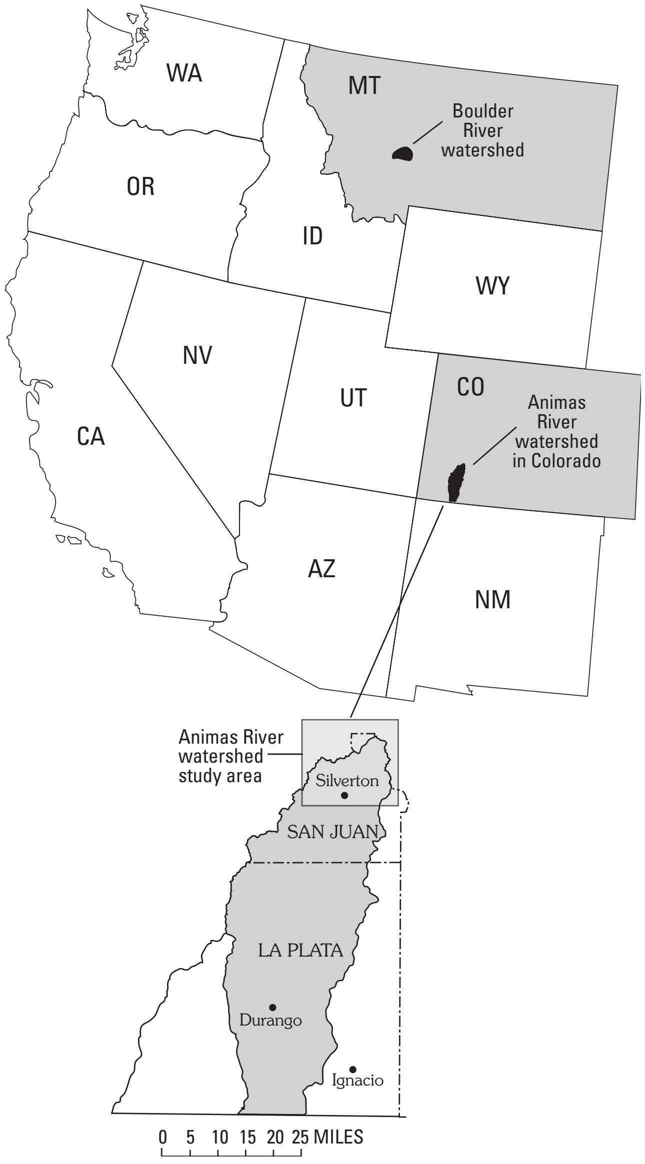

Figure 1. Western United States showing Boulder and Animas River watersheds. Animas River watershed study area is shown in inset map.

To answer these questions, the Abandoned Mine Lands Initiative adopted a watershed approach, rather than a site-by-site approach, to characterize and remediate AML sites (Buxton and others, 1997). This approach is based on the premise that acid mine drainage affecting watersheds in a State or region should be prioritized on the basis of its effect on the biological resources of the watershed so that the resources spent on remediation will have the greatest benefit on affected streams. Within these watersheds, contaminated sites that have the greatest impact on water quality and ecosystem health within the watershed would then be identified, characterized, and ranked for remediation. The watershed approach establishes a framework of interdisciplinary scientific knowledge and methods that can be employed at similar inactive mine sites throughout the Nation. The watershed approach

- Gives high priority to actions likely to most significantly improve water quality and ecosystem health
- Enables assessment of the cumulative effect of multiple and (or) nonpoint sources of contamination
- Encourages collaboration among Federal, State, and local levels of government and stakeholders
- Provides information that will assist the siting of mine-waste disposal areas
- Accelerates remediation and reduces total cost compared to remediating on a site-by-site basis
- Enables consideration of revenue generation from selected sites to supplement overall watershed remediation costs.

This report provides detailed review of field and laboratory work conducted in the Animas River watershed during 1996–2000. The objectives of this work were the following:

- Estimate premining geochemical baseline (background) conditions
- Define current geochemical baseline conditions
- Characterize processes affecting contaminant dispersal and effects on ecosystem health
- Develop remediation goals on the basis of scientific study of watershed conditions
- Transfer useful data and information to users in a timely and effective manner.

Expertise in water quality, hydrology, geology, geochemistry, geophysics, biology, mapping, and database management was applied during these investigations. Investigations were coordinated with the Animas River Stakeholders Group, Colorado Division of Wildlife, Colorado Department of Public Health and Environment, Colorado Division of Mines and Geology, Colorado Geological Survey, U.S. Environmental Protection Agency, USDA Forest Service, and U.S. Bureau of Land Management, all of which are coordinating the design and implementation of remediation activities within the watershed.

Acknowledgments

Our work would not have been possible without the assistance of individuals in various State and Federal agencies. We thank personnel in the following agencies:

Colorado Division of Wildlife and Parks, particularly Barbara Horn and Mike Japhet for their local insights, sharing of data, and assistance in obtaining collection permits;

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Special thanks to the Animas River Stakeholders Group (ARSG), with whom we worked during the course of the study, particularly William Simon, the ARSG coordinator, the San Juan County Commissioners, and the San Juan County Historical Society. Finally, we thank the private property owners in the Animas River watershed who allowed us access to their property during this study. We also thank the residents of Silverton for their hospitality while we were conducting fieldwork in the area.

Description of the Study Area

The Animas River watershed study area, hereinafter called the study area, is located in southwestern Colorado, about 40 miles north of Durango (fig. 1). Four candidate watersheds were nominated in Colorado on the basis of analysis of geologic factors, metal loading, the status of ongoing remediation activities, general knowledge of the candidate watersheds, and extent of Federal lands within the watershed. The study area was chosen as one of two pilot watersheds for the AML Initiative in May 1996.

The study area, as defined herein, is the drainage area of three tributaries: Mineral and Cement Creeks, and the Animas River upstream from Silverton. The study area for some studies was extended downstream from the confluence of Mineral Creek to an area known as Elk Park, just above the confluence of the Animas River with Elk Creek (fig. 2). Most of the study area is in four mining districts: the Silverton district, which covers the southeastern part of the study area from South Fork Mineral Creek to north of Howardsville; the Eureka district, which covers the northern part of the Mineral and Cement Creek basins as well as the upper Animas River basin from Eureka north (Davis and Stewart, 1990); the Red Mountain district, which extends up the Mineral Creek basin from Ohio Peak to the north, largely outside the study area; and the Ice Lake district, which is in the headwaters of South Fork Mineral Creek (Church, Mast, and others, this volume, Chapter E5). During watershed studies, some additional sampling and investigations were conducted downstream of the study area to document the extent of enriched trace-element concentrations in the downstream reach and to provide reference localities unaffected by historical mining.

The watershed is mountainous; elevations range from about 9,300 feet at Silverton to more than 13,800 feet above sea level. The terrain is rugged, with U-shaped and hanging valleys carved out during the last glaciation. Mean annual precipitation is about 24 to 40 in./yr (ftp://ftp.ftw.nrcs.usda.gov/pub/ams/prism/maps/co.pdf/). Although the population changes seasonally as temporary summer residents move into and out of the area, about 400 people live in the study area year-round.

Hydrologic Setting

Streamflow in the study area is typical of mountain streams throughout the southern Rocky Mountains. Streamflow is dominated by snowmelt runoff, which typically occurs between April and July. Snowmelt runoff is augmented by rain during the summer from July through September. Streamflow typically peaks in May or June and decreases in July. Low-streamflow conditions are typical from late August to March. Rainfall runoff during the summer monsoon season (frontal systems and thunderstorms) can cause increased streamflow in the area (fig. 3). Base streamflow in the study area is maintained by ground-water flow. Fractures that are densely spaced, interconnected, and unfilled by mineralization processes help to focus near-surface ground-water flow at the local or subbasin scale. The USGS streamflow-gauging station 09359020, Animas River below Silverton (fig. 2*B*, A72; period of record 1991–2003, drainage area of 146 mi^2) is 0.7 mi downstream from the confluence of Mineral Creek. Streamflow gauges are also located at the mouth of the major tributaries in the study area: 09358000, Animas River at Silverton (A68; period of record 1991–1993 and 1994–2003, drainage area 70.6 mi^2); 09358550, Cement Creek at Silverton (C48; period of record 1991–1993 and 1994–2003, drainage area 20.1 mi^2); and 09359010, Mineral Creek at Silverton (M34; period of record 1991–1993 and 1994–2003, drainage area 52.5 mi^2). These three gauges represent 98 percent of the drainage area at the streamflow-gauging station of the Animas River downstream from Silverton. The State of Colorado operates a streamflow-gauging station 09357500, Animas River at Howardsville (A53; period of record 1935–2002, drainage area 55.9 mi^2). Real-time and historical streamflow data are available on the Internet at http://co.water.usgs.gov. Data are also published in the U.S. Geological Survey annual data report, Water Resources Data Colorado, volume 2, Colorado River Basin, and the Colorado Division of Water Resources annual publication, Streamflow for Colorado.

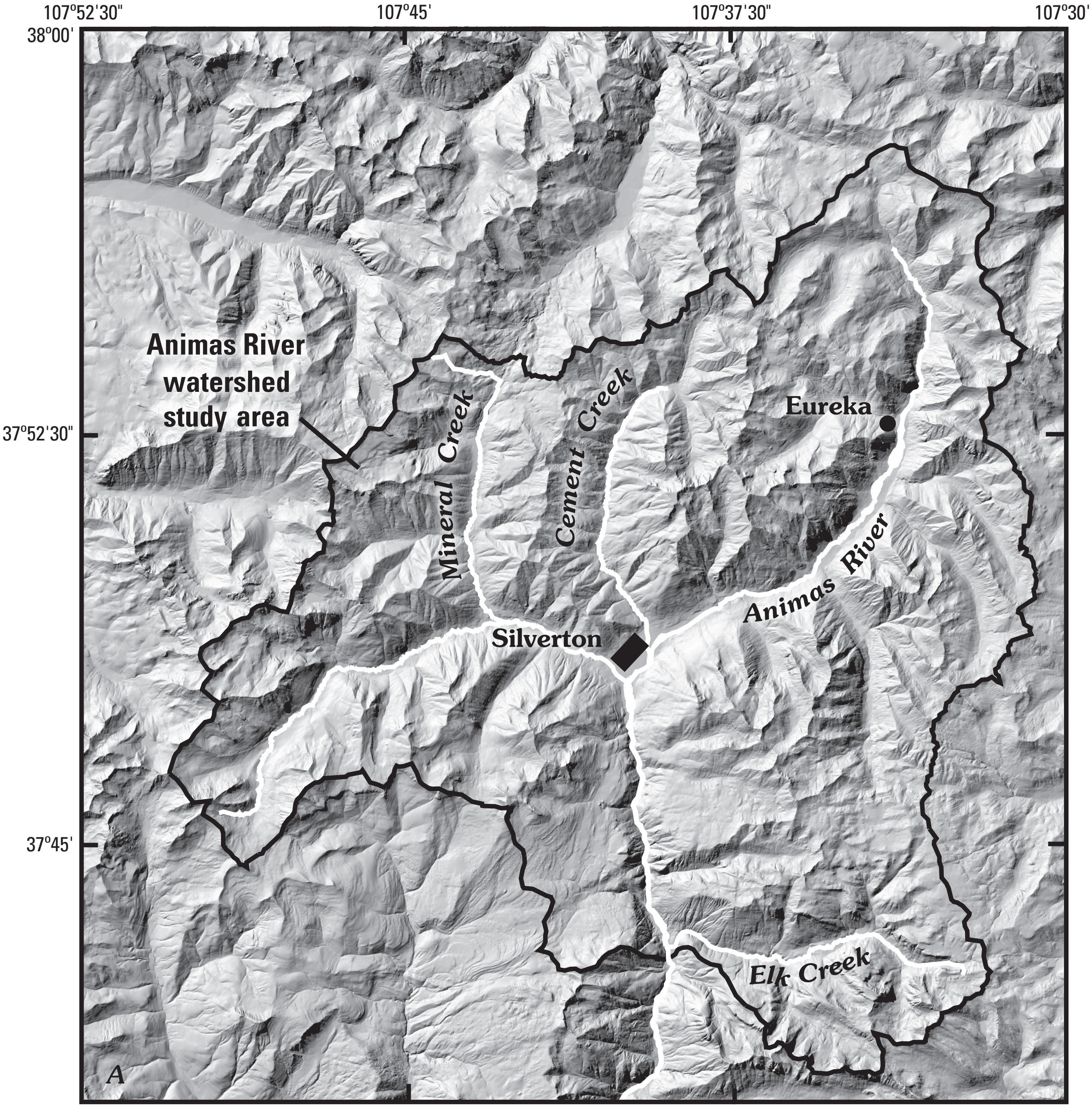


Figure 2. Animas River watershed study area labeling the Animas River and the main tributaries, Mineral and Cement Creeks, affected by historical mining. *A*, shaded relief map; *B*. location of features in text. Study area boundary in black.

The study area (fig. 2*A*) is subdivided into three large basins, the Mineral Creek and Cement Creek basins (52.5 mi^2 and 20.1 mi^2) and the upper Animas River basin (70.6 mi^2). Drainage basin areas of tributary streams to the mainstem drainages are referred to as "subbasins." Subbasins discussed in some of the chapters in section E include the headwaters area of the upper Animas River upstream from Eureka; Ross Basin, which is the headwaters area of Cement Creek; South Fork Mineral Creek subbasin, which extends outside the Silverton caldera margin to the west and is underlain by a large volume of Mesozoic and Paleozoic sedimentary rocks; and Mineral Creek upstream from the confluence with South Fork Mineral Creek.

Ground-water flow in the Animas River watershed is largely controlled by topography, distribution of unconsolidated Quaternary deposits that overlie bedrock units, and the decreasing hydraulic conductivity of geologic units with depth. Topography strongly controls direction of ground-water flow and location of discharge areas. Recharge occurs on topographic highs, with greater amounts of recharge on

Figure 2—Continued. Animas River watershed study area. *B*, location of features in text. Small triangle, streamflow gauging station.

areas with the greatest precipitation and hydraulic conductivity. Ground-water discharge, in the form of numerous seeps and small springs, occurs in topographic lows and at breaks in land-surface slope. Ground-water flow paths, from recharge to discharge areas, are short (commonly less than a few thousand feet). Regional ground-water flow is limited by the very low permeability of the bedrock. The upper, thin unit of unconsolidated deposits has the highest hydraulic conductivity. The uppermost, fractured and weathered zone in the igneous bedrock has a lower hydraulic conductivity than the unconsolidated deposits. Fractures are the major conduits for ground-water flow in bedrock, with more flow in the uppermost zone where the fractures are weathered and open.

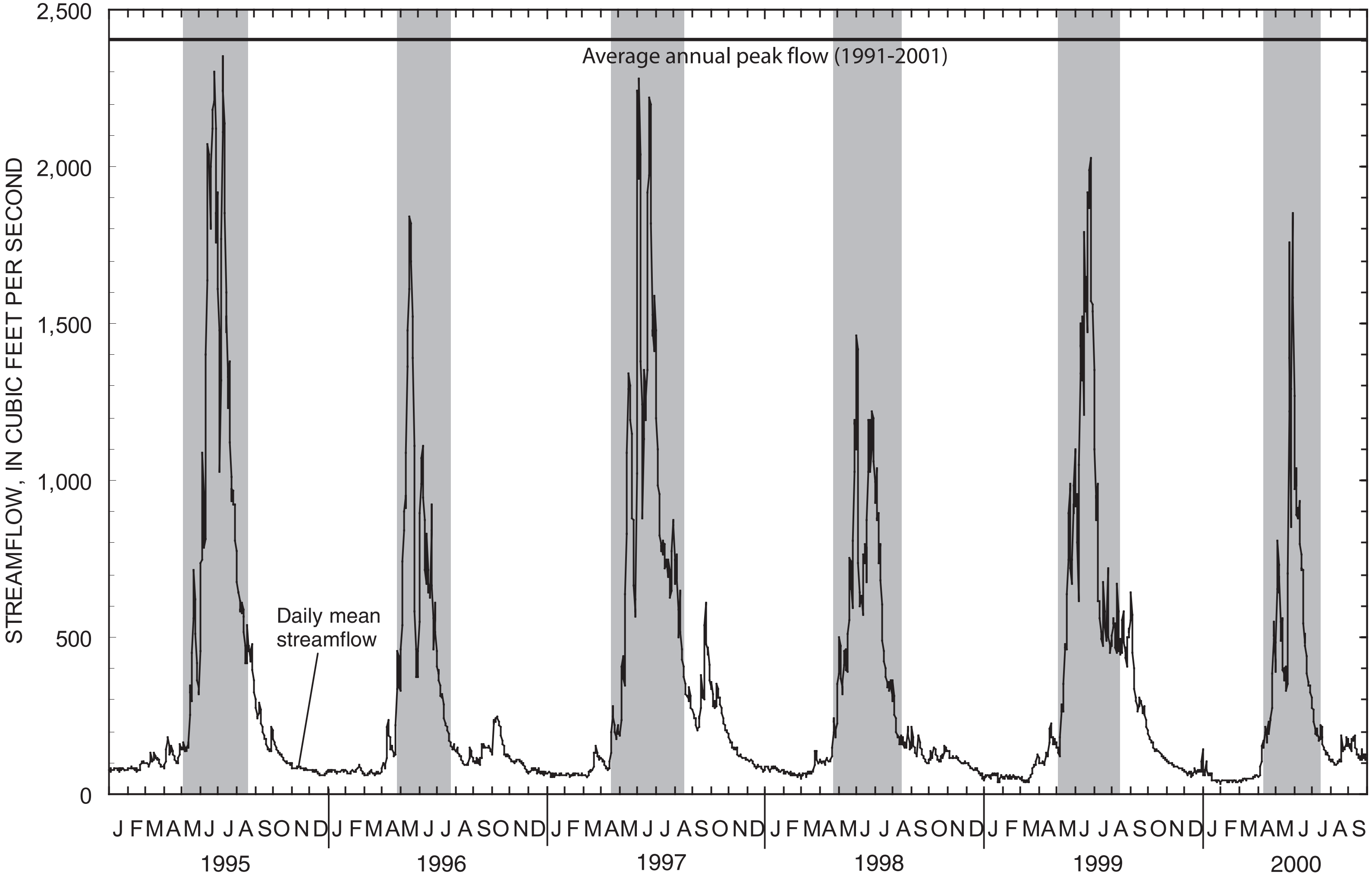


Figure 3. Daily mean streamflow during 1995–2000 at the Animas River downstream from Silverton, Colo., USGS streamflow gauging station 09359020. Average annual peak flow is 2,420±500 ft^3/s for water years 1992–2001. Shaded areas indicate periods of spring runoff during April through July.

Biologic Setting

The Animas River watershed study area consists entirely of alpine and subalpine habitats. The headwaters and tributaries of the three principal basins (upper Animas River, Cement Creek, and Mineral Creek) originate in treeless alpine regions, where vegetation cover ranges from essentially none (especially in highly mineralized areas of the Cement and Mineral Creek basins) to relatively lush alpine meadows. Streams follow high-gradient, narrow glaciated valleys, with the exception of a few low-gradient areas, such as the Animas River between Eureka and Howardsville, Mineral Creek near Chattanooga, and Bakers Park, the open wide valley where Silverton is located (Blair and others, 2002). Vegetation on valley walls is restricted in many areas by extensive areas of exposed rock and talus, but some areas of sparse coniferous Engelmann spruce forest occur on north-facing slopes and in valley bottoms, where deciduous trees also occur. Riparian vegetation is limited along many stretches of the high-gradient streams, but low-gradient reaches typically contain extensive areas of beaver ponds and associated willow thickets—except where limited by mining activity and mill tailings disposal (for example, Vincent and Elliott, this volume, Chapter E22).

The native fish community of the watershed, before European settlement, was restricted by climate and hydrology, and by barriers to upstream movement of fish in the Animas River canyon, downstream of Silverton. The only native fish species known to occur in the watershed is the Colorado River cutthroat trout (*Oncorhynchus clarkii pleuriticus*), although one account suggests that the mottled sculpin (*Cottus bairdi*), a species that occurs commonly in downstream reaches, may have occurred in portions of the upper watershed (Peter Butler, Robert Owen, and William Simon, Unpublished report to Colorado Water Quality Control Commission, Animas River Stakeholders Group, 2001).

Accounts of the aquatic biota of the Animas River watershed before the most active period of mining are few and far between. Noted ichthyologist David Starr Jordan (1891) visited the Animas River watershed in 1889 and made the following references, based on second-hand accounts:

> In the deep and narrow "Cañon de las Animas Perdidas" [Animas canyon] are many deep pools, said to be full of trout.
>
> Above its cañon of "Lost Souls," it is clear, shallow, and swift, flowing through an open cañon with a bottom of rocks. In its upper course it is said to be without fish, one of its principal tributaries, Mineral Creek, rising in Red Mountain and Uncompahgre Pass, being highly charged with iron.

The distribution of cutthroat trout in the Animas River watershed study area before settlement is unknown. Trout may have been prevented from colonizing portions of the watershed by poor water quality downstream of Mineral and Cement Creeks, or by the physical barrier of the waterfall at Rockwood, downstream of Cascade Creek. Newspaper accounts suggest that the Animas River upstream of Silverton did not support trout before brook trout were stocked in March 1885 into the upper Animas River "and the non mineral bearing streams emptying into it," including Cunningham Creek, Arrastra Creek, and Boulder Gulch (*La Plata Miner*, March 21, 1885). However, the existence of water quality and habitat suitable for trout is indicated by subsequent newspaper reports of good populations of stocked trout in artificial ponds near Silverton and in the Animas River upstream of Silverton.

Surveys by Federal and State agencies in the 1960s and 1970s indicate that the many decades of mining and milling activity had a significant adverse effect on stream biota. The reach of the Animas River upstream of Silverton, which had supported trout in previous years, yielded only a single trout in an electrofishing survey in 1968 (U.S. Department of the Interior, 1968). N.F. Smith (unpublished aquatic inventory: Animas–La Plata project, Colorado Division of Wildlife, Durango, Colorado, 1976) declared this reach of the Animas River to be "essentially dead." The Colorado Division of Wildlife stocked rainbow trout, brook trout, and brown trout in the watershed between 1973 and 1993. There is no evidence that either rainbow or brown trout were able to reproduce upstream from the Animas River canyon reach, but brook trout, which are more tolerant of low pH and elevated toxic-metal concentrations than the other species, were more successful. Brook trout is the predominant fish species in the study area, despite no documented stocking of this species since 1985.

Recent surveys of fish and benthic invertebrate communities (Besser and Brumbaugh, this volume, Chapter E18; Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001) indicate that effects of poor water quality on stream communities vary widely among the three basins and suggest that stream biota have responded to some improvements in water quality. The headwaters of the upper Animas River, the entire length of Cement and Mineral Creeks, and several smaller tributaries support little or no aquatic life due to the effects of mining and of naturally acidic water draining from hydrothermally altered areas (Bove and others, this volume, Chapter E3). The South Fork Mineral Creek and several tributaries of the upper Animas River, which drain basins that provide substantial acid-neutralizing capacity, support viable populations of brook trout and a even few cutthroat trout. The Animas River between Maggie Gulch and the mouth of Cement Creek in Silverton supports brook trout and a substantial invertebrate community, suggesting that substantial improvements in water quality have occurred in this reach since the 1970s. Impacts of degraded water quality on stream biota persist in the Animas River into the Animas River canyon downstream of Silverton, although some evidence of recovery of fish and invertebrate communities has been seen since the Sunnyside mine closed in 1991 and remediation efforts in the watershed began in 1993.

Geologic Setting

The geology of the rugged western San Juan Mountains is exceptional in that many diverse rock types representing every geologic era from the Proterozoic to Cenozoic are preserved. It is also an area that has high topographic relief, providing excellent bedrock exposures. The general stratigraphy of the San Juan Mountains near Silverton consists of a Precambrian crystalline basement overlain by Paleozoic to Tertiary sedimentary rocks and by voluminous Tertiary volcanic rocks (fig. 4).

Precambrian rocks are exposed south of Silverton along the Animas River and in upper Cunningham Creek and are part of a broad uplifted and eroded surface (fig. 4). The Precambrian section near the study area consists primarily of amphibolite, schist, and gneiss. South and west of Silverton, gently dipping Paleozoic to Tertiary age sedimentary strata of varying lithologies overlie Precambrian basement rocks. The sedimentary section, which crops out in subbasins above South Fork Mineral Creek and in other subbasins south of Silverton, comprises primarily marine and terrestrial limestone and mudstone in addition to terrestrial deposits of sandstone, siltstone, and conglomerate (fig. 4). Many of these units contain calcite and are therefore important for their acid-neutralizing potential. A thick section of Tertiary volcanic rock caps the sedimentary rocks west and southwest of Silverton and covers most of the central part of the study area. The majority of study area streams and tributaries have their headwaters in Tertiary volcanic and silicic (high silica content) intrusive rocks that have been deposited or emplaced in the area defined by Mineral Creek on the west and by the Animas River on the east, north of Silverton (fig. 5).

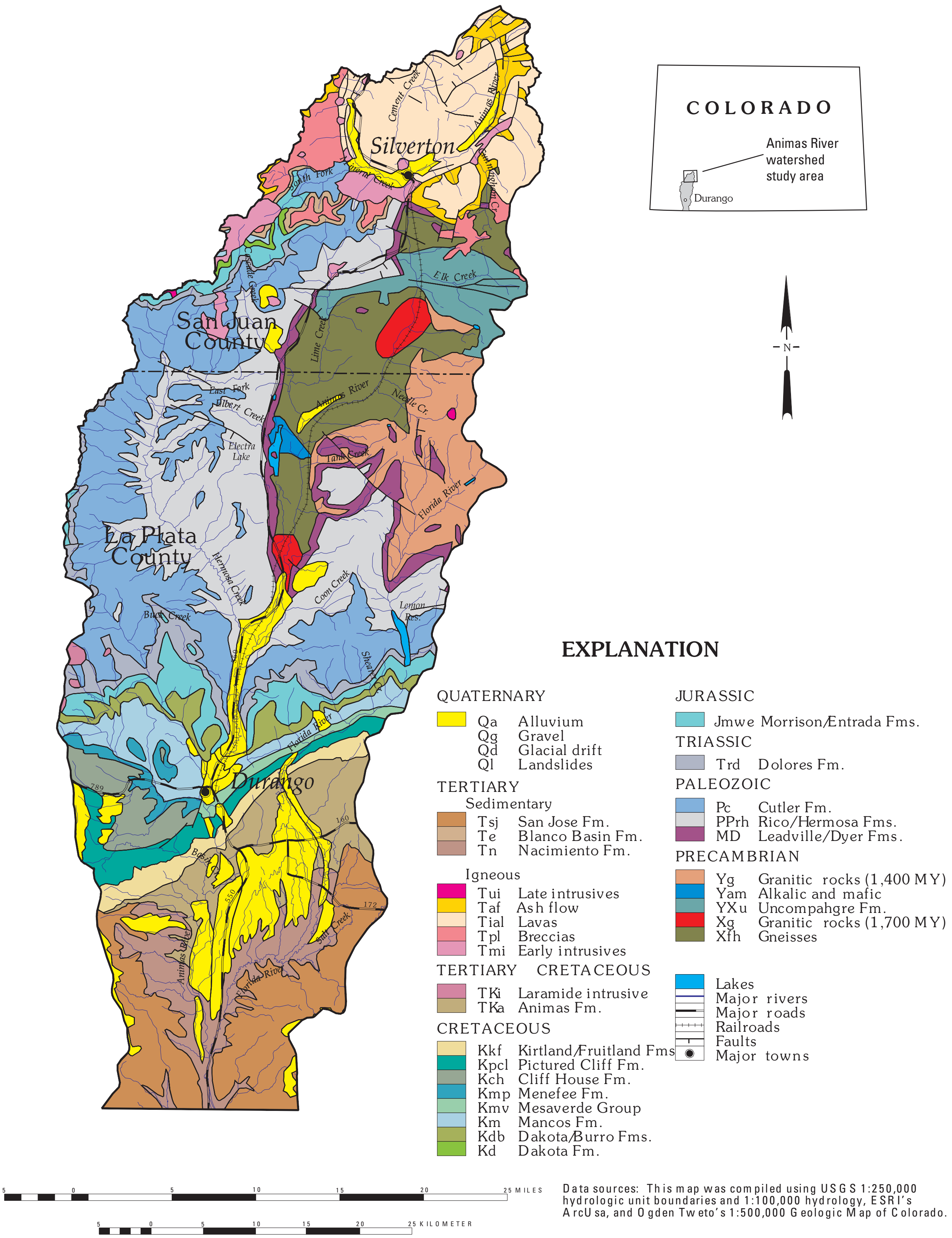
Thus, much interest in this study has focused on the Tertiary volcanotectonic history and mineralization events that have contributed to present water-quality issues. A discussion of this important aspect of the volcanotectonic geologic history follows.

Onset of volcanism in the study area commenced between 35 and 30 Ma: eruption of intermediate-composition (52 to 63 percent SiO_2) lava flows and deposition of related volcaniclastic sedimentary rocks resulted in the construction of a plateau that covered much of the San Juan Mountains area to an average thickness of about 1 km (Lipman and others, 1976). Following the early phase of intermediate-composition volcanism, silicic calderas began to form throughout the entire San Juan Mountains region. A caldera is a volcanic subsidence feature and develops when the central core of a volcanic edifice catastrophically collapses. The mechanism for collapse is the void space created by partial to complete emptying of the subterranean magma chamber beneath the upper surface or "roof" of the volcano. The volcano roof subsides into the void created as magma is simultaneously ejected from an arcuate ring-shaped fault on the volcano periphery. Caldera ring faults, also known as the structural margin, are pervasive and can extend into the crust to several kilometers depth. Calderas are roughly circular to elliptical in map view and, in the western San Juan Mountains, are typically several kilometers across. Calderas frequently resurge as new magma pushes the collapsed caldera floor upward. Resurgent magma intrudes the caldera core, causing uplift and extensive faulting that may later produce flow paths for mineralizing fluids.

Two calderas formed in the study area between about 28 and 27 Ma (fig. 5): eruption of the late Oligocene (27.6 Ma) Silverton caldera created a large semicircular depression approximately 13 km (8 miles) in diameter, which is nested within the older (28.2 Ma) San Juan caldera (Lipman and others, 1976; Yager and Bove, this volume, Chapter E1 and pl. 1). The central part of the San Juan caldera is partially filled by ash-flow tuff and by later intermediate-composition lava flows, volcaniclastic sedimentary rocks, and igneous intrusive rocks. Ash-flow tuff is a volcanic rock containing pumice, broken crystals, and wall rock fragments in a matrix of ash-size material ejected from the ring fracture zone of an actively forming caldera. Eruption of intermediate-composition lava flows and related volcaniclastic rock filled the San Juan caldera volcanic depression and hosted the majority of the mineralization processes in the study area. Granitic igneous magmas intruded the southern margins of the Silverton and San Juan calderas shortly after the Silverton caldera formed. The intrusions south of Silverton have formed along the calderas' structural margins and are centered near the area between Sultan Mountain and peak 3,792 m, in lower Cunningham Creek from Howardsville to lower Maggie Gulch, and near the mouth of Cement Creek.

An extensive bedrock fracture and fault network has developed in response to the caldera-related volcanotectonic history of the region (fig. 5). Structures related to caldera formation not only influence the hydrologic system today, but also are largely responsible for controlling where post-caldera hydrothermal fluids altered the country rock and focused the emplacement of mineral deposits. Important faults related to caldera formation include the arcuate faults that form the caldera structural margin (fig. 5). In addition, northeast-southwest-trending faults and veins that make up the Eureka graben and that cross the central core of the caldera are extensively mineralized prominent features mined for base and precious metals (Casadevall and Ohmoto, 1977; Yager and Bove, this volume, pl. 1). Northwest-southeast-trending faults and veins that are radial to the caldera ring fault zone have also been extensively mineralized. Caldera-related faults, which in places were only partially closed by later mineralization, can extend laterally and vertically from tens of meters to a few kilometers. The structures related to the San Juan–Uncompahgre and Silverton calderas are pervasive features that were not sealed by mineralizing fluids and may provide important ground-water flow paths at the basin-wide scale.

Pre- and post-caldera crustal stresses have also resulted in an extensive near-surface fracture network. Fractures at the outcrop scale commonly are spaced from 1 centimeter to several meters apart and have developed either as volcanic rocks cooled forming cooling joints, or in response to regional and local tectonic stresses. Fractures that are densely spaced, interconnected, and unfilled by later mineralization processes help to focus near-surface ground-water flow at the local or subbasin scale.



Data sources: This map was compiled using USGS 1:250,000 hydrologic unit boundaries and 1:100,000 hydrology, ESRI's ArcUsa, and Ogden Tweto's 1:500,000 Geologic Map of Colorado.

Figure 4. Generalized geology of the Colorado part of the Animas River watershed (digitized from Tweto, 1979).

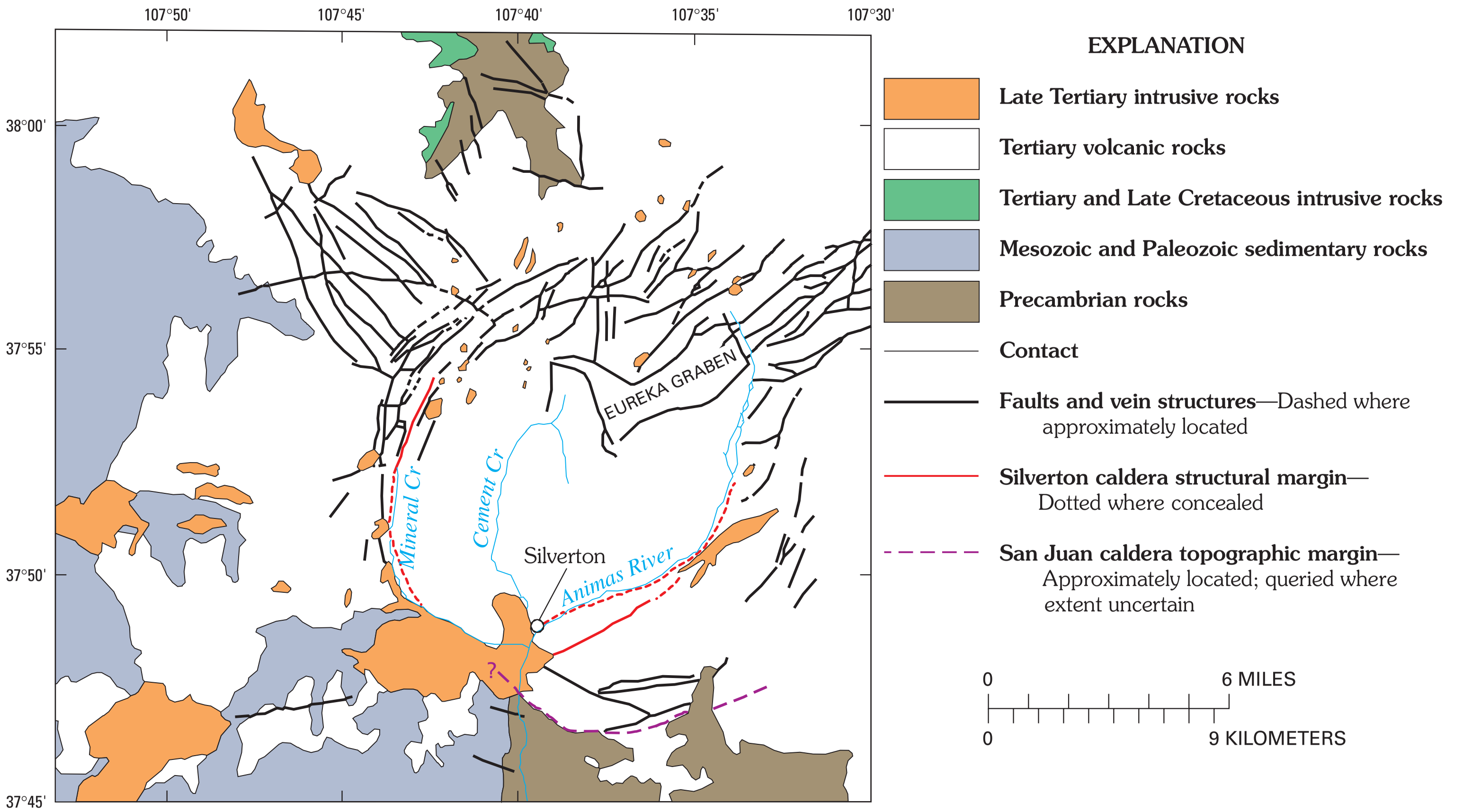


Figure 5. Generalized structure and geology of Silverton caldera, Animas River watershed study area and vicinity. Animas River and Mineral Creek follow structural margin of the Silverton caldera. In addition to the ring fractures that were created when the Silverton and the earlier San Juan calderas formed, radial and graben faults, which host much of the subsequent vein mineralization, are shown schematically (modified from Casadevall and Ohmoto, 1977).

Multiple hydrothermal alteration and mineralization events that span a 20 m.y. history from about 27 Ma to 10 Ma are the culmination of a complex cycle of volcanotectonic events that have affected the region (Lipman and others, 1976; Bove and others, 2000). The first episode of hydrothermal alteration formed during the cooling of the San Juan caldera volcanic fill, when lava flows cooled, degassed, and released large quantities of water and CO_2 (carbon dioxide) as well as other volatile constituents such as SO_2 (sulfur dioxide). Geologic mapping and airborne geophysical surveys suggest that regional alteration extended from the surface to depths as great as 1 km (Smith and others, this volume, Chapter E4; McDougal and others, this volume, Chapter E13). This event altered the primary mineral assemblage of the lava flows, and formed an alteration assemblage that includes calcite, epidote, and chlorite (Burbank, 1960). This mineral suite is part of the pre-ore propylitic hydrothermal assemblage, which has a high acid-neutralizing capacity (Desborough and Yager, 2000). Near-surface spring and surface water that has interacted mainly with propylitic rocks is found to have a pH range from 6.0 to 7.5 (Mast, Evans, and others, 2000).

Mineralization events that postdated the pre-ore propylitic hydrothermal assemblage contained sulfur-rich hydrothermal fluids and metals that produced various vein and alteration mineral assemblages, all of which include abundant pyrite (Burbank and Luedke, 1968; Casadevall and Ohmoto, 1977). Host-rock alteration in many places throughout the study area effectively removed the acid-neutralizing mineral assemblage of calcite-epidote-chlorite from these subsequently altered areas. This phase of mineralization was contemporaneous with emplacement of multiple silicic intrusions, which likely provided the heat sources for the mineralizing fluids.

Surface-water quality that results from weathering of highly altered areas is notable. One of many such examples is centered near peak 3,792 m between South Fork Mineral Creek and Middle Fork Mineral Creek northwest of Silverton. Headwater tributaries that form to the west of peak 3,792 m have a near neutral pH between 6.5 and 6.8, and originate in propylitically altered volcanic and volcaniclastic rocks. As surface water and ground water interact with assemblages containing abundant pyrite downstream, however, pH drops below 3.5 (Mast, Verplanck, and others, 2000; Yager and others, 2000; Mast and others, this volume, Chapter E7). Because of the combined effects of hydrothermal alteration that is directly associated with the mineral deposits and the widespread distribution of historical mine sites throughout the basin, it is difficult to attribute low pH values and high trace-metal concentrations exclusively to either source. The pH of samples collected at background sites ranged from 2.58 to 8.49, compared to pH at mine sites, which ranged from 2.35 to 7.77 (Mast, Evans, and others, 2000).

Late Tertiary erosion was important in exposing large surface areas of hydrothermally altered rocks in the study area to weathering processes. Younger, Pleistocene glaciation further sculpted the landscape, creating the classic U-shaped valleys, carving the cirque headwater subbasins, and depositing glacial moraine that is partly responsible for the spectacular scenery seen near Silverton. Multiple surficial deposits, including alluvium, talus, and landslide deposits (Yager and Bove, this volume, pl. 1) formed during and subsequent to glaciation and have covered more than 25 percent of the bedrock of the study area with a veneer of porous and permeable sediment (Blair and others, 2002; Vincent and Elliott, this volume). A several-thousand-year history of acidic drainage is recorded in many of the surficial deposits, where iron-rich ground water derived from weathering of pyrite has infiltrated these deposits and cemented them with oxides of iron, forming what is called ferricrete (Yager and Bove, this volume, pl. 2; Verplanck and others, this volume, Chapter E15; Wirt and others, this volume, Chapter E17). These recent geologic events have exposed mineral deposits to surface weathering prior to the mining era (Church and others, 2000). As a result, weathering reactions with these more intensely altered rocks produce acidity and release metals to the surface and ground water (Bove and others, 2000; Mast, Verplanck, and others, 2000; Yager and others, 2000). Springs draining ground water from these intensely altered rocks have pH values in the range of 2.7 to 4.0 (Mast and others, this volume).

More than 100 years of historical mining activity created many miles of underground workings and produced large volumes of mine-waste rock that have been pulverized to remove sulfide ore (Jones, this volume, Chapter C). These mine workings provide flow paths for ground water that has reacted with mineralized rock, producing acidic waters that flow from mine adits. The increase in the surface area and exposure of large amounts of pyrite to oxidation in the waste-rock piles has resulted in large anthropogenic sources of acidic drainage that affect water quality and aquatic and riparian habitats in the watershed. This process and its results add to the cumulative water-quality effect that weathering of intensely altered rock has on the watershed. Changes in the different drainage basins resulting directly from historical mining activities can be seen by the comparison of the streambed-sediment geochemical baseline prior to mining and today (Church and others, 2000). As a result, both a loss of productive aquatic and riparian habitat and a reduction in recreational and esthetic values have occurred. Further, the increased acidity and metal loading constitute a potential threat to downstream drinking water supplies.

Remediation Activities

Many of the inactive historical mine sites in the Animas River watershed study area have been inventoried for the State and Federal land-management agencies. These inventories include some data on water quality and chemistry of tailings and have been used to rank inactive mine sites that are likely candidates for remedial activities.

Interest in reducing the environmental effects of the many inactive mines and prospects in the study area increased in the 1990s. In 1991–1992, preliminary watershed analysis was coordinated by the Colorado Department of Health and Environment. The Colorado Division of Mines and Geology, USDA Forest Service, and the U.S. Bureau of Land Management inventoried and ranked inactive mines in the study area. The following unpublished reports of mine inventories in various parts of the watershed from the Colorado Division of Mines and Geology (CDMG) and the Colorado Geological Survey (CGS) were used to supplement our data:

Jonathan Lovekin, Michael Satre, William Sheriff, and Matthew Sares, Unpublished abandoned mine land inventory report for San Juan Forest, Columbine Ranger District (Colorado Geological Survey, 1997);

Jim Herron, Bruce Stover, Paul Krabacher, and Dave Bucknam, Unpublished Mineral Creek feasibility investigations report, Upper Animas River Basin (Colorado Division of Mines and Geology, 1997);

Jim Herron, Bruce Stover, and Paul Krabacher, Unpublished Cement Creek reclamation feasibility report, Upper Animas River Basin (Colorado Division of Mines and Geology, 1998);

Jim Herron, Bruce Stover, and Paul Krabacher, Unpublished Upper Animas River reclamation feasibility report, Upper Animas River Basin (Colorado Division of Mines and Geology, 1999);

Jim Herron, Bruce Stover, and Paul Krabacher, Unpublished Lower Animas River reclamation feasibility report, Upper Animas River Basin (Colorado Division of Mines and Geology, 2000).

The Animas River Stakeholders Group and Federal land-management agencies began planning for cleanup activities in the mid-1990s. Since 1991, Sunnyside Gold, Inc., has completed numerous remediation projects including removal of tailings deposits in the Animas River between Eureka and Howardsville, removal of mine dumps at the Longfellow mine and the Koehler tunnel, construction of hydrologic controls to prevent surface runoff from flowing overland through dump and tailings piles, and plugging of the numerous portals and adits (Finger and others, this volume, Chapter F). Remediation activities by BLM include mine drainage collection and diversion at the Joe and Johns mine, acid mine drainage collection and hydrologic controls at the Lark mine, acid mine drainage collection and passive wetland treatment at the Forest Queen mine, hydrologic controls and capping of the mine dump at the May Day mine, acid mine drainage collection and removal of waste rock at the Bonner mine, and the removal of tailings from the Animas River flood plain at the Lackawanna Mill site. Other remediation work has been done by the San Juan Resource and Conservation District, Silver Wing Mining Company, Gold King mine, Office of Surface Mining, Salem Minerals, and Mining Remedial Recovery (William Simon, coordinator of the Animas River Stakeholders Group, written commun., 2002).

Overview of This Volume

Chapters in this volume are arranged from general conclusions to more specific detailed and technical studies. Chapter A, 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, provides an overview and summary of this volume for those who have limited time or are unaware of which subjects presented in the volume would be most applicable to their interests. Historical mining has elevated the concentrations of cadmium, copper, and zinc in surface water of the study area. Weathering of mine wastes, and particularly of mill tailings in the study area, has also resulted in elevated concentrations of cadmium, copper, lead, and zinc in streambed sediment, resulting in stream reaches that have not historically supported aquatic life. Research by local citizen groups, the State, Federal land managers, and the USGS has led to some collaborative remediation activities carried out by Sunnyside Gold, Inc., the State of Colorado, the USDA Forest Service, and the U.S. Bureau of Land Management, and by the ARSG through funding from EPA grants that have resulted or should result in improvements in water quality and stream habitat.

Chapter C, History of Mining and Milling Practices and Production in San Juan County, Colorado, 1871–1991, by William R. Jones, describes the historical development of mining in the Animas River watershed with emphasis on the role that technological development had on mining practices, production, and mine-waste disposal. The four historical periods of development are identified: (1) The Smelting Era, 1871–1889; (2) The Gravity Milling Era, 1890–1913; (3) The Early Flotation Era, 1914–1935; and (4) The Modern Flotation Era, 1936–1991. The chapter documents the progression of milling technology and its effect on mining and milling practices in the study area. Historical photographs document the evolution of these practices. Total metal production increased as advances in mining technology made it possible to mine and mill larger volumes of ore, at increasingly lower grade, more efficiently. Total metal production generally exceeded 200,000 short tons (2,000 pounds/ton) of ore per year in the periods 1895–1910, 1924–1930, 1933–1952, 1966–1977, 1981–1984, and 1987–1990. Mining and production at the Shenandoah-Dives mine and the Mayflower Mill dominated district production from 1933 to 1952 when the Shenandoah-Dives mine closed. Mining and production from the Sunnyside mine and its new flotation mill at Eureka dominated district production from 1917 until Sunnyside closed in 1930. Discovery of new ore reserves at the Sunnyside mine spurred a new development and it again dominated production from 1966 to 1991, with a brief hiatus in production caused by the collapse of the mine workings and draining of Lake Emma, largely through the Gladstone portal, in 1978.

Mill tailings were disposed of in surface streams until legal action pushed the mining industry to change this practice. Charles Chase, superintendent of the Mayflower Mill, was one of the industry leaders in building successful mill tailings repositories at the Mayflower Mill in the mid-1930s. Total ore production for the entire period of historical production from 1871 to 1991 was 18.1 million short tons of ore. Jones estimates that during the period prior to retention of mill tailings (that is, up until about 1935) about 8.6 million short tons of mill tailings entered the Animas River and its tributaries. Knowledge of the historical practices during a century of mining helps to provide a clearer understanding of potential effects of mining on the environment. Such valuable historical context will aid land managers in evaluating the effects of historical mining, effects that are observed today in the study area.

Chapter D, Impacts of Historical Mining on Aquatic Ecosystems—An Ecological Risk Assessment, by John M. Besser, Susan E. Finger, and Stanley E. Church, is a synthesis of the combined hydrologic, geologic, and biologic studies conducted in the study area. This chapter is based on the principles of ecological risk assessment, which compares levels of exposure of aquatic biota to metals or other stressors with levels demonstrated to cause adverse ecological effects. This approach is used to identify physical and chemical characteristics that are most likely to adversely affect aquatic biota under current conditions in the watershed and to evaluate prospects for remediation and recovery at the watershed level. The chapter analyzes short-term (acute) and long-term (chronic) exposure of fish and invertebrate communities to metals, based on concentrations of lead, cadmium, copper, iron, zinc, and aluminum in water, sediment, and diet. These exposure levels are compared to site-specific toxicity thresholds determined for high-priority species, such as brook trout, *Salvelinus fontinalis*, and to State and Federal water-quality standards for these metals. Results of this analysis are interpreted both in terms of the current geographic extent and severity of ecological risks and a prospective assessment of the effects of ongoing and planned remediation efforts in the watershed.

Chapter E groups 25 reports that provide the scientific basis for conclusions and recommendations made in this volume. These reports describe detailed studies focused on particular aspects of the Animas River watershed study.

Chapter E1, Geologic Framework, by Douglas B. Yager and Dana J. Bove, summarizes the geology of the study area and focuses on the extensive Tertiary volcanic events. It includes two oversize plates. Plate 1 is a geologic map of the study area at a scale of 1:48,000. Pre-caldera Tertiary conglomerates and volcanic rocks overlie Precambrian crystalline and Paleozoic and Mesozoic sedimentary rocks in the Animas River watershed. Caldera volcanism began 28.2 Ma with the formation of the San Juan caldera. Subsequently, the Silverton caldera formed at 27.6 Ma. Regional propylitic alteration affected all the lavas within the caldera. Subsequent multiple episodes of mineralization resulted in overprinting of four distinct types of hydrothermal alteration having different mineral assemblages and occurrences: weak sericite-pyrite alteration, vein-related quartz-sericite-pyrite alteration, quartz-sericite-pyrite alteration, and acid-sulfate alteration. The regional propylitic alteration provides some acid-neutralizing capacity whereas the others are all acid-generating mineral assemblages. The study area was extensively glaciated, producing U-shaped river valleys (Blair and others, 2002) and exposing fresh mineralized rock surfaces to weathering. Weathering of rock containing acid-producing alteration assemblages resulted in the formation of acid and the release of metals prior to historical mining. Plate 2 of this report (scale 1:48,000) maps the distribution of ferricrete, a conglomerate that is cemented by iron-oxide minerals, and shows photographs of these deposits.

Chapter E2, Imaging Spectroscopy Applied to the Animas River Watershed and Silverton Caldera, by J. Bradley Dalton, Dana J. Bove, Carol S. Mladinich, and Barnaby W. Rockwell, is a study that mapped the distribution of minerals in the watershed using AVIRIS (Airborne Visible and Infrared Imaging Spectrometer) technology. This technology allows preparation of maps using data acquired by high-altitude aircraft. The detector is flown over the study area and light reflected from the ground surface is acquired using a 254-channel recorder. The dominant minerals at the surface (AVIRIS measures surface reflectance) from each 17-m by 17-m AVIRIS pixel were identified by comparison to a spectral library (Clark and others, 2003), and the images were corrected for optical distortions to produce a series of mineral maps. This procedure allows the uniform preparation of maps showing mineral assemblages across the study area, where the ground surface is not obscured by vegetation or snow. The resultant mineral assemblages were then verified in the field before they were used to construct maps of the hydrothermal mineral assemblages of the watershed. This methodology was used to provide a spatial assessment of acid-generating and acid-neutralizing areas within the study area (Dalton and others, 2004). Propylitically altered rocks dominate the east side of the caldera, whereas acid-sulfate and quartz-sericite-pyrite altered areas are spatially more limited and occur on the west side of the caldera. Surface water pH in the western subbasins is generally less than 4.5. The chapter demonstrates a method to obtain maps showing hydrothermal alteration at a scale needed for the assessment of acidity and metals contributed by weathering processes.

Chapter E3, Major Styles of Mineralization and Hydrothermal Alteration and Related Solid- and Aqueous-Phase Geochemical Signatures, by Dana J. Bove, M. Alisa Mast, J. Bradley Dalton, Winfield G. Wright, and Douglas B. Yager, describes the hydrothermal alteration and mineralization of five discrete periods: regional propylitic alteration of the lavas in the Silverton caldera, which make up 90 percent of the altered rock in the study area; porphyry Cu-Mo mineralization (26–25 Ma) and its associated quartz-sericite-pyrite alteration zone on the west side of the Silverton caldera centered on peak 3,792 m; acid-sulfate alteration and mineralization in the Red Mountain and Ohio Peak–Anvil Mountain areas (23 Ma); northeast-trending polymetallic vein mineralization associated with the Eureka graben (18–10 Ma) and associated vein quartz-sericite-pyrite alteration; and the northwest- and northerly-trending veins and associated alteration associated with the south Silverton area along the caldera margin. Water from mine adits is compared with that from springs in each of these altered areas. Mine-adit discharge consistently contains higher metal content than the springs, but water from altered but unmined areas in each of the hydrothermally altered areas reflects the geochemistry of the mineral assemblage. Water from the acid-sulfate and quartz-sericite-pyrite mineral assemblages is acidic, whereas that from the propylitic assemblage is near neutral. Water from the propylitic rocks, which contain calcite, chlorite, and epidote, provides alkalinity that contributes acid-neutralizing capacity to surface water in streams and thus may mitigate some of the effects caused by historical mining.

Chapter E4, Helicopter Electromagnetic and Magnetic Surveys, by Bruce D. Smith, Robert R. McDougal, Maryla Deszcz-Pan, and Douglas B. Yager, summarizes the new helicopter geophysical data and the data reduction method used to produce geophysical maps for the study area. A plate showing the draped helicopter magnetic data (pl. 3, a high-pass-filtered, reduced-to-the-pole, color-shaded relief of the total-magnetic field map at a scale of 1:48,000) overlies the topographic map of the study area and provides a geophysical image of the upper 200 m of the crust. Three different frequencies were separated to produce maps of magnetic features at depths of 200 to 1,300 m below the surface. Interpretations of the primary spatial and linear magnetic features are given and compared with the geologic map (pl. 1, Yager and Bove, this volume). A second plate (pl. 4, an apparent conductivity map at 4,310 Hz, color-shaded relief map, scale 1:48,000) is draped over the topographic map of the study area and shows the electrical conductance characteristics of the crust in the study area. Spatial and linear features in this data set are also interpreted using the geologic and magnetic data to provide insight into the interpretation of ground-water flow and possible buried and unexplored features that may be mineralized.

Chapter E5, Mine Inventory and Compilation of Mine-Adit Chemistry Data, by Stanley E. Church, M. Alisa Mast, E. Paul Martin, and Carl L. Rich, is an inventory of the significant mines, mills, and mill-tailings sites in the study area. Three hundred seventy-three historical and inactive mine, mill, and mill-tailings sites were accurately located using digital orthophoto quadrangles (DOQ) and verified in the field. Prospect pits were too numerous to list, but more than 5,000 mine features were located on early USGS topographic maps. Detailed site characterization, including flowing adits, their pH and water chemistry, and the size and distribution of mine and mill waste, was compiled into a relational database. Tables of adit-flow chemistry are provided for evaluation of the effect of mine adit drainage on surface water. Observations on changes in flow rate and water chemistry from seven mines monitored monthly for a year or more are discussed in terms of their potential effects on remediation strategies. Water chemistry from these mines did not change much during the year, but flow rate increased during spring runoff in some of them, indicating that the increased flow results from increased infiltration into the mine pool during snowmelt.

Chapter E6, Mine Adits, Mine-Waste Dumps, and Mill Tailings as Sources of Contamination, by J. Thomas Nash and David L. Fey, provides data on metals from 97 mine-waste sites, 18 mill-tailings sites, and 60 flowing adits located on Federal lands in the study area. Because remediation of private sites is outside the public purview, these studies focused on sites where public funds may be spent to reduce their impact on water quality within the watershed. Geochemical and observational data were used to rank sites on the basis of their potential to affect surface water in the watershed. Most of the mines examined on Federal land were distant from major streams and had minimal effect on surface water. Also, most of the disturbed sites in the watershed on Federal lands are small prospect pits with less than 50 tons of disturbed rock. Three factors—acid generation, metals released in leach tests, and size of the mine or mill wastes—were used to rank solid materials, whereas copper and zinc loading and acidity were used to rank adit drainage. Of the more than 500 sites identified on Federal lands, only about 40 sites had sufficient size, adit discharge, and mine-waste chemistry to be considered significant sources of metal contamination. On the basis of the work reported here and the analysis presented by the Animas River Stakeholders Group (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001), which included data from private mine sites, the majority of the metal contamination in the watershed comes from privately held mine sites or from sites with mixed private-public ownership.

Chapter E7, Characterization of Background Water Quality, by M. Alisa Mast, Philip L. Verplanck, Winfield G. Wright, and Dana J. Bove, characterizes water quality from unmined sites in the study area. Water quality in historical mining districts is affected by metal-rich drainage from inactive mines and by weathering of mineralized bedrock in unmined areas. One hundred and forty-six streams and springs minimally affected by mining (background sites) were sampled during low-flow conditions in 1997–1999. The primary factor controlling the chemistry of background sites was the degree of bedrock alteration. Drainage from propylitically altered rock produced neutral surface water with low dissolved metal concentrations, whereas drainage from quartz-sericite-pyrite altered rock generated surface water with low pH and elevated dissolved metal concentrations. Drainage from 75 inactive mine sites and 95 mining-affected surface-water sites were sampled for comparison with background water quality. Comparison of background samples with mine drainage samples showed statistically significant differences in concentrations for all the major ions and many dissolved metals, including barium, copper, iron, manganese, strontium, and zinc. Higher concentrations of all metals except barium were from the mine sites. Estimation of metal contributions from background sources on a watershed scale was complicated by a number of factors including the large number of mining-related features, rugged topography, complex geology, and contributions of ground water from unknown sources. Several different approaches were explored to estimate background water quality in the study area on different scales including statistical descriptions, mass-balance calculations, isotopic applications, and rare-earth-element geochemistry. The results demonstrate that metals released from weathering of altered rock from unmined areas are significant in some stream reaches and must be taken into account when water-quality standards and remediation goals are established for the study area.

Chapter E8, Aqueous-Sulfate Stable Isotopes—A Study of Mining-Affected and Undisturbed Acidic Drainage, by D. Kirk Nordstrom, Winfield G. Wright, M. Alisa Mast, Dana J. Bove, and Robert O. Rye, is the summary of stable isotope data (sulfur in pyrite and sulfur and oxygen in aqueous sulfate and sulfate minerals) from more than 100 samples, including water, pyrite, gypsum, and anhydrite, that were collected and analyzed to evaluate processes of mineral dissolution and pyrite oxidation on aqueous sulfate from both mined and unmined but mineralized areas. The combined results from major ion chemistry and sulfur isotopes show three dominant processes affecting water quality: (1) gypsum and anhydrite dissolution, (2) pyrite oxidation, and (3) calcite dissolution. Gypsum and anhydrite are primarily shown to be hypogene in origin whereas sulfur in pyrite has a significantly lighter signature ($\delta^{34}S = -7$ to 2.5 per mil). Distinct trends of mixing between aqueous sulfate in water dominated by gypsum/anhydrite dissolution and in water dominated by pyrite oxidation are apparent from the data. A tendency for aqueous sulfate in water samples from unmined areas to have slightly heavier $\delta^{18}O$ relative to aqueous sulfate in water from mined areas is also apparent in the data, although these data exhibit considerable overlap. Factors such as evaporation, mixing of pyrite oxidation-dominated water with gypsum/anhydrite-dominated water and dilution or mixing of water after the site of pyrite oxidation are important in the interpretation of oxygen isotopic data in aqueous sulfate.

Chapter E9, Quantification of Metal Loading by Tracer Injection and Synoptic Sampling, 1996–2000, by Briant A. Kimball, Katherine Walton-Day, and Robert L. Runkel, is a compilation of efforts to characterize metals loading and trace- and major-element sources in the watershed. This chapter presents the hydrologic framework, established by conducting a series of tracer-injection studies, for the study of metal loading in the study area. Each study used the tracer-dilution method to quantify stream discharge in conjunction with synoptic sampling to provide downstream profiles of pH and solute concentration. Discharge and concentration data were then used to develop mass-loading curves for the various solutes. The discharge and load profiles (1) identify the principal sources of solute load to the streams; (2) demonstrate the scale of unsampled, dispersed subsurface inflows; and (3) estimate the amount of solute attenuation resulting from physical, chemical, and biological processes. Mass-loading analysis indicates that at low flow, Mineral Creek basin dominates the contribution of total copper load in the study area. The Mineral Creek basin contributes 60 percent, Cement Creek basin contributes 30 percent, and the upper Animas River basin contributes 4 percent of the cumulative instream copper load in the watershed. The remaining 6 percent is from sources downstream from these basins. Cement Creek had the greatest contribution of total zinc load: 40 percent of the cumulative instream load at the A72 gauging station, downstream from Silverton, was from the Cement Creek basin, 31 percent was from the upper Animas River basin, and 24 percent was from Mineral Creek basin. The contribution of aluminum and iron loads from Cement and Mineral Creek basins was more substantial than for copper and zinc. Mass-loading results indicate that 9 percent of the aluminum load was from the upper Animas River basin, 43 percent from Cement Creek basin, and 42 percent from Mineral Creek basin. The contribution of iron from the upper Animas River basin was 4 percent, from Cement Creek basin 49 percent, and from Mineral Creek basin 43 percent. Manganese loading differed from the other metals because the greatest percentage, 49 percent, came from the upper Animas River basin, while 31 percent came from Cement Creek basin, and 15 percent came from Mineral Creek basin. The greater loads from Cement and Mineral Creek basins correspond to geologic patterns of hydrothermal alteration. Within these basins, 24 locations have been identified that account for 73 and 87 percent of the total mass loading of these selected metals. These locations include both mined and unmined areas. This detailed snapshot of mass loading during low flow can be used to guide remediation decisions and to quantify processes affecting metal transport.

Chapter E10, Distribution of pH Values and Dissolved Trace-Element Concentrations in Streams, by Winfield G. Wright, William Simon, Dana J. Bove, M. Alisa Mast, and Kenneth J. Leib, describes dissolved trace-metal concentrations and pH values in streams throughout the study area. Dissolved trace-metal concentrations and pH values were highly variable and depended on factors such as hydrothermal alteration, acid-neutralizing capacity of the rocks, and mixing of different waters. Hydrothermal alteration was the primary control on distribution of dissolved trace-metal concentrations in streams because the rocks in the study area have a wide range of mineral assemblages. Maps of the spatial distribution of dissolved trace-element concentrations and pH are presented for low-flow and high-flow conditions. Ribbon maps show different pH ranges and dissolved trace-metal concentrations in study area streams. The distribution maps also display areas of hydrothermal alteration and locations of selected historical mine sites. There are numerous mines, prospect pits, and mining-related features in the study area, many of which do not affect water-quality conditions. Therefore, a subset of mines was selected representing draining adits, mine-waste dumps, and permitted mine and mill sites that may affect the dissolved trace-element concentrations. Because of the combined effects of hydrothermal alteration and historical mines, it is difficult to attribute low pH values and high trace-metal concentrations to either source. However, the highest concentrations of metals were in headwater streams near high-ranking historical mines and drainage from those areas clearly affects the streams. Flows from several iron- and manganese-rich springs cause low pH values and high trace-metal concentrations in streams, for example, in Mineral Creek near peak 3,792 m, in upper Cement Creek, and in California Gulch.

Chapter E11, Characterization of Mainstem Streams Using Water-Quality Profiles, by Kenneth J. Leib, M. Alisa Mast, and Winfield G. Wright, characterizes the seasonal pattern of toxic trace-metal concentrations and loads for the major tributaries in the study area. These tributaries are Mineral Creek on the west, Cement Creek, and the upper Animas River upstream from the gauge below Silverton (fig. 2*B*). Seasonal patterns in water quality are estimated using water-quality profiling, which allows for the assessment of priority areas to be targeted for characterization and (or) remediation by quantifying the timing and magnitude of contaminant occurrence. Streamflow and water-quality data were collected at 15 sites in the upper Animas River basin during water years 1991–99. Water-quality regression models were developed to estimate hardness and dissolved cadmium, copper, and zinc concentrations based on streamflow and seasonal terms. Results from the regression models were used to calculate water-quality profiles for streamflow, constituent concentrations, and loads. The water-quality profiles are used, along with mass accounting, to quantify the portion of metal loading in the segment derived from uncharacterized sources during different seasons. Results indicated that metal sources in the study area may change substantially with season.

Chapter E12, Trace Elements and Lead Isotopes in Modern Streambed and Terrace Sediment—Determination of Current and Premining Geochemical Baselines, by Stanley E. Church, David L. Fey, and Daniel M. Unruh, is a study of the streambed-sediment chemistry in the major streams and tributaries in the watershed study area and the effect of historical mining on sediment quality. Concentrations of arsenic, copper, lead, and zinc in modern streambed sediments exceed published sediment-quality guidelines downstream from historical mine sites. Following the geomorphological studies of the watershed (Blair and others, 2002), terrace deposits were sampled to determine premining geochemical baseline concentrations of potentially toxic metals. In comparison with the premining sediment data, concentrations of arsenic, copper, lead, zinc, cadmium, silver, manganese, iron, and aluminum are elevated at sites downstream from historical mines and mills. The effect of these elevated metal concentrations can be seen in sediment downstream to Elk Park at the southern boundary of the study area. Ribbon maps showing the concentration of metals and their lead isotopic signatures indicate that the majority of the metals in streambed sediment in the Animas River upstream of the confluence with Cement Creek are from a single site, the flotation mill, Sunnyside Eureka Mill, which discharged more than 500 tons of tailings per day of mill waste from 1917 to 1930 (Vincent and others, 1999).

Chapter E13, Topographic, Geophysical, and Mineralogical Characterization of Geologic Structures Using a Statistical Modeling Approach, by Robert R. McDougal, Anne E. McCafferty, Bruce D. Smith, and Douglas B. Yager, is an analysis of the potential of the airborne magnetic and electromagnetic data to predict additional veins and structures that could influence the flow of ground water or control undiscovered mineralized rock in the subsurface. Faults and veins shown by geologic mapping and the topographic features determined by the convexity of the digital elevation model are compared with the magnetic and electromagnetic data and their derivative maps to evaluate the predictive capability of these two methods to find buried or concealed faults and veins. Blind tests of the model showed a high probability for identification of known structures. Faults and veins are characterized by moderately high electrical resistivities that are interpreted to indicate that these structures are quartz filled. Numerous undiscovered structures should exist in areas where they are concealed by alluvium or colluvium. The model predicts that 36 percent of the structures in the caldera are not exposed. The predictive model based on the topographic data also predicts that numerous features extend beyond their mapped extent. Electrical resistivity gradient maps showed a preferred orientation of east-west structures that appear to be poor conductors and may act as barriers to ground-water flow. Ground-water flow modeling must incorporate the findings of this model to accurately predict subsurface flow.

Chapter E14, Formation and Geochemical Significance of Iron Bog Deposits, by Mark R. Stanton, Douglas B. Yager, David L. Fey, and Winfield G. Wright, describes the occurrence and geochemistry of several iron bogs in the study area. Iron bogs form when oxygen-poor ground water discharges to the surface. Ground-water chemistry is controlled by leaching of metals present in the hydrothermally altered rock up gradient of the iron bogs. Dissolution of pyrite results in ground water rich in dissolved iron and sulfate with some trace elements. This process has been ongoing since at least the end of the last glacial period 12,000 years B.P. Following discharge, subsequent oxidation of ferrous to ferric iron results in the lowering of pH and the precipitation of iron oxyhydroxides (schwertmannite and goethite) forming the iron bogs. More than 50 percent of the solids precipitated are amorphous. Geochemically active microbes and plants influence the formation, growth, and persistence of the iron bogs themselves. Cyanobacteria and algae were observed in these iron bogs; they act as traps for iron oxyhydroxide precipitates. Iron and aluminum concentrations as high as 46.0 and 12.1 weight percent were measured in these chemical precipitates. Maximum concentrations of copper (110 ppm), lead (60 ppm), zinc (660 ppm), and arsenic (5,000 ppm) were detected in sediment from the iron bogs. Retention of these metals in iron bogs is both pH dependent and probably flow-rate dependent. Thus, the iron bogs represent both sources of metals and acidity to streams and transient reservoirs of potentially toxic metals concentrations and acidity to basin streams in the study area. Although the iron bogs studied resulted from natural processes of weathering, some sites immediately down gradient from historical mines or adits rely on these processes to remove metals from acidic adit flow. Modern iron-oxide-cemented deposits are present in mine-waste dumps, indicating that they can form over tens of years.

Chapter E15, Ferricrete Classification, Morphology, Distribution, and Carbon-14 Age Constraints, by Philip L. Verplanck, Douglas B. Yager, Stanley E. Church, and Mark R. Stanton, provides descriptions of the methods used to classify and map the distribution of ferricrete in the study area. Ferricretes are stratified iron oxyhydroxide deposits, or clastic sedimentary deposits cemented by stratified iron oxyhydroxide, and they represent the sites in the watershed where paleo ground water emerged. The ferricrete map is an important component that aids in the understanding of premining conditions in the watershed (Yager and Bove, this volume, pl. 2). Three deposit types were distinguished: (1) those that contained essentially no clasts and are formed by iron springs or in iron bogs, (2) those that contain monolithic angular to subrounded clasts and are cemented colluvium, and (3) those that contain subrounded to rounded clasts of several different lithologies and are cemented alluvium. Ferricrete deposits were not found to be uniformly distributed throughout the watershed; instead, they are concentrated in areas where hydrothermal alteration was most intense. Mineralogical data show that these deposits commonly contain goethite, schwertmannite, and amorphous iron oxides. Schwertmannite was found in actively forming (wet) ferricrete deposits and iron bogs as well as in ancient (dry) bog iron deposits, indicating that schwertmannite, although a relatively unstable mineral and once formed, subject to alteration, may persist in deposits that range in age from modern to thousands of years B.P. A subclass of ferricrete, manganocrete, was distinguished by the occurrence of black cement and manganese content that exceeded 5 weight percent. Manganocrete is primarily associated with weathering of manganiferous ore deposits in the Eureka graben. Thirty-five ^{14}C dates from stumps in growth position or from logs in the alluvial deposits cemented by ferricrete gave ages ranging from 9,150 years B.P. to modern. Most ages are less than 5,000 years B.P. Because the wood fragments were incorporated into the clastic sediment at the time of sedimentation, these fragments represent a maximum age of cementation.

Chapter E16, Geomorphology of Cement Creek and its Relation to Ferricrete Deposits, by Kirk R. Vincent, Stanley E. Church, and Laurie Wirt, is a detailed geomorphic study of the lower 6.2-mile reach of Cement Creek shown on plate 5 (scale 1:6,000). The data provide a context for timing of Holocene events and an interpretation of processes that control the formation of ferricrete. Glaciers have had a major influence on the drainage and landforms that control the movement and emergence of ground water. Thick deposits of ferricrete at the mouths of Cement and Mineral Creeks and Blair Gulch represent glacial outwash gravel deposited in Bakers Park during the last glacial period about 10,000 years B.P. and incision of these deposits about 6,000 years B.P. The distribution of clastic ferricrete deposits relative to bogs and standing water in sedge marshes indicates that the geomorphology of the Cement Creek drainage provides important controls on the formation of ferricrete. Contemporary rates of flow at base flow are not useful predictors of the occurrence of ferricrete. The ^{14}C dates provide age control on the incision and aggregation of alluvium and thus constrain the maximum age of formation of ferricrete.

Chapter E17, Geochemical and Hydrologic Processes Controlling Formation of Ferricrete, by Laurie Wirt, Kirk R. Vincent, Philip L. Verplanck, Douglas B. Yager, Stanley E. Church, and David L. Fey, is a study of processes that are analogous to acid mine drainage and that provide a baseline for premining conditions near unmined mineral deposits. Ferricrete forms down gradient from areas of hydrothermal alteration and is a long-term sink for elevated concentrations of iron, sulfate, copper, zinc, and arsenic. The occurrence of schwertmannite in ferricrete deposits provides evidence that premining water chemistry had a pH in the range of 3–4.5, which is too acidic to support aquatic life. Ferricrete forms when reduced, acidic ground water comes in contact with oxygen, causing the precipitation of iron oxyhydroxide minerals. Weathering of hydrothermally altered rock results in the formation of acid-sulfate type ground water that concentrates copper and zinc by 100 fold. As extreme as this natural acid-sulfate water is, it is not as enriched in trace elements as water from areas affected by historical mining. Areas most heavily affected by mining have water with pH less than 3 and sum of metals (arsenic, cadmium, cobalt, copper, nickel, and zinc) greater than 1,200 µg/L (micrograms per liter).

Chapter E18, Status of Stream Biotic Communities in Relation to Metal Exposure, by John M. Besser and William G. Brumbaugh, summarizes recent studies of the fish and macroinvertebrate communities of the study area. Both fish and invertebrate communities show trends that are apparently related to the location and severity of contributions of acidity and toxic metals associated with historical mining activities and weathering of hydrothermally altered rock. Cement Creek and the mainstem of Mineral Creek were devoid of fish (trout are present in South Fork Mineral Creek). The chapter summarizes trends in distribution and density of populations of brook trout and trends in abundance and number of taxa of aquatic macroinvertebrates, as they are related to concentrations of metals (cadmium, copper, lead, and zinc) in tissues of fish, invertebrates, and attached algae tissue communities (periphyton). Associations between metal concentrations and population status of fish and invertebrates are used to indicate which metals have the greatest potential for causing adverse effects on stream ecosystems in the study area. Chronic copper toxicity appears to be an important limiting factor for the distribution and abundance of brook trout in the watershed.

Chapter E19, Toxicity of Metals in Water and Sediment to Aquatic Biota, by John M. Besser and Kenneth J. Leib, summarizes results of field and laboratory toxicity studies and presents models of seasonal patterns of toxicity of stream water. The toxicity of stream water and fine-grained streambed sediment to fish and invertebrates was evaluated in several studies conducted on-site and in the laboratory between 1997 and 1999. Additional laboratory studies using brook trout and a freshwater amphipod, *Hyalella azteca*, characterized the toxicity of dissolved copper and zinc in test waters representative of water-quality conditions in the Animas River at Silverton. Toxicity thresholds for copper and zinc were combined with models of seasonal variation of water hardness and dissolved metals concentrations to predict seasonal variation in toxicity of stream water at three streamflow gauging stations near Silverton. Seasonal patterns of toxicity predicted by these models were consistent with observed seasonal differences in toxicity and with differences in resident fish and invertebrate communities, suggesting that toxicity models could be used to predict improvements in aquatic biota following remediation.

Chapter E20, Effects of Mining on Benthic Macroinvertebrate Communities and Monitoring Strategy, by Chester R. Anderson, characterizes the species composition, taxa richness, density, and diversity of the benthic macroinvertebrate community in the Animas River watershed during 1996 and 1997. Results of these surveys indicate that reaches of the Animas River affected by mining had lower densities and lower numbers of taxa of aquatic macroinvertebrates, relative to reference streams. Both density and taxa richness also showed longitudinal patterns relative to mining-affected tributaries, with low values upstream of Eureka Gulch and downstream of Cement and Mineral Creeks, and increases in the Animas River reach between Eureka and Silverton, and in the Animas River canyon downstream of Mineral Creek. These data document current ecological conditions in the watershed and provide a biological baseline for assessing future changes in water and habitat quality due to remediation efforts in the watershed. This chapter highlights the importance of intensive monitoring of the recovery of the benthic macroinvertebrate community following remediation, and includes methods and strategies for evaluation of its effectiveness.

Chapter E21, Application of Physical Habitat Simulation in the Evaluation of Physical Habitat Suitability, by Robert T. Milhous, describes the suitability of stream habitat for survival of trout by applying a physical habitat simulation model to measurements of stream velocity, channel depth, and nature of substrate from the Animas River. Results from the model suggest that available winter habitat in the upper Animas River can limit survival of adult trout populations and that overall habitat suitability may reduce their reproductive success in the fall. The analysis also suggests that increased stream velocities associated with high-flow events may limit the density of trout populations in some years. This chapter provides information on the potential for physical habitat quality to limit recovery of a trout fishery in the study area.

Chapter E22, Response of the Upper Animas River Downstream from Eureka to Discharge of Mill Tailings, by Kirk R. Vincent and John G. Elliott, is a detailed study of the effects of extensive mill tailings disposal on the flood plain. To establish the impact of mill waste discharge, the authors used geologic mapping and stratigraphic and sedimentological studies of a 984-ft long trench across the Animas River flood plain 0.4 mi downstream from the mill site, combined with analysis of the geomorphological development of the flood plain, which was documented through use of historical photographs, chronometry developed from artifacts, and ^{14}C dating. Milling essentially ceased at the site by 1930. Using aerial photographs taken in nearly every decade since 1945, the authors document the recovery of the flood-plain vegetation and presumably the rate of “natural” recovery from the effects of high metal concentrations in flood-plain sediment. Prior to mining, the reach of the Animas River immediately downstream of the mills at Eureka was a braided meandering stream containing willow thickets. Metal concentrations in premining sediment, although elevated, apparently did not impair the growth of plants or prevalence of beaver ponds. At the end of the period of milling, no well-defined river channels existed. The increased sediment load contributed by the discharge of mill waste on the flood plain had caused about 3.3 ft of aggradation. Willow thickets and beaver ponds were essentially nonexistent. Subsequent to cessation of milling, sediment transport by floods and normal meandering of the river across the flood plain has resulted in steady improvement of the flood plain and recovery of willows along its banks in lower reaches downstream. Analysis of the flood plain downstream of the mill site at Eureka suggests that a substantial portion, about 76 percent, of the original 2,500,000 yd^3 of mill tailings released has been removed by erosion. Estimates of the volume of tailings remaining in the flood plain following the removal of about 120,000 yd^3 of highly contaminated flood-plain sediment by Sunnyside Gold, Inc., indicate that about 12 percent of the tailings released, or about 240,000 tons, remain in the flood plain, dispersed in river gravel immediately downstream from the mill site.

Chapter E23, Effects of the May Day Mine Site on Stream-Water Quality in the Cement Creek Basin, August 2000, by Winfield G. Wright, Briant A. Kimball, and Robert L. Runkel, presents results of a detailed tracer-injection study done in the reach of Cement Creek that included Illinois Gulch and the May Day mine site. Water-quality samples were collected from stream sites, tributaries, springs, and seeps within the study reach. The May Day mine does not have any obvious mine drainage discharging from the adit; therefore, well points were installed down gradient from the May Day mine to further characterize flow paths from the site. Dissolved-constituent concentrations fluctuated throughout the study reach, but the dissolved concentrations decreased most noticeably downstream from Illinois Gulch due to dilution by the large inflow. The inflows in Cement Creek reach affected by the May Day mine site had low pH values but also had low discharges; hence, the pH of the stream was not substantially affected by the inflows. Total-constituent (unfiltered) concentrations increased in the reach affected by the May Day mine. Cumulative inflow loads were less than cumulative instream loads, indicating that diffuse ground-water sources were contributing loads to the study reach. Sources of water to the study reach were explored using light stable isotopes of hydrogen and oxygen in water and principal components analysis. Mineral saturation calculations indicated supersaturation of iron and sulfate phases downstream from Illinois Gulch.

Chapter E24, Using the OTIS Solute-Transport Model to Evaluate Remediation Scenarios in Cement Creek and the Upper Animas River, by Katherine Walton-Day, Suzanne S. Paschke, Robert L. Runkel, and Briant A. Kimball, presents results of solute-transport modeling used to simulate ambient conditions and remediation scenarios for four subbasins in the study area. Results from water-quality sampling during metal-loading studies conducted in Cement Creek, and in the Animas River from Eureka to Howardsville and from Howardsville to Silverton, were used to calibrate the solute-transport models. Remediation targets simulated in each subbasin included either the largest sources of loading, the largest sources of loading that occurred on Federal land, or sources of mining-related loading. Results of the simulations indicate that remediation is likely to effect the greatest water-quality improvement in areas where loading is limited to a small number of distinct sources, such as in the upper Cement Creek reach. Remediation will have a smaller effect in streams where a substantial proportion of the load is supplied from diffuse sources of seepage and ground water such as in a lower Cement Creek reach.

Chapter E25, Processes Affecting the Geochemical Composition of Wetland Sediment, by Mark R. Stanton, David L. Fey, Stanley E. Church, and Charles W. Holmes, presents the results from studies in four different wetlands in the study area to determine processes and geochemical attributes of these depositional environments. Geochemical and radioisotope profiles provide a chronological record that can be used to calculate depositional fluxes of metals in the wetlands. A detailed study was conducted in the Forest Queen wetlands to determine the role of sulfate reduction and sequestering of metals from acidic drainage from the Forest Queen mine. In contrast with iron bogs, the wetlands are dominated by deposits rich in organic material and have wide ranges in metal concentrations. Metal fluxes varied prior to mining as well as during mining. Sequestering of metals in monosulfide minerals is spotty and variable. Sorption of metals by organic material is an important mechanism for metal sequestration where the flux is limited by seasonal variation in surface-water flow. Near-surface sediment in some wetlands contains abundant iron oxyhydroxides that sequester metals, but this is a seasonal phenomenon associated with lowered water tables and precipitation of metal-bearing iron oxyhydroxides at the wetland surface.

Chapter F, Potential for Successful Ecological Remediation, Restoration, and Monitoring, by Susan E. Finger, Stanley E. Church, and Paul von Guerard, describes the potential for successful recovery of the aquatic community in the study area. Successful restoration is influenced by both the removal of the residual levels of contamination and the establishment of physical or chemical conditions that will support desired or realistic biological communities. Any restoration action involves a certain amount of risk of failure including the realities of natural environmental variability, the scale of the restoration effort, and external catastrophic influences such as flood or drought. Although the desire of land-management agencies may be for ecological recovery to a preexisting baseline condition, this is often not feasible. Numerous factors must be considered before the restoration alternative that has the highest probability of success can be identified. The success of any restoration effort can be best documented via a well-designed monitoring program that collects physical, chemical, and biological information to provide a comparison with conditions prior to cleanup activities. Necessary monitoring activities are developed to chart the progress of aquatic recovery following these remediation efforts.

Chapter G, Digital Databases and CD-ROM for the Animas River Watershed, by Tracy C. Sole, Matthew Granitto, Carl L. Rich, David W. Litke, and Richard T. Pelltier, describes the content and format of the data and information contained on the accompanying CD-ROM. Included are a relational database, a GIS database, and various map, image, and graphic products created during the study. The relational database contains sample site data collected and produced for the study and an inventory and description of mine-related sites located and compiled for the study. The GIS database contains the sample site data and the information for mine-related sites stored as data layers and associated tables. In addition, the GIS database contains base cartographic data and other thematic data layers collected or produced during this study, as well as data layers and information that resulted from use of a GIS to analyze the sample site, mine-related site, base cartographic, and thematic data. ArcExplorer and MapSheets Express, two commercial software packages that use .e00 files (export file format), are provided so that the reader can conduct elementary GIS analysis of the data and prepare simple illustrations. Queries are provided to allow users to extract data from the Access database for use in commercially available spreadsheets for independent analysis.

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