The Boulder River Watershed Study, Jefferson County, Montana

By Stanley E. Church, David A. Nimick, Susan E. Finger, and J. Michael O'Neill

Chapter B of

Integrated Investigations of Environmental Effects of Historical Mining in the Basin and Boulder Mining Districts, Boulder River Watershed, Jefferson County, Montana

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Professional Paper 1652–B

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

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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 contaminating 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 terrestrial bird species are negatively affected by uptake of metals through the food chain. Although estimates of the number of abandoned, inactive mine 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. Clearly, remediation of Federal lands affected by inactive historical mines will require substantial investment of resources.

Numerous AML sites are located on or adjacent to public lands, or affect aquatic or wildlife habitat on public lands. In 1995, personnel from a U.S. Department of the Interior and U.S. Department of Agriculture (USDA) interagency task force, including the Bureau of Land Management, National Park Service, USDA Forest Service, and U.S. Geological Survey (USGS), developed a coordinated strategy for the cleanup of environmental contamination from inactive historical mines 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 inactive historical mines on Federal land. Objectives of the AML Initiative included watershed-scale and site characterization, understanding of the effect and extent of natural sources, and communication of these results to stakeholders, land managers, and the general public. Additional objectives included transfer of technologies developed within the AML Initiative into practical methods at the field scale and demonstration of their applicability to solve this national environmental problem in a timely manner within the framework of the watershed approach. Finally, developing working relationships with the private sector, local citizens, and State and Federal land-management and regulatory agencies will 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 (fig. 1), the upper Animas River watershed in Colorado (U.S. Geological Survey, 2000) and the Boulder River watershed in Montana. In selection of a pilot watershed in Montana for the AML Initiative, five candidate watersheds were considered. These watersheds were ranked on the basis 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 Boulder River watershed was selected from these five candidate watersheds in May 1996.

Land-management and regulatory agencies face two fundamental questions when they approach a region or watershed affected by abandoned mines. First, with potentially hundreds of dispersed contaminated inactive historical mine sites, 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 (including any effects that may have been present even under premining conditions or still may persist from unmined deposits adjacent to existing abandoned or inactive mines)

Figure 1. Location of the Boulder and Animas River watershed study areas in the western United States. Watershed boundaries are based on the 8-digit hydrologic units as defined by U.S. Geological Survey (1982).

- The possible impact of incomplete cleanup of specific inactive historical mine sites
- Other factors that may limit sustainable development of desired ecosystems?

To answer these questions, the Abandoned Mine Lands Initiative adopted a watershed approach rather than a site-by-site approach to characterize and remediate abandoned mines (Buxton and others, 1997). This approach is based on the premise that watersheds affected by acid mine drainage in a State or region should be prioritized on the basis of its effect on the biologic 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 in which interdisciplinary scientific knowledge and methods can be employed at similar inactive historical mine sites throughout the Nation. The watershed approach

- Gives high priority to actions most likely to 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 disposal-siting decisions
- 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 a detailed review of work conducted in the Boulder River watershed during 1996–2000. The objectives of this work were to

- 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 data and information to users in a timely and effective manner.

Expertise in water quality, hydrology, geology, geochemistry, geophysics, biology, mapping, and digital-data collection and management was applied during these investigations. Investigations were coordinated with stakeholders, the Montana Department of Environmental Quality, Montana Fish, Wildlife and Parks, Montana Bureau of Mines and Geology, U.S. Environmental Protection Agency, USDA Forest Service, and 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 several State and Federal agencies. We thank personnel in the following agencies:

Montana Fish, Wildlife and Parks, particularly Don Skaar, Ron Spoon, and Kurt Hill, for their assistance with collection and analysis of fisheries data.

U.S. Fish and Wildlife Service, particularly Elizabeth MacConnell, for assistance with analysis of fisheries data.

Montana Department of Environmental Quality, particularly Vic Anderson and Ben Quinones, for providing data on their agency's efforts to evaluate mine sites.

Montana Bureau of Mines and Geology, particularly John Metesh for data and discussions on particular mines and their impact on the environment, and Joel Hall for his assistance with merging of the two geologic maps.

U.S. Environmental Protection Agency, particularly Mike Bishop for his efforts to coordinate subsequent Superfund work in the Boulder River and Tenmile Creek watersheds, and Steve Way for providing U.S. EPA and unpublished contractor reports related to the Luttrell pit.

USDA Forest Service, particularly Robert Wintergerst, Ray TeSoro, David Ruppert, Grant Godbolt, and Pat Barringer, for GIS data sets and general information about the study area, and for arranging access to some private lands.

Bureau of Land Management, particularly Tim Bozorth and Mike Browne, for their support and information on environmental issues in the High Ore Creek basin.

We also thank Dan Adams, Basin Creek mine geologist, formerly of Pegasus Gold Corp., for his assistance with the report on the Luttrell pit (Smith and others, this volume, Chapter E3). Finally, we thank the land owners in the Boulder River watershed who allowed us access to their property during this study. We also thank the residents of the towns of Basin and Boulder, Mont., for their hospitality while we were conducting fieldwork in the area.

Funding for some of the site-characterization work in the study area was provided by the USDA Forest Service and U.S. Environmental Protection Agency.

Description of Study Area

The Boulder River watershed is located in southwestern Montana (fig. 1). The Boulder River watershed study area, as defined in this study, is the drainage area of three large tributaries (Basin, Cataract, and High Ore Creeks) and the approximately 9 mi reach of the Boulder River that extends from just upstream to just downstream of these tributaries. The watershed study area does not include the large upstream drainage of the Boulder River or the reach downstream to the Jefferson River, even though effects of historical mining are apparent through these reaches. Studies focused on the watershed; however, some added sampling and regional investigations were conducted outside this study area to document the extent of enriched trace-element concentrations in adjacent areas and to provide reference localities unaffected by historical mining. The Basin and Cataract Creek basins are within the Beaverhead-Deerlodge National Forest, while much of the land in the High Ore Creek basin is managed by the Bureau of Land Management.

The watershed area is mountainous (fig. 2): elevations range from about 4,900 to 8,800 feet above sea level. Mean annual precipitation ranges from about 18 to 26 in./yr (Parrett, 1997). Although the population varies seasonally as temporary residents move into the area during the summer, about 200 people live year-around in the Boulder River watershed study area. Residents are engaged primarily in mining, logging, or tourism.

For ease of discussion, figure 2 includes various basin and subbasin boundaries where work in the study area was concentrated. In the Basin Creek basin, the upper Basin Creek subbasin and the Jack Creek subbasin contain the Buckeye and Bullion mine sites, respectively. The Cataract Creek basin is subdivided into the upper, middle, and lower Cataract Creek subbasins and the Uncle Sam Gulch subbasin, which contains the Crystal mine. The High Ore Creek basin has not been subdivided.

The trace elements in which we were particularly interested for this investigation were those related to the mineral deposits in the watershed and that occur in concentrations sufficiently high to cause concern about their potential effect on aquatic organisms. These trace elements include arsenic, cadmium, copper, lead, silver, and zinc. In contrast, other trace elements such as chromium, cobalt, strontium, titanium, and many others occur in rocks throughout the watershed but are not concentrated in the mineral deposits.

Hydrologic Setting

Streamflow in the Boulder River watershed study area is typical of mountain streams throughout the northern Rocky Mountains. Streamflow is dominated by snowmelt runoff, which typically occurs between April and June; this snowmelt runoff often is augmented by rain. Streamflow typically peaks in May or June and decreases as the shallow ground-water system drains. Spring runoff conditions extend into July. Low streamflow conditions are typical from August to March (fig. 3). The nearest streamflow gauging station is 5 mi downstream of the study area on the Boulder River near Boulder, Mont. Although the magnitude of streamflow is less than at this gauging station, streamflow in study area streams is proportional (based on drainage area) to that at the gauge and has similar seasonality.

Water quality in many study area streams is good; however, water quality is degraded by high trace-element concentrations in reaches downstream from some of the inactive mines. The major-ion chemistry of stream water varies depending on geology and the relative amount of mine drainage. Calcium or calcium-sodium bicarbonate water is the

Figure 2. Shaded relief map of Boulder River watershed showing the study area; Boulder River; the three main tributaries—Basin, Cataract, and High Ore Creeks, impacted by past mining in the study area; and selected subbasins. Basin Creek basin was subdivided into three subbasins: upper Basin Creek, which contains the Buckeye mine and the Basin Creek mine; Jack Creek subbasin, which contains the Bullion mine; and lower Basin Creek subbasin. Cataract Creek basin is subdivided into four subbasins: lower, middle, and upper Cataract Creek, and Uncle Sam Gulch subbasins. Drainage from the Crystal mine affects both the Uncle Sam Gulch and the lower Cataract Creek subbasins. High Ore Creek basin, which contains the Comet mine, was not subdivided. The generalized Boulder River watershed study area boundary is the area of these three targeted tributary drainages (outlined in black). Area south of Boulder River, containing Galena and Little Galena Gulches, is not included in this study. Luttrell pit at Basin Creek mine site southwest of Luttrell Peak is the U.S. EPA repository site for mine wastes from both Boulder River watershed and Tenmile Creek watershed to north.

Figure 3. Daily mean streamflow during 1996–2000 at the Boulder River at Boulder, Mont. (USGS gauging station 06033000). Average annual peak flow is for water years 1929–72, 1975, 1981, and 1985–2000. Shaded areas indicate periods of spring runoff, which was arbitrarily defined as streamflow greater than 150 cubic feet per second.

norm. Streams affected by inactive mines have larger proportions of sulfate. All but a few small streams receiving adit discharge have alkaline pH (Nimick and Cleasby, this volume, Chapter D5).

Near-surface ground-water flow is largely controlled by topography, by the distribution of unconsolidated Tertiary and Quaternary deposits that overlie the Boulder batholith (fig. 4), and by the decrease in hydraulic conductivity of geologic units with depth (McDougal and others, this volume, Chapter D9). Topography strongly controls the direction of ground-water flow and the location of discharge areas. Recharge primarily occurs on topographic highs, and greater amounts of recharge occur in areas with the greatest precipitation and hydraulic conductivity. Discharge, in the form of numerous seeps and small springs, occurs in topographic lows and at breaks in slope. The upper, thin unit of unconsolidated deposits has the largest hydraulic conductivity. Flow paths in this near-surface aquifer, from recharge to discharge areas, are short, commonly less than a few thousand feet. Regional ground-water flow is limited by the low permeability of the underlying bedrock, except in areas of high fracture intensity. The uppermost, fractured and weathered zone in the igneous bedrock has a smaller hydraulic conductivity than the overlying unconsolidated deposits but has a much greater hydraulic conductivity than the underlying unweathered granitic to granodioritic Butte pluton. Fractures are the major conduit for ground-water flow in bedrock, with more flow in the uppermost zone (about 50 ft) where the fractures are weathered and fairly open.

Biologic Setting

Little historical information is available on biological communities in the Boulder River watershed (fig. 1), making it difficult to determine biological conditions in this watershed prior to mining. In recent years, however, a complete biological characterization of the watershed was done by the Montana Department of Fish, Wildlife and Parks (1989). Mule deer, elk, moose, and antelope are year-round residents in the Boulder River watershed, and black bear are present seasonally. Mink and beaver also are found in the river and riparian zone.

The Boulder River upstream from the town of Boulder (fig. 1) has a narrow flood plain, and the riparian vegetation is dominated by willow, alder, conifer, and, to a lesser extent, cottonwood and aspen. At the lower elevations, downstream from the town of Boulder, the river meanders with a gradual gradient; as a result, riparian vegetation consists of cottonwood, aspen, and willow. The river supports brook trout, brown trout, rainbow trout, and mountain whitefish; some tributaries of the Boulder River provide habitat for native westslope cutthroat trout. Other species, such as mottled sculpin, longnose dace, longnose sucker, and white sucker, also reside in the Boulder River.

Past mining activity has affected aquatic communities in this watershed. Gardner (1977) found that elevated concentrations of metals and sedimentation affected the distribution and abundance of aquatic invertebrates. Vincent (1975) and Nelson (1976) attributed reduced populations of trout in the lower Boulder River to elevated concentrations of metals in the water and streambed sediment.

Geologic Setting

The geologic setting of a watershed provides a framework for understanding the scope and cause of environmental effects of historical mining. The geologic setting includes the main types of rock and their spatial distribution in the watershed, the degree of faulting and fractures in these rocks, and finally the type and location of the mineralized areas, ore deposits, and associated mines. These factors play an important role in determining the way the watershed responds to mine discharge and waste and in controlling the flow of ground water to and from these sites. In addition, understanding the rock composition and geologic architecture can help identify suitable mine-waste repository sites that have more abundant acid-neutralizing capacity but yet have limited geologic- or fracture-controlled ground-water flow.

The Boulder River watershed is largely underlain by the Cretaceous Boulder batholith, which is a large mass of granitic rock that cooled and crystallized at depth, and the overlying Elkhorn Mountains Volcanics, which formed as the molten granitic magma erupted (fig. 4). This entire assemblage of granitic and volcanic rocks was later eroded so that lower elevation areas of the watershed, such as valley bottoms, generally are carved through granitic rocks while higher elevation areas, such as ridges and mountain tops, are formed in the overlying volcanic rocks.

The bulk of the Boulder batholith within the study area is the granitic to granodioritic Butte pluton (Becraft and others, 1963; Ruppel, 1963; O'Neill and others, this volume, Chapter D1). Most of the intrusive rocks are porphyritic and contain variable amounts of mafic minerals (5–15 percent biotite and hornblende; Ruppel, 1963) and vein calcite, all of which contribute to the acid-neutralization capacity of rocks in the watershed (Desborough, Briggs, and Mazza, 1998; O'Neill and others, this volume). The presence of these minerals may help explain why, in general, few streams in the study area are acidic even though acidic conditions existed at many mine sites. The Elkhorn Mountains Volcanics include welded tuff, tuff and flow breccia, and volcanic sandstone and conglomerate. The volcanic rocks are predominantly quartz latite to andesite and also include varying amounts of mafic minerals. Andesite intrusions within the Elkhorn Mountains Volcanics occur near the confluence of Basin and Jack Creeks (Ruppel, 1963).

Small outcrops of the Lowland Creek Volcanics of Eocene age (Smedes and Thomas, 1965) and of quartz latite composition also are present but are restricted to the southern and eastern parts of the study area. In addition to volcanic rocks, the Lowland Creek Volcanics include tuffaceous sandstone and siltstone as well as structurally controlled northeast-trending dike swarms.

Unconformably overlying the older Elkhorn Mountains and Lowland Creek Volcanics are lower Oligocene rhyolitic flows (younger volcanic rocks in fig. 4), part of the nearby Avon volcanic field. Tertiary rhyolitic flows occur extensively in the western and northern parts of the study area (Becraft and others, 1963; Ruppel, 1963). These rhyolitic rocks host the disseminated gold-pyrite ore deposit in the northern part of the study area near Luttrell Peak (location, fig. 2).

The Butte pluton is extensively jointed; the joints consist of three prominent sets that trend north or east or are subhorizontal (Ruppel, 1963; Becraft and others, 1963). Because the sets of joints in the Butte pluton commonly are filled with leucocratic veins that most likely represent late-stage magmatic fluids, Ruppel (1963) interpreted them to be related to batholithic cooling phenomena. This interpretation has been confirmed on the basis of new $^{40}Ar/^{39}Ar$ ages determined in this study (O'Neill and others, this volume; Lund and others, 2002). Associated with the intrusion of these late-stage aplites is an altered leucocratic granite that is exposed in rubble in Uncle Sam Gulch upstream from the Crystal mine.

The batholithic rocks are cut by numerous faults and lineaments of uncertain age. Some of the faults are mineralized and host the largest ore deposits in the study area. Most of the faults trend east or northeast; a minor but important subset of faults and lineaments trends northwest (fig. 4). The northeast- and northwest-trending faults appear to be recurrently active, related to tectonic activity restricted to the northeast-trending Great Falls tectonic zone (O'Neill and Lopez, 1985) or to southwest-northeast-directed basin and range extension (Reynolds, 1979). The east-trending, strongly mineralized faults or shear zones appear to be related to emplacement of the Boulder batholith (Schmidt and others, 1990; O'Neill and others, this volume).

Acid-neutralizing potential of bedrock is an important control on water quality in mined areas. The granitic rocks that underlie much of the study area contain minerals that provide a moderate amount of acid-neutralizing potential. These minerals include iron and magnesium minerals (for example, biotite and hornblende) that formed when the magma was cooling, and calcite (calcium carbonate) that formed later after the magma cooled. These minerals are widely disseminated and provide significant and widespread acid-neutralizing capacity. The presence of these minerals may help explain why, in general, few streams in the study area are acidic even though acidic conditions existed at many mine sites.

Pleistocene glacial till is present on some of the upland surfaces in the study area. Till is present in many of the flat areas in the valleys, and lateral moraines are present along some of the valleys, such as along Jack Creek. Outwash deposits are present in a few of the larger valleys. Tertiary unconsolidated sand and gravel locally mantle upland surfaces in areas previously mapped as glacial deposits (Ruppel, 1963; J.M. O'Neill, written commun., 1999). Holocene fluvial-alluvial and minor pond and bog deposits have accumulated in the study area along valley floors.

Mining History

The mineral deposits of the Boulder River watershed include disseminated deposits of auriferous pyrite, placer deposits of gold and tin, and a large number of base- and

Figure 4. Generalized geology of Boulder River watershed study area (modified from O'Neill and others, this volume, Chapter D1, pl. 1). Dashed outline shows the area of the target drainages in the study area.

precious-metal-bearing quartz veins. Auriferous pyrite occurs in rhyolite on the divide between Tenmile and Basin Creeks at the Basin Creek mine (fig. 2). Most placer deposits are in coarse gravel deposits along upper Basin Creek downstream of the area of rhyolite outcrop (younger volcanic rocks, fig. 4; Becraft and others, 1963; Ruppel, 1963).

The ore deposits in the watershed occur primarily in thin veins, which formed as the last vestiges of molten rock from the cooling granitic body filled thin fractures and small faults in the solidified magma rock and overlying volcanic rocks. These ore deposits are called polymetallic quartz-vein deposits and were mined primarily for silver and for base metals (copper, lead, and zinc), although some contained economic quantities of gold. The inactive mines in the study area are located mostly along these veins. The polymetallic quartz veins typically are short, but some extend for as much as several miles. Most of the largest ore-bearing veins occupy east-trending Late Cretaceous extensional structures. The hydrothermal alteration common in and adjacent to all veins generally is confined to thin zones, typically about 1 ft thick and rarely more than a few feet thick. The veins contain abundant base-metal sulfides with high silver:gold ratios. Pyrite is the most abundant sulfide mineral but had no economic value to miners. Other sulfide minerals, such as arsenopyrite, chalcopyrite, tetrahedrite, galena, and sphalerite, contained the metals that miners targeted.

The Boulder River watershed study area encompasses the Boulder and Basin mining districts. Mining in these districts started in the mid-1860s with the discovery of gold placer deposits. Production of placer gold reached a maximum between 1868 and 1872, although placer operations continued intermittently through about 1940. Roby and others (1960) reported that an estimated 845 fine ounces of placer gold were recovered between 1933 and 1938 from lower Basin Creek. A small amount of placer gold was also recovered from the Boulder River during this time period. Auriferous pyrite deposits that had been mined previously in small underground mines were mined briefly by open-pit and cyanide extraction at the Basin Creek mine in the early 1990s.

The first discoveries of base-metal vein deposits were made at about the same time as the first placer discoveries. Lead-silver ore was discovered at the Ada mine in the early 1860s and gold was discovered at the Buckeye mine in 1868. After 1872, lode mining completely overshadowed placer mining. The main period of lode mining began about 1880, reached a peak between 1895 and 1903, and ended about 1907. Production prior to 1902 is largely undocumented because records were not kept prior to Montana statehood. After 1907, mining was intermittent and largely restricted to a few mines, especially the Comet, Gray Eagle, Crystal, and Bullion mines, which yielded most of the ore mined in the study area (Martin, this volume, Chapter D3). Mining generally had ceased by the 1940s at these mines, but some production continued into the 1960s and 1970s. Figure 5 shows the recorded production from Jefferson County from approximately 1900 through 1958 from the Basin-Cataract mining district (Roby and others, 1960). Many of the smaller mines and prospects were reopened from time to time after 1903 for further exploration and for speculation, but none yielded appreciable quantities of ore (Becraft and others, 1963; Ruppel, 1963). Much of the mining occurred on privately owned (patented) mining claims. However, some mine, mill, and smelter sites, and some mill-tailings deposits, along with eroded tailings distributed along various reaches of stream channels and flood plains, are located on Federal land.

Figure 5. Produced tonnage of copper, lead, and zinc; annual production, expressed as tons (2,000 lb) of ore; and production of gold and silver, in troy ounces, from the Basin-Cataract mining district from 1902 to 1958 (Roby and others, 1960).

In the 1800s and early 1900s, mills treated ores by crushing and grinding and then concentration by gravity separation, or, after about 1914, by flotation methods. Some of the larger mines had small stamp mills at the mine site. Ore from smaller mines was transported to off-site mills. Concentrates from these mills generally were transported to smelters in Basin or outside the Boulder River watershed (Metesh and others, 1994).

More than 140 inactive mine-related sites lie in the Boulder River watershed study area (Martin, this volume). These sites include mines, where ore was recovered, and prospects, where rock was removed in search of ore deposits. Rock that was mined but that had insufficient economic value typically was left near the mine in waste-rock piles. Ore was stockpiled at mine sites for later transport to a mill, and some stockpiles remain in the watershed. Ore was crushed and processed at a mill to concentrate the valuable metals. Wastes from mills, called tailings, typically were discharged to areas, including valley bottoms, downhill from the mill. Many of the mine and mine-related sites in the study area had been inventoried for State and Federal agencies to help target likely mine and mill sites for remediation. Inactive mine-related sites affect streams through direct discharge of acid drainage from adits, seepage from waste-rock and tailings piles, and erosion of tailings piles and fluvial tailings deposits by storm runoff or streambank erosion.

Remediation Activities

Interest in reducing the environmental effects of the many inactive mines and prospects in the Boulder River watershed increased in the 1980s as the studies of the effects of historical mining on water quality increased. One of the first actions taken was the construction of a diversion channel in the 1980s to route High Ore Creek (fig. 2) around the large quantity of tailings deposited in the valley bottom at the Comet mine site. The State of Montana inventoried and ranked inactive mines in the study area (Montana Department of State Lands, 1995) and conducted a preliminary watershed analysis (Montana Department of Environmental Quality, 1997). Federal land-management agencies began planning for cleanup activities in the mid-1990s after the completion of inventories of inactive mines (Metesh and others, 1994, 1995, 1996; Marvin and others, 1997). Studies were conducted to locate suitable sites for small, local mine-waste repositories (Desborough and Fey, 1997; Desborough and Driscoll, 1998; Desborough, Briggs, and Mazza, 1998; Desborough and others, 1998) as well as to site a larger regional repository at the Luttrell pit at the Basin Creek mine (fig. 2; Smith and others, this volume, Chapter E3). In 1997, the State of Montana began cleanup activities at the Comet mine, and large quantities of mill tailings in the High Ore Creek valley bottom were removed to the former open pit at the Comet mine site. In 1999, the BLM removed flood-plain tailings from the valley floor along the 4-mi reach between the Comet mine and the Boulder River (Gelinas and Tupling, this volume, Chapter E2) to a new repository near the Comet mine. In 1999, the U.S. Environmental Protection Agency listed the Basin and Cataract Creek drainages and the adjacent Tenmile Creek drainage immediately to the north as Superfund sites on the National Priorities List. Also in 1999, the U.S. EPA and USDA Forest Service cooperatively developed the Luttrell pit as a repository for mine wastes that would be removed from sites in the Boulder River and Tenmile Creek watersheds. In 2000, the U.S. EPA continued moving mine wastes from the Tenmile Creek area to the Luttrell pit. The USDA Forest Service removed mine wastes and flood-plain tailings from the Buckeye and Enterprise mine area to the Luttrell pit in 2000.

Overview of this Volume

Chapters in this volume are arranged from general conclusions to more specific detailed and technical studies. The following summaries provide an overview and summary of the chapters contained in this report for those who have limited time or are unaware of which subjects presented in the volume would be most applicable to their interests. Chapter A, “Summary and Conclusions from Investigation of the Effects of Historical Mining in the Boulder River Watershed, Jefferson County, Montana,” provides a brief summary of our major findings. Historical mining has elevated the concentrations of cadmium, copper, and zinc in surface water of the Boulder River watershed study area. Weathering of mine wastes, and particularly of mill tailings in the study area, has also resulted in elevated concentrations of arsenic, cadmium, copper, lead, and zinc in streambed sediment in Basin Creek downstream from the Buckeye and Enterprise mines, in Jack Creek downstream from the Bullion mine, in Uncle Sam Gulch downstream from the Crystal mine, in High Ore Creek downstream from the Comet mine, and in the Boulder River downstream from the Jib Mill site. Studies of fish in the stream reaches downstream of these sites indicate that fish cannot survive in the most severely affected reaches; chronic effects were documented where trace-element concentrations were significantly elevated. The Montana Department of Environmental Quality, Bureau of Land Management, USDA Forest Service, and U.S. Environmental Protection Agency initiated remediation planning of these sites following our initial characterization studies summarized in this volume.

Chapter C, “Synthesis of Water, Sediment, and Biological Data Using Hazard Quotients to Assess Ecosystem Health,” by Susan E. Finger, Aïda M. Farag, David A. Nimick, Stanley E. Church, and Tracy C. Sole, is a multidisciplinary synthesis of the studies conducted in the watershed, using what is called an ecological risk assessment approach. This approach explains the relevance of the combined studies, hydrologic, geologic, and biologic, in terms of remediation and recovery at the watershed level. This chapter evaluates the physical and chemical characteristics of the watershed that may limit the recovery of those species that are negatively affected by historical mining. Specifically, it evaluates effects of trace-element exposure on fish communities. Such exposure can be from the water in which these organisms live and (or) through the food chain. The potential for adverse biological effects associated with elevated concentrations of cadmium, copper, and zinc in water and streambed sediment is assessed by comparison with aquatic regulatory standards for water and consensus-based sediment-quality guidelines. Ribbon maps showing the distribution of trace elements in stream water and streambed sediment demonstrate the severity of contamination in specific stream reaches within the study area. Chronic effects are documented in trout in some Boulder River tributaries.

Chapter D, consisting of "subchapters" D1–D10, provides the scientific basis for the conclusions and recommendations made in this volume. The subchapters describe detailed scientific studies focused on particular aspects of the Boulder River watershed study.

Chapter D1, "Geologic Framework," by J. Michael O'Neill, Karen Lund, Bradley S. Van Gosen, George A. Desborough, Tracy C. Sole, and Ed H. DeWitt, summarizes the geology of the study area. Polymetallic quartz-vein deposits, which were emplaced along tensional structures in the Butte pluton, formed the sulfide ore veins that were exploited in the Basin and Boulder mining districts between 1868 and about 1970. Premining water and streambed-sediment geochemistry was controlled by the composition of the granitic Butte pluton, which underlies most of the Boulder River watershed study area. In contrast, the water and streambed-sediment geochemistry today is significantly affected by the accelerated weathering of disturbed waste rock and mill tailings produced by historical mining. Studies of the chemistry of the rocks indicate that unaltered Butte pluton probably contained sufficient calcite to neutralize much of the acid generated by sulfides exposed prior to mining.

Chapter D2, "Geophysical Characterization of Geologic Features with Environmental Implications from Airborne Magnetic and Apparent Resistivity Data," by Anne E. McCafferty, Bradley S. Van Gosen, Bruce D. Smith, and Tracy C. Sole, summarizes aeromagnetic and resistivity geophysical data that were collected using airborne data sensors flown over the study area with a helicopter. The airborne geophysical data primarily reflect the mineralogy of the bedrock to depths of several hundred feet and are able to see through shallow ground cover. These data provide a more complete coverage of the bedrock features than can be mapped by standard geologic field methods. The airborne geophysical data were used to show where hydrothermal alteration events caused subtle changes in the mineralogy and chemistry of the Butte pluton. About 20 percent of the Butte pluton has been altered by hydrothermal activity, and these areas of altered rock would not constitute suitable sites for repositories for mine waste, because they have been leached of their acid-neutralizing potential by the hydrothermal alteration processes. The data provide one basis for the interpretation of the environmental geology of the watershed study area.

Chapter D3, "Mine Inventory," by E. Paul Martin, is an inventory of significant mines, mill sites, and prospects in the watershed study area. One hundred forty-three sites were identified from literature searches and then accurately located from digital orthophoto quadrangles (DOQs). Detailed site characteristics, including flow rates and pH of acid mine drainage, numbers of mine features, and size estimates of mill tailings and mine wastes, were compiled into a single database.

Chapter D4, "Metal Leaching in Mine-Waste Materials and Two Schemes for Classification of Potential Environmental Effects of Mine-Waste Piles," by David L. Fey and George A. Desborough, provides data on mine wastes from 10 mine sites in the study area. Mine-waste piles are of particular environmental concern because large quantities of acid and trace elements commonly leach from the rock material in these piles. These factors are key in determining how large an effect an individual mine-waste pile might have on the environment. A new surface-sampling procedure was developed that provided a statistically representative sample of an individual waste pile. These samples were analyzed for total and water-soluble trace-element content of each sample, the amount of specific minerals likely to release acid or trace elements, and the potential to produce or neutralize acid. Two water-leach methods for evaluating metal mobility were compared. The standard EPA 1312 protocol was compared with a less labor-intensive static leach method. Both methods gave similar results. Mineralogical studies of the samples indicated that the secondary sulfates anglesite and jarosite were present in about 80 percent of the mine wastes, indicating active weathering in the mine waste. Results from these chemical analyses suggest that the mine-waste dumps represent an essentially infinite source of water-soluble trace elements and acid.

To help land managers prioritize these piles for remediation, the authors developed a ranking system based on the size of the pile and used results of the chemical analyses in developing the rankings. The ranking system was used to classify 19 waste piles that they had permission to sample. For the sampled mine sites, the ranking system showed that waste piles at the Buckeye, Bullion, Daily West, Cracker, and Boulder Chief mine sites had a high potential for environmental degradation, whereas piles at the Crystal and Sirius mine sites had intermediate potential, and piles at the Morning Marie and Waldy mine sites had low potential.

Chapter D5, "Trace Elements in Water in Streams Affected by Historical Mining," by David A. Nimick and Thomas E. Cleasby, describes surface-water chemistry in the watershed, focusing on variation in major-element chemistry and concentrations, loads, and sources of trace elements. Few stream reaches have pH less than 6.5 in contrast to what is typical of many other historical mining districts. Dissolved concentrations (0.45-micrometer filtered water) of cadmium, copper, lead, and zinc commonly exceeded aquatic-life standards downstream from inactive historical mine sites. Ribbon maps show the distribution of pH and metal concentrations in stream reaches in the watershed. The Bullion, Comet, and Crystal mine sites produced most of the dissolved trace-element load in the study area. Cataract Creek contributed larger dissolved loads than either Basin or High Ore Creeks.

Chapter D6, "Quantification of Metal Loading by Tracer Injection and Synoptic Sampling, 1997–98," by Briant A. Kimball, Robert L. Runkel, Thomas E. Cleasby, and David A. Nimick, describes the results from detailed metal-loading studies conducted in Cataract Creek, Uncle Sam Gulch, and the Bullion Mine tributary on Jack Creek. Individual sources of metals were identified and quantified from the downstream changes in metal loads in each study reach. Metal loads were calculated using data from the dilution of a tracer (sodium chloride) that was injected at the upstream end of each study reach and from metal concentration data determined in synoptic water-quality samples. The major sources of metal loadings for dissolved metals in these creeks were shown to be the Crystal mine adit flow on Uncle Sam Gulch and the Bullion mine adit flow on the Bullion Mine tributary. The Crystal mine adit flow provided a daily load of about 35 lb of zinc to Cataract Creek whereas the zinc load from the Bullion mine adit was about 7 lb per day. About one-third of the calculated zinc load in Cataract Creek came from unsampled inflows, possibly ground water, and about one-third was lost to colloidal deposition on the streambed.

Chapter D7, "Short-Term Variation of Trace-Element Concentrations during Base Flow and Rainfall Runoff in Small Basins, August 1999," by John H. Lambing, David A. Nimick, and Thomas E. Cleasby, details the short-term variation of arsenic, copper, manganese, and zinc concentrations in High Ore, Jack, and Cataract Creeks. Dissolved zinc concentrations varied by a factor of three in High Ore Creek over the 24-hour observation period. Maximum dissolved zinc concentrations occurred in early morning hours, whereas minimum concentrations occurred in the late afternoon. Interpretation of these data suggests that the cause of this variation may be the sorption of dissolved zinc onto particulate material in the stream as temperature and pH of the water change throughout the day.

Concentrations of these trace elements were also shown to increase in response to runoff during rainfall. The lag time following onset of rainfall before the arrival of the peak concentration of dissolved metals was short, on the order of 3 hours, whereas the decay curve following the rainstorm lasted 8–10 hours. Both phenomena, the changes in trace-element concentrations caused by daily fluctuations in temperature and the changes caused by a rainfall event, may have substantive effects on the toxicity of dissolved trace elements on aquatic life. At sites where the dissolved metal concentrations were measured late in the day, the daily variation would result in a calculated toxicity for aquatic life that would be underestimated. During periods following runoff from a summer thunderstorm, the calculated toxicity would be dependent on the time lag associated with runoff for each mine waste site.

Chapter D8, "Trace Elements and Lead Isotopes in Streambed Sediment in Streams Affected by Historical Mining," by Stanley E. Church, Daniel M. Unruh, David L. Fey, and Tracy C. Sole, is a study of the present streambed-sediment geochemistry of the watershed. Concentrations of arsenic, cadmium, copper, lead, and zinc exceed published sediment-quality guidelines in many of the streams downstream from historical mine sites. The effect of historical mining on trace-element concentrations in streambed sediment in the Boulder River can be followed all the way to the confluence with the Jefferson River 55 mi downstream from the Basin and Boulder mining districts. Studies of the concentrations of these trace elements in premining streambed sediment preserved in terrace deposits in the watershed show that these trace elements are concentrated in streambed sediments today by factors of 50 to 100 times more than were present in the streambed sediment prior to historical mining.

Lead isotopes provide a "fingerprint" that can be used to tie sources of metals to groups of mineral deposits. The signature from the polymetallic veins exploited in the Basin and Cataract Creek basins is different from that in the High Ore Creek basin at the Comet mine. The lead isotope data have been used to quantify the contributions of the inactive historical mines to Boulder River streambed sediment. These calculations indicate that (1) about 35 percent of the lead in streambed sediment of the Boulder River was derived from Basin Creek and the Jib Mill site located on the Boulder River immediately above the confluence of Basin Creek, (2) 13 percent of the lead in streambed sediment was derived from Cataract Creek, and (3) about 50 percent of the lead in streambed sediment was derived from High Ore Creek. Data from streambed sediment in a terrace immediately downstream from the Jib Mill indicate that ores from outside the district were milled at this site and contributed elevated trace-element concentrations to Boulder River streambed sediment.

Chapter D9, "Hydrogeology of the Boulder River Watershed Study Area and Examination of the Regional Ground-Water Flow System Using Interpreted Fracture Mapping from Remote Sensing Data," by Robert R. McDougal, M.R. Cannon, Bruce D. Smith, and David A. Ruppert, describes a reconnaissance level study of ground-water flow in the study area. Ground water can play an important role in determining the extent of contamination in historically mined areas. If ground water moves freely, dispersal of trace elements can be large, whereas if ground-water movement is restricted, effects of historical mining can be more localized. A conceptual model of how ground water flows in the study area was developed based on observations made in the field near the Buckeye, Bullion, and Crystal mines. The model then was used to help interpret the metal-loading studies and field observations made by other scientists. Ground water occurs primarily in the surficial unconsolidated deposits that blanket much of the study area and in the upper 50 ft of the bedrock, where the fractures are open and allow flow. At depth, fractures in the bedrock are tight and restrict ground-water flow. Flow paths for ground water from areas of recharge to areas of discharge are generally short (less than 1,000 ft) because of the shallow nature of the permeable rocks. Ground-water flow from adits appears to be the major contribution from the ground-water system; ground-water flow through major geologic structures does not appear to contribute significantly to water-quality degradation in the study area. This conceptual idea of ground-water flow was expanded by mapping of linear features visible on images of the watershed taken from satellites and aircraft. These linear features were assumed to represent the expression at the land surface of faults, joints, fractures, and mineralized veins that cut the bedrock. Quantification of the primary orientations, the average lengths, and the relative spatial frequency of the features allowed areas where recharge and discharge might be more likely to be identified.

Chapter D10, “Aquatic Health and Exposure Pathways of Trace Elements,” by Aïda M. Farag, David A. Nimick, Briant A. Kimball, Stanley E. Church, Don Skaar, William G. Brumbaugh, Christer Hogstrand, and Elizabeth MacConnell, assesses aquatic community health, food supply, and pathways of exposure for toxic trace elements in the aquatic ecosystem. Laboratory and field methods were applied to evaluate the effects of metals released by past mining activity on fish at the individual organism and the population levels. Population surveys confirmed the absence of fish in some reaches of the watershed near mine sites, but trout populations were documented downstream of these source areas. Instream experiments using caged trout showed that elevated concentrations of cadmium, copper, and zinc in the water column were associated with increased trout mortality at sites near mine-waste sources. Physiological changes in the gill tissue from these fish indicated that the cause of death was related to elevated trace-element concentrations in the water column. Assessment of resident trout revealed impaired health at a downstream site in lower Cataract Creek, where reduced fish population densities also occurred. Exposure pathways and partitioning of metals in the aquatic environment were determined by measurement of trace-element concentrations in water, colloids, streambed sediment, biofilm (that is, algae and bacteria that grow on rocks in the stream), invertebrates, and fish at many sites throughout the watershed. The interrelationship of the trace elements accumulating in these biotic and abiotic components suggests that copper, cadmium, and zinc concentrations increased in fish tissues as a result of direct exposure from water and sediment and from indirect exposure through the food chain. Through contact by these two pathways, the health of aquatic biota in the watershed has been compromised.

Chapter E, consisting of three “subchapters,” describes site-specific studies that focused on important aspects of abandoned mine land remediation. The three subchapters describe site characterization of the Buckeye and Enterprise mine sites on upper Basin Creek, water-quality monitoring of the Comet mine on High Ore Creek, and geologic evaluation of the Luttrell pit mine-waste repository site at the Basin Creek mine.

Chapter E1, “Understanding Trace-Element Sources and Transport to Upper Basin Creek in the Vicinity of the Buckeye and Enterprise Mines,” by M.R. Cannon, Stanley E. Church, David L. Fey, Robert R. McDougal, Bruce D. Smith, and David A. Nimick, describes detailed studies of the mine wastes and mill tailings at the Buckeye and Enterprise mines, in particular, their effect on water quality in upper Basin Creek. Geochemical studies of a mill-tailings site at the Buckeye mine indicated that weathering of processed sulfide wastes had resulted in widespread dispersion of oxidized materials containing high concentrations of arsenic, cadmium, copper, lead, and zinc on the Basin Creek flood plain. Trenching at the site showed that unoxidized sulfides existed at depth. Data for chemistry, water levels, and hydraulic characteristics from 10 shallow ground-water wells showed that although concentrations of trace elements were high in ground water near the mill and Enterprise mine sites, ground-water discharge contributed only a small part of the trace-element load to upper Basin Creek. Ground geophysical studies helped define the extent of the inferred plume of contaminated ground water. Observations of the local hydrology indicated that saturation of the mill-tailings pile on the flood plain occurred in the spring during snowmelt, and as a result, trace elements were transported both in solution and as suspended sediment into upper Basin Creek during high flow. Mill tailings and waste rock were removed to the Luttrell pit repository during summer 2000.

Chapter E2, “Monitoring Remediation—Have Mine-Waste and Mill-Tailings Removal and Flood-Plain Restoration Been Successful in the High Ore Creek Valley?” by Sharon L. Gelinas and Robert Tupling, describes the cleanup actions taken by the Montana Department of Environmental Quality and the Bureau of Land Management in the High Ore Creek valley. The Comet mine operated as a small open-pit mine briefly during the early 1970s. Mill tailings were impounded in High Ore Creek. The tailings impoundment was breached, and eroded tailings contaminated High Ore Creek and the Boulder River. Water quality and streambed-sediment quality in High Ore Creek and the Boulder River are affected by trace elements leached from these dispersed mill tailings. The tailings impoundment and the High Ore Creek flood plain were reclaimed during the course of this study. Preliminary evaluation of water-quality data collected before and after cleanup indicates that dissolved zinc concentrations have decreased, whereas dissolved arsenic concentrations have increased. Variations of the concentrations of these trace elements indicate a significant change in dissolved trace-element concentrations downstream of High Ore Creek in the Boulder River, but the dissolved trace-element concentrations have not stabilized.

Chapter E3, “Geologic, Geophysical, and Seismic Characterization of the Luttrell Pit as a Mine-Waste Repository,” by Bruce D. Smith, Robert R. McDougal, and Karen Lund, provides an evaluation of the geologic suitability of the Luttrell pit site as a mine-waste repository. The Basin Creek mine went into Chapter 11 Bankruptcy by Pegasus Gold Corp. in 1999. The U.S. EPA eventually acquired the site and requested an evaluation of the geologic suitability of the site as a mine-waste repository. Detailed drilling data, mine-site geology, and fracture density at the Basin Creek mine site were provided by

Pegasus Gold for USGS evaluation of the site to determine the local geologic characteristics and suitability as a mine-waste repository. No evidence of recent faulting in the vicinity of the Luttrell pit was found. Historical seismic data were evaluated to determine that the risk of earthquakes at the proposed repository site was acceptable. Fracture analysis indicated areas where ground-water flow paths from the repository may intersect local structures; these areas were suggested as sites for monitoring wells for the repository. A brief summary of the liner and drain system engineered by independent contractors documents the level of protection provided to prevent escape of any potentially toxic wastes from the Luttrell mine-waste repository site.

Chapter F, "Evaluating the Success of Remediation in the Boulder River Watershed," by Susan E. Finger, Stanley E. Church, and David A. Nimick, describes the potential for successful ecological restoration and 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 identifying the restoration alternative that has the highest probability of success. 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 recommended to chart the progress of aquatic recovery following these remediation efforts.

Chapter G, "Digital Databases and CD-ROM for the Boulder River Watershed," by Carl L. Rich, David W. Litke, Matthew Granitto, Richard T. Pelltier, and Tracy C. Sole, 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.

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