

# **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

Chapter D8 of

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

Edited by David A. Nimick, Stanley E. Church, and Susan E. Finger

Professional Paper 1652–D8

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

# Contents

Abstract.....	283
Introduction .....	283
Purpose and Scope .....	284
Previous Geochemical Investigations.....	284
Sample Collection and Preparation.....	285
Streambed Sediment .....	285
Suspended Sediment .....	285
Premining Sediment .....	285
Sample Analysis.....	289
Geochemical Methods.....	289
Lead Isotopic Methods .....	289
Dendrochronology and the Historical Record .....	289
Trace Elements in Streambed Sediment.....	289
Geochemical Mapping Using Streambed-Sediment Data.....	290
Estimating the Premining Geochemical Baseline from Regional Geochemical Data.....	290
Regional Geochemical Mapping—The Late 1970s Geochemical Baseline .....	290
Current Studies of Streambed Sediment—Definition of Sources of Contaminants.....	291
Geochemical Baseline Maps from Streambed Sediment, 1996–1999 .....	292
Basin Creek.....	297
Cataract Creek .....	300
High Ore Creek .....	302
Boulder River .....	302
Summary .....	305
Premining Geochemical Baseline.....	305
Basin Creek.....	306
Cataract Creek .....	311
High Ore Creek .....	311
Boulder River .....	311
Boulder River Watershed .....	314
Lead Isotopic Results.....	314
Basin Creek .....	317
Cataract Creek .....	319
High Ore Creek .....	322
Boulder River .....	322
Calculation of the Effect of Historical Mining on the Streambed Sediment in the Boulder River .....	325
Comparison of the Boulder River Watershed Streambed-Sediment Data with Sediment-Quality Guidelines .....	330
Summary .....	332
References Cited .....	333

## Figures

1.	Map showing localities of current and previous sediment samples .....	286
2.	Map showing localities where stream-terrace sites were sampled for premining streambed sediment, as well as several mine and mill sites also sampled for this study .....	287
3.	Photographs of four stream-terrace deposit sites.....	288
4–6.	Regional geochemical maps from total-digestion data from NURE streambed-sediment data, contrasted with concentrations in streambed sediment from major tributaries:	
4.	Copper .....	293
5.	Lead .....	293
6.	Zinc .....	294
7.	Regional geochemical map for total arsenic from analysis of streambed sediment from Butte 1°x 2° study contrasted with concentrations in streambed sediment from major tributaries.....	294
8–10.	Ribbon maps showing concentrations of:	
8.	Silver, from total-digestion data from streambed sediment.....	295
9.	Cadmium, from total-digestion data from streambed sediment.....	295
10.	Leachable iron in streambed sediment .....	296
11–13.	Diagrams showing concentrations of copper, lead, zinc, arsenic, silver, cadmium, and antimony, and their effect on streambed sediment of Boulder River:	
11.	Streambed sediment from Basin Creek and its tributaries .....	299
12.	Streambed sediment from Cataract Creek and its tributaries.....	301
13.	Streambed sediment from High Ore Creek and its tributaries.....	303
14.	Concentration profiles of copper, zinc, lead, and arsenic determined from total and partial digestion of streambed sediment in Boulder River.....	304
15–18.	Plots of geochemical data for the elements copper, lead, zinc, arsenic, iron, and manganese from cores for determination of premining geochemical baseline in streambed sediment from:	
15.	Basin Creek basin.....	309
16.	Jack Creek basin .....	310
17.	Uncle Sam Gulch basin and High Ore Creek basin.....	312
18.	Boulder River watershed in the Basin and Boulder mining districts.....	313
19–22.	Ribbon maps showing concentrations of elements in premining streambed sediment of the Boulder River watershed study area:	
19.	Copper .....	315
20.	Lead .....	315
21.	Zinc .....	316
22.	Arsenic .....	316
23.	Plot of concentration of lead versus isotopic composition of lead ( $^{206}\text{Pb}/^{204}\text{Pb}$ ) showing the dominant effect of mixing of contaminant lead derived from mining on isotopic composition of leachable lead in streambed sediment.....	319

24–27.	Profile plots of lead isotopic composition and lead concentration determined in streambed sediment with respect to:	
24.	Boulder River and Basin Creek .....	320
25.	Boulder River and Cataract Creek .....	321
26.	Boulder River and High Ore Creek.....	323
27.	Boulder River.....	324
28.	Plot of the calculated percent deposit-lead contamination added to the streambed sediment of the Boulder River by the addition of tailings from the Jib Mill site and streambed sediment from Basin Creek, Cataract Creek, and High Ore Creek .....	328
29.	Ribbon map showing calculated percentages of deposit lead in streambed sediment today.....	329

## Tables

1.	Trace-element data from streambed sediment from tributary drainages that have little impact from past mining in the Boulder River watershed, Montana.....	291
2.	Statistical summaries of the mine waste data.....	298
3.	Descriptions of sites sampled for possible premining geochemical baseline, age control, and determination of premining concentrations of selected deposit-related trace elements at those sites.....	307
4.	Estimates of contaminant and premining baseline lead isotopic compositions from Boulder River watershed study area .....	318
5.	Calculated copper, zinc, arsenic, and lead contributions from Basin, Cataract, and High Ore Creeks to Boulder River .....	326
6.	Summary of screening level concentrations proposed as possible measures for sediment-quality guidelines.....	331
7.	Sites where the leachable deposit-related trace-element concentrations in streambed sediment from the study area exceed recommended screening levels....	332

## ***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

### **Abstract**

Assessment of deposit-related and rock-forming trace elements in streambed sediment in the Boulder River watershed has provided the data necessary to delineate stream reaches having elevated contaminant concentrations in tributary streams, to determine anthropogenic sources of contaminated streambed sediment, to understand the transport of dissolved and particulate trace elements, and to establish the streambed-sediment framework needed to evaluate toxicity to aquatic biota. Concentrations of the suite of deposit-related trace elements—copper, lead, zinc, arsenic, silver, cadmium, and antimony—were elevated in modern streambed sediment in the Boulder River downstream from the confluence with Basin, Cataract, and High Ore Creeks. The major sources of these contaminants were tied directly to historical mining. All major tributary basins, Basin Creek, Jack Creek, Cataract Creek, Uncle Sam Gulch, and High Ore Creek, and the Boulder River downstream from the confluence of Basin Creek, had concentrations of leachable copper, lead, and arsenic in modern streambed sediment that exceeded the apparent effects threshold for aquatic biota. In the Boulder River, these effects can be traced for a distance of about 55 river miles downstream to the confluence with the Jefferson River. Concentrations of cadmium and zinc exceeded the apparent effects threshold in streambed sediment in the Boulder River downstream from the confluences of Cataract and High Ore Creeks. Everywhere within the three basins downstream from the major mines, the concentrations of all the deposit-related trace elements exceeded the screening level concentration for aquatic biota.

Comparison of the concentrations of this suite of deposit-related trace elements in streambed sediment today with that in premining streambed sediment from terrace deposits in the flood plains of these streams showed that the concentrations of the deposit-related trace elements were substantially elevated, from several to more than 100 times that prior to historical mining. Lead isotopic data from these two media indicated that the effect of mineralized rock on the streambed-sediment geochemistry prior to mining was small, but nevertheless greater than the concentrations of deposit-related trace

elements in tributaries unaffected by historical mining or mineralized rock.

Two different sources of deposit lead were defined by the lead isotopic data, one representing the polymetallic vein deposits in both the Basin and Cataract Creek basins, and a second at the Comet mine in the High Ore Creek basin. Calculations of the extent of the contamination of the streambed sediment in the Boulder River indicate about 35 percent of the lead contamination was introduced by streambed sediment from Basin Creek and the Jib Mill, about 15 percent was derived from Cataract Creek, and about 50 percent was from High Ore Creek. Contaminants carried in streambed sediment from High Ore Creek dominated the concentrations of deposit-related trace elements in stream sediment of the Boulder River below the confluence downstream to the Jefferson River. Data from suspended sediment, when compared with that from the streambed sediment, indicated that copper and zinc were being actively and differentially transported in the suspended-sediment phase relative to arsenic and lead.

### **Introduction**

Streambed-sediment geochemical studies have been used in mineral exploration programs for more than 50 years, using the principle that the presence of elevated trace-element concentrations at a locality or localities may be an indication of undiscovered mineral deposits upstream. Erosion of these mineral deposits or the altered rock surrounding them provides evidence of their presence at specific sites in the watershed. In the case of historical mining districts such as the Basin and Boulder districts discussed here, no historical data exist to indicate either what the concentrations of several important trace elements in water or streambed sediment might have been prior to mining, or whether aquatic life was present in or downstream of these historical mine and mill sites. This report examines the concentrations and sources of selected trace elements in streambed sediment in the Boulder River and its major tributaries near the town of Basin in southwestern Montana.

Ruppel (1963) and Becraft and others (1963) described the mineralogy of the veins that were mined in the Boulder River watershed study area. In general, the miners exploited polymetallic quartz veins containing pyrite, galena, sphalerite, chalcopyrite, arsenopyrite, and minor amounts of tetrahedrite. For purposes of this report, we focus on the distribution of a subset of trace elements that are specifically associated with these polymetallic vein deposits: copper, lead, zinc, arsenic, silver, cadmium, antimony, and gold. We refer to this trace-element suite as the deposit-related trace elements. In contrast, trace elements that are not associated with and enriched in the polymetallic vein deposits are herein referred to as rock-forming trace elements and include chromium, cobalt, strontium, titanium, vanadium, the rare-earth elements, and many others.

Fundamental time-frame differences are present in the data obtained from different sample media collected in the Boulder River watershed study. Water-quality data provide an instantaneous measure of the concentrations of constituents in the water column in a dynamic system. Concentrations of dissolved trace elements in water varied widely depending on streamflow conditions, ground- and surface-water flow, daily variations caused by plant uptake, and instream geochemical reactions (Nimick and Cleasby, this volume, Chapter D5; Lambing and others, this volume, Chapter D7; Kimball and others, this volume, Chapter D6). Suspended-sediment samples, which also included colloidal material, provided data on the concentrations of trace elements in the sediment fraction being transported in the water column. In contrast, streambed-sediment samples integrated conditions at a sample site over a longer time period because the streambed deposits were composed of detrital material transported and deposited during high flow as well as additional material that accumulated at the site during low-flow conditions (Church, Nimick, and others, this volume, Chapter B, fig. 3). This additional material included colloidal material composed of amorphous oxyhydroxides of aluminum, iron, and manganese that either coated these detrital grains or coalesced and settled to the streambed. These coatings and colloids contained and continued to sorb the deposit-related trace elements, effectively lowering their dissolved concentrations in water. Both processes, grain coating and colloidal settling, and continued sorption by these reactive aluminum, iron, and manganese oxyhydroxide surfaces, enriched the streambed sediment with deposit-related trace elements. This enrichment process continued throughout low-flow periods and caused concentrations of the deposit-related trace elements to increase with time during low-flow conditions for a period of several months each year following spring runoff.

## Purpose and Scope

Major objectives of this study were four-fold.

- The primary goal was to characterize one aspect of the current aquatic environmental conditions in the Boulder River watershed—that is, to determine the

present-day spatial distribution of deposit-related trace elements in streambed sediment throughout the watershed. This objective was achieved through geochemical analysis of streambed-sediment samples collected at 63 sites throughout the basin during low flow over the 3-year period from 1996 through 1998.

- A second objective was to identify those mining sites that provide the major contributions of deposit-related trace elements to the streams. This objective was achieved through spatial analysis of contributions of these deposit-related trace elements from mine sites to streambed sediment in specific stream reaches.
- A third objective was to determine the premining geochemical baseline—that is, the concentrations of the deposit-related trace elements in streambed sediment that predate historical mining. Determination of the premining geochemical baseline was necessary to define the minimum concentrations of the deposit-related trace elements that feasible remediation efforts might be expected to achieve. This goal was achieved by sampling of streambed sediment in tributaries located upstream from past mining activities and by sampling premining fluvial deposits in old stream terraces. However, we were limited by the distribution, preservation, and recognition of, as well as access to, these old stream-terrace deposits downstream from historical mining sites. Dendrochronology and historical records have been used to provide a chronology for these terrace deposits (Unruh and others, 2000).
- A fourth objective was to quantify the deposit-related trace-element contribution to the streambed sediment today from historical mine sites within the watershed. The data sets could then be used to evaluate the elevated deposit-related trace-element concentrations found in water and their potential detrimental effects on aquatic habitat in the Boulder River study area (Nimick and Cleasby, this volume; Farag and others, this volume, Chapter D10; Finger, Farag, and others, this volume, Chapter C).

## Previous Geochemical Investigations

Analytical results for major- and trace-element concentrations in streambed sediment have been reported from two previous studies: the Butte 1° × 2° study (McDanal and others, 1985; Elliott and others, 1992) conducted from 1975 to 1983, and the National Uranium Resource Evaluation (NURE) program conducted from 1976 to 1977 (Aamodt, 1978; Broxton, 1980; Van Eeckhout, 1981). In both studies, streambed sediment was collected from small, first-order tributaries, as indicated on 1:24,000-scale topographic maps, with drainage areas of about 1 to 4 or more mi<sup>2</sup>, in order to evaluate the sources

of deposit-related trace elements for mineral exploration. Not all first-order tributary streams within the Boulder River study area were sampled in the NURE or the Butte  $1^\circ \times 2^\circ$  studies. Analytical results from the NURE studies were used to develop regional geochemical maps for copper, lead, and zinc; and results from the Butte  $1^\circ \times 2^\circ$  study were used to develop the regional geochemical map for arsenic. These geochemical maps provide a regional geochemical baseline circa the late 1970s for the Boulder River watershed study area. Sample localities are shown in figure 1. These regional geochemical maps showed the effects of past mining on the first-order tributary drainages and defined an area within the study area with elevated concentrations of copper, lead, zinc, and arsenic. The regional geochemical maps were used to focus the current study on critically affected stream reaches.

The NURE data (Broxton, 1980; Van Eeckhout, 1981) also indicated that the Boulder batholith contained elevated concentrations of uranium. The uranium is in pitchblende in chalcidony veins that occur with the base- and precious-metal polymetallic veins in the Boulder batholith in the study area (Ruppel, 1963; Becraft and others, 1963). No new data have been collected on the occurrence and distribution of the uranium-bearing minerals in these veins.

## Sample Collection and Preparation

### Streambed Sediment

Streambed-sediment samples were collected from 38, 31, and 18 sites, respectively, in October 1996, July 1997, and July 1998 at a total of 63 separate localities on Basin, Cataract, High Ore, and Jack Creeks, Uncle Sam Gulch, and the Boulder and Little Boulder Rivers, or their first-order tributaries (fig. 1). Some samples were collected from outside the study area to sample basins with the same geology, to determine the geochemical baseline in unmineralized streams, and to evaluate the downstream limits of effects in the Boulder River. Streambed-sediment samples were collected during low-flow conditions, thus ensuring collection of colloidal material in the streambed sediment. At each sampling site, streambed-sediment samples were collected, using a plastic scoop, from the surfaces of fluvial sediment deposits in pool or low-velocity areas on both sides of the stream along a 100–150 foot reach. The samples were composited, wet sieved with ambient stream water to pass through a 10-mesh ( $<2$  mm) stainless steel screen, and collected in a plastic gold pan. About 6.5 lb of material was sealed in plastic containers at the site. During the 1996 sampling, a few streambed-sediment samples from the first-order tributary basins were collected to both augment and verify previous work conducted in the NURE and Butte  $1^\circ \times 2^\circ$  regional geochemical studies (fig. 1). Seven pairs of streambed-sediment samples, one each from the north and south sides of the Boulder River, were collected upstream and

downstream of the confluences of Basin, Cataract, and High Ore Creeks (sites 5S, 6S, 8S, 9S, 11S, 12S, and 13S; fig. 1).

In the laboratory, the samples were air dried and sieved to minus 100-mesh ( $<150$   $\mu\text{m}$ ) to correspond directly with the procedure used in the NURE study (the Butte  $1^\circ \times 2^\circ$  study used minus-80-mesh sediment), and split for analysis (Fey, Unruh, and Church, 1999). The sample material analyzed constitutes the very fine sand, silt, and clay size fractions of the fluvial sediment in the active stream channel. Results are in the database (Rich and others, this volume, Chapter G).

Low-flow conditions in the watershed, defined as less than 150  $\text{ft}^3/\text{s}$  at U.S. Geological Survey gauging station 06033300 located 2 mi east of Boulder, started in mid-July in each of the 3 years streambed sediment was sampled (Church, Nimick, and others, this volume, fig. 3). The 1996 samples were collected about 3 months after the onset of low flow, whereas the 1997 and 1998 samples were collected shortly after the spring-runoff period. The samples collected in the latter 2 years are therefore not directly comparable to the data from the 1996 data set because of differences in the time period after runoff for accumulation of colloidal components at the sampling sites. In general, the latter two data sets contain lower concentrations of the deposit-related trace elements, although they exhibit the same trends as were found in the 1996 data set. In construction of the trace-element maps, the 1996 data were used wherever possible. This choice particularly affects sites 7S, 10S, and 14S on the Boulder River (fig. 1).

### Suspended Sediment

In May 1997 during spring runoff, D.A. Nimick collected suspended-sediment samples from six localities (fig. 1) using a DH-74-TM sampler and width- and depth-integrated sampling procedures. Approximately 8 L of water were collected. After the suspended sediment settled in plastic containers, it was collected and air dried for analysis (Fey, Unruh, and Church, 1999).

### Premining Sediment

Stream terraces were sampled at a number of localities (fig. 2) in the study area using either trenches or cores through stream deposits preserved in cutbanks along the creeks and river (Unruh and others, 2000). The terrace deposits were generally composed of poorly sorted fluvial silt, sand, and gravel containing lithic clasts ranging in size up to 12 in. in diameter (fig. 3). Because no discernible stratigraphy was preserved in the gravel deposits, samples were taken in 6- to 12-in. intervals throughout the exposed terrace section. We dug back into the terrace deposit at least 8 in., carefully removing any materials that might have been deposited on the surface or cut bank of the terrace by historical floods that might have contaminated the sample. We removed unvegetated sand and gravel deposited on top of the terrace deposits unless covered by a



**Figure 1.** Localities where suspended-sediment and streambed-sediment samples were collected during current study, and where streambed-sediment samples were collected in Butte 1° x 2° and NURE studies during the 1970s. Some small tributaries sampled during Butte 1° x 2° study are not shown. Prior to this study, no samples were collected from the major tributaries or Boulder River. The Jib Mill site is also shown.



**Figure 2.** Localities where stream-terrace sites were sampled for premining streambed sediment to determine premining geochemical baseline. Also shown are several mine and mill sites sampled for this study that were localities of the primary point sources of contamination reaching the streams. Fluvial tailings deposits and selected mine sites were also sampled.

**Figure 3.** Stream-terrace deposit sites. *A*, Terrace sampled on Basin Creek (near site 10*B*). Notice mottled iron staining in layer below the well-developed soil horizon and above the gravel indicating postdepositional oxidization and possible movement of iron in the terrace sediments. *B*, Terrace site sampled at beaver dam impoundment on upper Jack Creek downstream from Bullion Mine tributary (site 14*B*). Note thick deposit of fluvial tailings from blowout of the mill tailings dams at the Bullion mine. Core sample was taken using a 2-in.-diameter PVC pipe near base of a 99-year-old Lodgepole pine buried in the dam during construction. *C*, Flood-plain gravel deposit on Uncle Sam Gulch downstream from Crystal mine (site 17*B*). The premining baseline core (foreground) was taken between two large stabilizing roots of a 252-year-old Ponderosa pine harvested in 1983. Stainless steel coring probe used for the 1-in. diameter cores is lying on top of stump. Note contaminated water and streambed sediment in Uncle Sam Gulch (background). *D*, fluvial deposits from near site 6*B*, downstream from High Ore Creek on the Boulder River. Uppermost layer above white zone and in root zone contaminated by post-mining overbank sediment. Cottonwood growing on river bank at this locality gave dendrochronological age of 60 years.

well-developed soil horizon to prevent contamination by recently deposited gravel and silt. We took a minimum of three samples at each site to provide some measure of reproducibility of the analytical data, or to discern a geochemical trend in the data from the site. Where the analytical results were not consistent between samples collected at the same site, not all the results were used to estimate the premining geochemical baseline. The gravel samples were dry sieved in the field to pass a 2-mm stainless steel screen, and sent to the laboratory for further processing.

In the laboratory, the samples were air dried if needed, sieved to pass 100-mesh (<150  $\mu\text{m}$ ), and split to ensure homogeneity (Fey, Unruh, and Church, 1999). The sample material analyzed constitutes the very fine sand, silt, and clay size fractions of the premining fluvial sediment; results are in Unruh and others (2000) and in the database (Rich and others, this volume).

## Sample Analysis

### Geochemical Methods

Geochemical data for the streambed-sediment, suspended-sediment, and terrace samples were determined using inductively coupled plasma-atomic emission spectrometry (ICP-AES) from a mixed mineral-acid total digestion (Briggs, 1996; Church, 1981) and from a partial-digestion method using 2M HCl-1 percent  $\text{H}_2\text{O}_2$  (Fey, Unruh, and Church, 1999). This partial digestion or leach was designed to dissolve the aluminum, iron, and manganese oxyhydroxide component of the streambed sediment and isolate the deposit-related trace elements contained in this component of the streambed sediment from those trace elements in the rock-forming phases of the streambed sediment found in the total digestions of the residual phases (Rich and others, this volume). Total-digestion data were used for the geochemical maps (figs. 8–9) so that the data collected in this study are comparable with those from previous studies (figs. 4–7), whereas the partial-digestion data have been used to make the concentration versus distance diagrams (figs. 11–14) that showed the streambed-sediment geochemistry profiles. All analytical results are available in the database (Rich and others, this volume).

### Lead Isotopic Methods

Lead isotopic analyses of the streambed sediment were done on the partial-digestion solutions using standard lead isotopic methods (Fey, Unruh, and Church, 1999; Unruh and others, 2000). Results are reported in terms of the lead isotope ratio to  $^{204}\text{Pb}$ , the isotope of lead that has no radioactive parent. All analytical results are in the database (Rich and others, this volume).

## Dendrochronology and the Historical Record

We used historical data and dendrochronology to constrain the ages of premining gravel in terrace deposits used to determine the premining geochemical baseline. The dendrochronological data provide minimum ages for the terrace deposits whereas the historical data provide ages of structures or events within the mining district. Historical data for the Basin and Cataract mining districts were reviewed by Rossillon and Haynes (1999), who provided this work under contract with the USDA Forest Service.

Dendrochronological analysis was conducted by the Laboratory of Tree-Ring Research, University of Arizona, Tucson, Ariz.; the results are in Unruh and others (2000). Dates from live trees provided a minimum age of the terrace. Dates from dead standing trees sampled also provided only a minimum age, but with a larger uncertainty. Construction of a dendrochronological record from live trees to allow dating of dead trees was not achieved. The climate of the basin was sufficiently constant through time that a distinctive tree-ring structure versus time curve could not be constructed (Jeff Dean, Laboratory of Tree-Ring Research, University of Arizona, written commun., 1999). Development of a mature soil horizon on terraces was used in a qualitative sense to estimate the relative age and maturity of stream-terrace deposits.

## Trace Elements in Streambed Sediment

Deposit-related trace elements derived from acidic drainage and mine waste as well as from mineralized but unmined sources typically accumulate in the streambed sediment downstream from inactive, historical mines. In the Boulder River watershed study area, these trace elements were concentrated in the colloidal phase and the grain coatings of the streambed sediment. As seen from the data, the difference between the concentrations of the deposit-related trace elements in the total-digestion data and data from the residual silicates clearly showed that the deposit-related trace elements were concentrated in and associated with the iron oxyhydroxide component of the streambed sediment. Downstream concentration profiles for streambed sediment, constructed using the partial-digestion data, were used to delineate stream reaches that had elevated deposit-related trace-element concentrations, to locate sources of contaminated material, and to help understand the transport of dissolved and particulate trace elements. In addition, we used concentration data to evaluate the potential toxicity of deposit-related trace elements in streambed sediment to biota (Frag and others, this volume).

The measured concentrations of deposit-related trace elements in the streambed sediment varied with the velocity of the flow regime. The colloidal component and the suspended sediment tended to settle out of suspension in low-velocity reaches in the stream or river. Thus, the deposit-related trace-element concentrations were susceptible to temporal

variability caused by sorption to grain coatings and colloids, and by deposition of the suspended sediment during low flow. They were also dependent upon the frequency of summer storms because the increased flow may mobilize some fraction of the colloidal component that had settled to the streambed. In general, one would not expect temporal variability to affect spatial variation of the geochemical signature obtained from a streambed-sediment survey within a watershed as long as the entire sample suite was collected over a short time frame (barring a summer rainstorm during the sample collection period). No such rainfall event occurred during any of the three streambed-sediment sampling efforts in the Boulder River watershed (Church, Nimick, and others, this volume, fig. 3).

Downstream profiles of deposit-related trace-element concentrations in streambed sediment in the Boulder River watershed study area were similar to the concentration profiles observed for surface water for copper, lead, zinc, and cadmium (Nimick and Cleasby, this volume). The highest concentrations of leachable and total deposit-related trace elements in streambed sediment occurred immediately downstream from the large mines, the Buckeye, Bullion, Crystal, and Comet mines (fig. 2), whereas concentrations of these deposit-related trace elements were near average crustal abundance values in rocks underlying subbasins where mineral deposits have not been found. Copper, lead, zinc, arsenic, cadmium, and antimony were concentrated in the leachable phase, indicating sorption to the hydrous aluminum, iron, and manganese grain coatings and colloids in streambed sediment. Concentrations of trace elements not associated with the mineral deposits (for example, chromium, cobalt, strontium, titanium, vanadium, and the rare-earth elements) were similar throughout the watershed where underlain by the same rock type.

## Geochemical Mapping Using Streambed-Sediment Data

### Estimating the Premining Geochemical Baseline from Regional Geochemical Data

The geochemical baseline for the Boulder River watershed study area today was evaluated using geochemical data from small tributaries from both the current and previous studies. Data from these small tributaries where the drainage basin is underlain by unmineralized rocks of the Boulder batholith and the Elkhorn Mountains Volcanics (O'Neill and others, this volume, Chapter D1) provided but one measure of the geochemical baseline prior to historical mining. Tributary streams sampled in the earlier studies that had near-crustal-abundance trace-element concentrations were generally not resampled. Reference sites located in drainages that had a geologic setting similar to the study area were sampled outside the study area to provide data for comparison with mineralized areas. At site

1S on the upper Boulder River (fig. 1), the drainage basin is underlain by Cretaceous plutonic rocks of the Boulder batholith and the coeval Elkhorn Mountains Volcanics (Wallace, 1987). Elliott and others (1992) indicated one large past-producing mine, several small historical mines with no known production, and several prospects in the headwaters of the Boulder River substantially upstream of the sampling site. At site 19S on the Little Boulder River (fig. 1), the basin is underlain by Cretaceous plutonic rocks of the Boulder batholith and the coeval Elkhorn Mountains Volcanics (Wallace, 1987). Elliott and others (1992) indicated that a small gold placer, several prospects, and several small past-producing historical mines were located in the Little Boulder River basin upstream of the sampling site. With the exception of the placer mine, these mines and prospects were not close to the Little Boulder River. At site 2S (fig. 1), the drainage basin is underlain by Cretaceous plutonic rocks of the Boulder batholith and the coeval Elkhorn Mountains Volcanics on the north side of the Boulder River, but by the younger Lowland Creek Volcanics of Eocene age on the south side of the Boulder River (Wallace, 1987). Elliott and others (1992) indicated little past mining in this area of the Boulder River watershed.

Thirty-five streambed-sediment sites from the NURE study (Aamodt, 1978; Broxton, 1980; Van Eeckhout, 1981) were located within the Boulder River watershed study area (fig. 1). Many of these sites were on first-order tributary streams shown on 1:24,000-scale topographic maps (fig. 1). Results for copper, lead, and zinc from 16 streambed-sediment samples from the NURE study and 11 samples collected from the Boulder River watershed study area are summarized in table 1. Samples were restricted to those collected from tributary drainages generally underlain by rocks of the Butte pluton that appeared to have little or minimal effects from past mining activities. Arsenic was not analyzed, and only a few cadmium and silver concentrations were determined or were above the limit of detection in streambed sediment analyzed during the NURE study. Median and mean concentrations for this suite of trace elements are in reasonable agreement between the two data sets. The standard deviation of the data sets is small when compared to the median value. The median and mean concentrations of the deposit-related trace elements are near or below average crustal abundance values for cadmium, copper, and silver, and were elevated above crustal abundance values for arsenic, lead, and zinc (table 1). We used the median values determined from these two studies to define one measure of the premining geochemical baseline in the Boulder River watershed and to compare with enrichment for this same suite of trace elements downstream from inactive mine sites in the Boulder River watershed study area.

### Regional Geochemical Mapping— The Late 1970s Geochemical Baseline

Regional geochemical maps of the study area were constructed from the streambed-sediment data from first-order

**Table 1.** Trace-element data from streambed sediment from tributary drainages that have little impact from past mining in the Boulder River watershed, Montana.

[<, value below specific limit of detection (ICP-AES; this study); n.a., not analyzed; --, no data calculated; No. of sites does not include censored arsenic values in the new data set or censored zinc values in the NURE data set; crustal abundance data from Fortescue (1992)]

tributary drainages sampled in the NURE or Butte  $1^{\circ} \times 2^{\circ}$  studies using the procedures described in Smith (1994) and Smith and others (1997). The data sets for copper, lead, zinc, and arsenic were each gridded using 3,281-ft (1,000-m) cells from a block of data with a large margin surrounding the Boulder River watershed study area to ensure that the interpolation of the geochemical data surface was not affected by “edge effects.” Contoured geochemical maps were constructed from the gridded data using approximate multiples of crustal abundance (Fortescue, 1992; table 1) for four of the deposit-related trace elements. Sample localities appear in figure 1. The maps were trimmed to produce the regional geochemical base maps (figs. 4–7). Data from both regional geochemical studies were used to focus the investigations of the environmental effect of past mining activities in the study area. No regional geochemical maps were constructed for silver and cadmium because the data were censored below the detection limit of 2 ppm, which was substantially above the crustal abundance value (table 1).

### Current Studies of Streambed Sediment— Definition of Sources of Contaminants

Total-digestion streambed-sediment data collected from the main tributaries (Basin, Cataract, High Ore, and Jack Creeks, and Uncle Sam Gulch) during this study have been used to produce the ribbon maps superposed on the regional geochemical base maps of the Boulder River watershed

study area (figs. 4–7) to provide the basic framework for the interpretation of the distribution of the deposit-related trace elements. The deposit-related trace elements were derived from the weathering of both altered and unaltered rock (O’Neill and others, this volume; McCafferty and others, this volume, Chapter D2) as well as mine waste and mill tailings (Fey and Desborough, this volume, Chapter D4; Martin, this volume, Chapter D3). Ribbon maps for silver and cadmium are presented as figures 8 and 9. Values on the ribbon reflect the concentration of the deposit-related trace element measured at the nearest downstream sample site. Exceptions to this procedure have been made where additional field data supported these changes: (1) data from site 4S on the Boulder River were assumed to apply downstream to the Jib Mill site (figs. 1 and 2); (2) data from site 46S on upper Cataract Creek were assumed to apply to the reach of Cataract Creek upstream from the Eva May mine (near the confluence with Hoodoo Creek) to site 46S; (3) data from site 51S were assumed to apply to the reach between site 51S and the confluence with Big Limber Gulch; and (4) data from site 58S, in the headwaters of High Ore Creek, were assumed to apply to the entire reach upstream from the Comet mine. Data from sites 7S, 10S, and 14S on the Boulder River, which were collected in 1997 and 1998, were collected much earlier in the summer following the onset of low-flow conditions than those streambed-sediment samples collected from the Boulder River in 1996, so whenever in conflict with the data from the 1996 sampling, the 1997-98 data were not used to construct the

ribbon maps. Leachable iron concentrations determined using the partial-digestion data have been used to show that iron-rich sediment accumulates downstream from the major mine sites in the watershed (fig. 10). Some of the areas of high leachable iron concentrations were downstream from mine sites and corresponded to areas of low pH observed in the stream reaches at low flow (Nimick and Cleasby, this volume, fig. 3).

Rock-forming trace elements, such as chromium, cobalt, strontium, vanadium, titanium, and the rare-earth elements, showed no abrupt changes in concentration in the streambed sediment downstream from the major mines in the watershed in either the NURE, Butte  $1^\circ \times 2^\circ$ , or our data sets. This indicated that the source of the deposit-related trace-element enrichment found in some streambed-sediment samples downstream from historical mining sites in the study area was associated with past mining of the mineral deposits, as was shown in studies in other watersheds affected by historical mining activity (for example, Church and others, 1993, 1997). In the terrace deposits, as will be shown later, premining geochemical baseline data (with the exception of one site) did not show such profound enrichment of the deposit-related trace elements.

Streambed sediment was sampled at several localities in the Boulder River watershed for 2 or 3 consecutive years to evaluate the temporal stability of the geochemical maps. The data set was not sufficiently large to provide a rigorous statistical test, but it was sufficient to provide a general overview of the stability of the geochemical maps. In general, rock-forming trace-element concentrations were stable at the  $\pm 10$  percent level, whereas the deposit-related trace elements, which were controlled by the percentage of colloidal material in the streambed sediment, varied substantially between the 1996 and the 1997 and 1998 data sets as discussed in paragraph 1 of this section. Data used for the geochemical profile diagrams (figs. 11–13) and streambed-sediment ribbon maps (figs. 4–10) were primarily from samples collected during the 1996 field season. The concentrations of the deposit-related trace elements in the 1997–98 data sets generally were lower than those in the 1996 data set because of the difference in time frames for accumulation of colloids at these sites.

## Geochemical Baseline Maps from Streambed Sediment, 1996–1999

Studies of streambed sediment affected by mine drainage in other watersheds (Church and others, 1993, 1997; Kimball and others, 1995; Nordstrom and Alpers, 1999; Smith, 1999; Desborough and others, 2000) have shown that trace elements were sorbed to grain coatings and to iron and aluminum colloids, that is, hydrous iron oxyhydroxides (for example, ferrihydrite), iron oxysulphates (for example, schwertmannite), and aluminum oxysulphates. The results from the present study indicate that the mineralogical residence site for the sorbed deposit-related trace elements was the grain coatings and colloids formed in the water column during mixing of the acidic

drainage with more neutral water. Enrichment of iron from colloidal transport and settling on the streambed is a function of the pH of the water, sorption of deposit-related trace elements to the grain coatings and colloids, and the velocity of the stream. The enrichment of colloidal iron is shown on the ribbon map of leachable iron (fig. 10). Strongly elevated concentrations of leachable iron occurred in the stream reaches below the Comet, Crystal, and Bullion mines. The elevated concentrations of metals in Hoodoo and Rocker Creeks also may reflect past mining activity. Strongly elevated concentrations of leachable iron in upper Cataract Creek (fig. 10) appear to be related to wetland areas in the headwaters. Comparison of the partial-digestion data to crustal abundance is problematic because published crustal abundance data were determined from total-digestion results. Therefore, in the discussion following, enrichments of the deposit-related trace elements are expressed using the total-digestion data, whereas discussions of mechanisms of enrichment are drawn from the partial-digestion data. Partial-digestion concentrations were generally lower than the total-digestion concentrations because the deposit-related trace elements in rock-forming particles and sulfide grains, with the exception of galena, were not dissolved by the partial digestion.

Deposit-related trace elements were concentrated in the reaches of the major tributaries and creeks where leachable iron concentrations were generally greater than the 75th percentile (2.0 wt. percent or 20,000 ppm iron) downstream from major mine sites in the Boulder River watershed study area. Copper concentrations in streambed sediment below the Crystal and the Comet mines exceeded 20 times crustal abundance and affected Uncle Sam Gulch and Cataract Creek, and High Ore Creek, respectively, to their confluence with the Boulder River (fig. 4). Elevated concentrations of lead occurred in streambed sediment immediately downstream from the Buckeye and Bullion mine sites and affected upper Basin and Jack Creeks downstream to their confluence (fig. 5). In the stream reaches downstream from the Crystal mine, lead concentrations of greater than 140 times crustal abundance affected Uncle Sam Gulch and Cataract Creek for several miles downstream from the mine site to the confluence with the Boulder River. Streambed sediment in Cataract Creek between the confluence of Hoodoo Creek and Uncle Sam Gulch downstream from the Eva May mine had an elevated lead concentration in excess of 19 times crustal abundance. Lead concentrations exceeded 400 times crustal abundance in streambed sediment in High Ore Creek downstream from the Comet mine and in the Boulder River for at least 2 miles downstream from the confluence with High Ore Creek (fig. 5).

In general, the distribution of arsenic (fig. 7) and silver (fig. 8) in streambed sediment follows that of lead, although silver was more quickly attenuated than lead by instream processes. Elevated concentrations of zinc (fig. 6) and cadmium (fig. 9) were more dispersed downstream from the major mine sites than were copper, lead, arsenic, and silver, which reflect the tendency of cadmium and zinc to sorb less strongly than copper, lead, arsenic, and silver to the hydrous iron oxide



**Figure 4.** Regional geochemistry for copper from total-digestion data from NURE streambed-sediment data (Broxton, 1980) showing contrast with copper concentrations in streambed sediment from major tributaries. White, sample density insufficient to allow projection of geochemical surface using a 3,281-ft (1,000-m) grid-cell density. Dark-red square, Jib Mill site.

**Figure 5.** Regional geochemistry for lead from total-digestion data from NURE streambed-sediment data (Broxton, 1980) showing contrast with lead concentrations in streambed sediment from major tributaries. White, sample density insufficient to allow projection of geochemical surface using a 3,281-ft (1,000-m) grid-cell density. Dark-red square, Jib Mill site.



**Figure 6.** Regional geochemistry for zinc from total-digestion data from NURE streambed-sediment data (Broxton, 1980) showing contrast with zinc concentrations in streambed sediment from major tributaries. White, sample density insufficient to allow projection of geochemical surface using a 3,281-ft (1,000-m) grid-cell density. Dark-red square, Jib Mill site.

**Figure 7.** Regional geochemistry for total arsenic from analysis of streambed sediment from Butte 1° x 2° study (McDanal and others, 1985) showing contrast with arsenic concentrations in streambed sediment from major tributaries. White, sample density insufficient to allow projection of geochemical surface using a 3,281-ft (1,000-m) grid-cell density. Dark-red square, Jib Mill site.

**Figure 8.** Concentrations of silver from total-digestion data from streambed sediment collected from major tributaries during current study. Dark-red square, Jib Mill site.

**Figure 9.** Concentrations of cadmium from total-digestion data from streambed sediment collected from major tributaries during current study. Dark-red square, Jib Mill site.

**Figure 10.** Concentrations of leachable iron in streambed sediment from major tributaries (leachate data). Box plot shows distribution of leachable iron data; 75th percentile is 2.0 weight percent or 20,000 ppm, the 90th percentile is 3.0 weight percent, or 30,000 ppm. Dark-red square, Jib Mill site.

phases (Smith, 1999; Schemel and others, 2000). These same trends were seen in comparison of dissolved cadmium and zinc data with lead and arsenic in surface water (Nimick and Cleasby, this volume). Elevated cadmium and zinc concentrations (10 to more than 20 times crustal abundance) from the Bullion mine affected the lower reaches of Jack Creek and Basin Creek downstream from the confluence of Jack Creek. Elevated cadmium and zinc concentrations from the Crystal mine affected Uncle Sam Gulch and Cataract Creek downstream from Uncle Sam Gulch. The Boulder River had also been affected downstream from Cataract Creek. High Ore Creek downstream from the breached tailings dam at the Comet mine (Gelinas and Tupling, this volume, Chapter E2) had elevated concentrations of cadmium and zinc that affected streambed sediment in High Ore Creek as well as the Boulder River for about 2 miles downstream from the confluence.

Partial-digestion data for copper, lead, zinc, arsenic, silver, cadmium, and antimony are plotted as a function of river distance in figures 11–13. Distance is expressed in miles downstream from the confluence of Basin Creek with the Boulder River, which was assigned an arbitrary value of 15 miles (25 km). Samples from the principal tributary streams are plotted relative to the distance upstream from the confluence of the tributary with the stream it intersects. Streambed-sediment data from other tributary streams not affected by mining are not shown, but they are summarized in table 1. The tie lines show the substantial influx of deposit-related trace elements in the stream from particular mine sites as well as the dispersive effect of downstream transport and dilution by uncontaminated sediment from other tributary basins. This dispersive effect can also be seen on the ribbon maps (figs. 4–10). The concentrations of the deposit-related trace elements in the seven pairs of streambed-sediment samples from the north and south sides of the Boulder River (sites 5S, 6S, 8S, 9S, 11S, 12S, and 13S; fig. 1) were averaged to produce the ribbon maps and the geochemical profile diagrams (figs. 4–10, 11–13). The data from the Boulder River streambed sediment are plotted on all of the geochemical profile diagrams (figs. 11–13) so that the streambed-sediment contribution from each of the three principal tributaries to the Boulder River can be evaluated. Additional amounts of deposit-related trace elements were being contributed by both the dissolved and suspended loads (Nimick and Cleasby, this volume).

Major sources of mine waste sampled during this study (fig. 2) are also indicated on the geochemical profile diagrams. From the study of mine sites, Fey and Desborough (this volume) identified and ranked several major mine sites that contained substantial concentrations of deposit-related trace elements. Statistical data for deposit-related trace-element concentrations from five sites are summarized in table 2. Samples from three of the sites, Bullion, Buckeye, and Comet, represent a large enough number of mill tailings samples to be statistically meaningful. We use the 75th percentile as an estimate of the concentration of the contaminants in figures 11–13 because mixing with soil and streambed sediment in many of the samples had reduced the concentrations of the

deposit-related trace elements. Therefore, the median value was judged to not be a good indicator of the concentration of the deposit-related trace elements from the source.

## Basin Creek

Geochemical data for leachable copper, lead, zinc, arsenic, silver, cadmium, and antimony from streambed sediment from the Basin Creek geochemical profile are in figure 11. In addition to the data from the Boulder River, three stream reaches are distinguished on this diagram: (1) Basin Creek, a major contaminated tributary of the Boulder River, (2) Jack Creek, and (3) the unnamed tributary to Jack Creek that drains the Bullion mine, hereafter referred to as Bullion Mine tributary (fig. 2). Three major anthropogenic sources of deposit-related trace elements lie along Basin Creek: the Buckeye and Enterprise mines in the headwaters of Basin Creek, the Bullion mine in the headwaters of the Bullion Mine tributary, and the Bullion smelter reservoir on lower Jack Creek (site 15B, fig. 2). Mill tailings and mine waste from both the Buckeye and Enterprise mine sites and the Bullion mine site received high rankings. Both were recommended for remedial action (Fey and Desborough, this volume).

Exposed sulfidic wastes from the Buckeye and Enterprise mines caused an increase in deposit-related trace-element concentrations in streambed sediment (site 21S at about river mi 2; fig. 11) in the upper reaches of Basin Creek (Cannon and others, this volume, Chapter E1). Metesh and others (1994) reported surface water draining from this site with a pH of 3.12. Cannon and others (this volume) reported pH values of 3.1 to 4.1 that varied by season at this site. Copper, lead, zinc, and arsenic in the total-digestion data from site 21S below the Buckeye and Enterprise mines were enriched by factors of 4.1, 46, 4.5, and 129 respectively over the geochemical baseline (table 1). Concentrations of the deposit-related trace elements in streambed sediment decreased steadily until upstream from the confluence with Jack Creek at site 24S (river mi 7.5). The Bullion mine (fig. 2), on the Bullion Mine tributary of Jack Creek, was the major source of streambed-sediment contamination in Jack Creek (river mi 6). Metesh and others (1994) reported mine adit drainage at this site with a pH of 2.58, and Desborough and others (2000) reported schwertmannite, a hydrous iron sulfate, in streambed sediment below the Bullion mine. Schwertmannite forms in acidic waters in the pH range of 2.8 to 4.5 (Bigham and others, 1996). Concentrations of copper, lead, zinc, and arsenic were enriched in streambed sediment below the Bullion mine (site 33S) by factors of 10, 25, 4.6, and 66 respectively (table 1). Fluvial tailings in over-bank deposits downstream (35S–37S), presumably deposited after the breach of the tailings impoundments at the mine site, had deposit-related trace-element concentrations that substantially exceeded the enrichment factors found downstream (34S–36S) along Bullion Mine tributary. The addition of sediment from upper Jack Creek was responsible for the dilution of the deposit-related trace-element concentrations in streambed sediment immediately downstream from the confluence

**Table 2.** Statistical summaries of the mine waste data.

[75th percentile was used as the best estimate of the composition of the contaminant]

of Bullion Mine tributary with Jack Creek. Impoundment of these tailings and streambed sediment in an abandoned beaver pond at site *14B* just downstream from the confluence with the Bullion Mine tributary, and in an old reservoir at site *15B* (upstream from site *41S*), which was built to provide water for the Bullion smelter that operated from 1904 to 1906 (Rossillon and Haynes, 1999), trapped contaminated sediment in the lower reaches of Jack Creek.

Jack Creek provided a large contribution to the streambed sediment in Basin Creek, as can be seen by the major increase in deposit-related trace-element concentrations at the confluence of Jack Creek with Basin Creek at about river mi 7.6

(site *26S*, fig. 11). Deposit-related trace-element concentrations decreased slowly downstream in streambed sediment of Jack Creek from the confluence with the Bullion Mine tributary to the confluence with Basin Creek. The streambed sediment in Jack Creek was highly enriched in leachable iron (fig. 10) resulting from the acid mine drainage from the Bullion mine (Kimball and others, this volume).

The effect of deposit-related trace elements from the Bullion mine on the streambed sediment concentrations of copper, zinc, arsenic, and cadmium in Basin Creek downstream from the confluence with Jack Creek substantially overwhelmed the deposit-related trace-element concentrations in the streambed

**Figure 11.** Concentrations of copper, lead, zinc, arsenic, silver, cadmium, and antimony determined in the partial digestion of streambed sediment from Basin Creek and its tributaries, and their effect on streambed sediment of Boulder River. Trace-element concentrations determined for major sources within the watershed are also shown. Data plotted against distance; upstream always to left regardless of actual direction stream flows. Samples that represent streambed sediment from active stream or river channel are indicated by discrete solid symbols and connected by tie lines. Concentrations of antimony, cadmium, and silver are censored at 2 ppm and arsenic at 5 ppm.

sediment that were derived from the Buckeye and Enterprise mines. Concentrations of three trace elements increased substantially downstream from the confluence of Jack Creek with Basin Creek (sites 24S and 26S): copper from 29 to 130 ppm, zinc from 380 to 580 ppm, and arsenic from 140 to 330 ppm, in the total-digestion data and copper from 24 to 210 ppm, zinc from 290 to 840 ppm, and arsenic from 98 to 430 ppm in the partial-digestion data. Lead concentrations in the streambed sediment remained relatively constant at about 200 ppm in the total-digestion data, but lead concentrations increased in the partial-digestion data from 170 to 320 ppm. Differences in the total-digestion data and the partial-digestion data probably are not analytical but are more likely the result of the difference in sample size used for the analytical procedure (0.2 g for the total digestion versus 2.0 g for the partial digestion; Fey, Unruh, and Church, 1999). These differences between data sets are generally not large or very important in an absolute sense because the data always exhibit the same trends. The differences are largely the result of the “nugget effect,” that is, an observed difference when elements are concentrated in a single grain, in this case the deposit-related trace elements in the iron colloids.

Downstream from the confluence of Basin Creek with Jack Creek, deposit-related trace-element concentrations were diluted by uncontaminated streambed sediment that had lower concentrations of deposit-related trace elements entering Basin Creek from other tributary drainages. At the confluence of Basin Creek and Boulder River (site 31S), copper, lead, and arsenic concentrations in streambed sediment decreased from 130 to 93 ppm, from 210 to 160 ppm, and from 330 ppm to 110 ppm, respectively. Zinc concentrations increased slightly downstream from the confluence with Jack Creek from 580 to 600 ppm. Concentrations of leachable zinc in streambed sediment were about 900 ppm downstream and decreased near the confluence with the Boulder River to about 600 ppm.

As shown in figure 11, the data from the suspended sediment from the Boulder River upstream from the confluence with Basin Creek (4S) and from Basin Creek just upstream from the confluence (30S) with the Boulder River indicated that the total concentration of deposit-related trace elements in the suspended sediment was very similar to that found in the leachable phase of the streambed sediment in the stream reach where the suspended sediment was sampled. Such a correlation would be expected since the suspended sediments are dominated by the colloidal components extracted during the partial digestion. Concentrations of deposit-related trace elements were elevated relative to where they were collected because the suspended-sediment samples, which were collected in May 1997, represented streambed sediment that had accumulated upstream during low flow in 1996.

## Cataract Creek

In addition to the data from the streambed-sediment study, extensive water-quality data have been collected (Nimick and Cleasby, this volume) and a metal-loading

study conducted on Cataract Creek (Kimball and others, this volume; Cleasby and others, 2000). The results of the metal-loading study clearly showed little effect on the streambed-sediment geochemistry of Cataract Creek by past mining upstream from the Eva May mine, located near the confluence of Hoodoo Creek (river mi 10.5, fig. 12). Rocker Creek was contaminated by past mining in its headwaters (probably from the Ada mine), but little of that deposit-related trace-element contamination was transported into Cataract Creek as streambed sediment as evidenced by the NURE data from lower Rocker Creek (Broxton, 1980). The contamination likely was trapped in the low gradient reach of Rocker Creek upstream from the confluence and diluted by the relatively uncontaminated streambed sediment in Cataract Creek upstream from the Eva May mine site. In the reach from the Hoodoo Creek confluence (using the data from site 46S, river mi 10) downstream to Uncle Sam Gulch (site 49S, river mi 12.5), streambed-sediment concentrations of copper increased from 47 to 190 ppm, lead from 47 to 240 ppm, zinc from 280 to 610 ppm, and arsenic from 63 to 150 ppm. In the leachable phase, partial-digestion data for copper increased from 44 to 110 ppm, lead from 49 to 220 ppm, zinc from 250 to 440 ppm, arsenic from 41 to 96 ppm, silver from <1 to 5 ppm, and cadmium from 1.5 to 2.7 ppm. The increase in the deposit-related trace-element concentrations in the streambed sediment, by about a factor of four in this stream reach, was not caused by streambed sediment from Hoodoo Creek or by the influx of tailings from the Eva May mine site, even though direct field evidence showed transport of tailings from the Eva May mine site into Cataract Creek. The August 1997 metal-loading study (Kimball and others, this volume; Cleasby and others, 2000) indicated that the Cataract mine and mill tailings sites and the upper and lower Hattie Ferguson mine sites were probable sources of deposit-related trace elements in this reach. Additional sources of mine waste on private property, to which we did not have access, were located along Cataract Creek near the stream bank, such as the Morning Glory mine (Martin, this volume).

The Crystal mine (fig. 2, table 2), located in the headwaters of Uncle Sam Gulch (fig. 12, river mi 10), was the major source of deposit-related trace elements in the streambed sediment of Cataract Creek (table 2). Mine wastes from the Crystal mine were ranked as a moderate source of deposit-related trace elements (Fey and Desborough, this volume). Copper, lead, zinc, arsenic, silver, and cadmium concentrations in streambed sediment increased dramatically directly below the mine (sites 54S and 55S, river mi 10.5). Additional enrichments of copper and zinc occur at the confluence of Uncle Sam Gulch with Cataract Creek (site 57S, river mi 12.5), but lead and arsenic concentrations decrease. Desborough and others (2000) reported the presence of schwertmannite in streambed sediment from Uncle Sam Gulch immediately downstream from the Crystal mine adit. The pH of Uncle Sam Gulch downstream from the Crystal mine was 3.2–3.5 (Metesh and others, 1995; Nimick and Cleasby, 2000), which is within the pH stability field of



**Figure 12.** Concentrations of copper, lead, zinc, arsenic, silver, cadmium, and antimony determined in the partial digestion of streambed sediment from Cataract Creek and its tributaries, and their effect on streambed sediment of Boulder River. Trace-element concentrations determined for major sources within the watershed are also shown. Data are plotted against distance; upstream always to left regardless of actual direction stream flows. Samples that represent streambed sediment from active stream or river channel are indicated by discrete solid symbols and connected by tie lines. Concentrations of antimony, cadmium, and silver are censored at 2 ppm and arsenic at 5 ppm.

schwertmannite (Bigham and others, 1996); pH increased to  $7.3 \pm 0.2$  at the confluence with Cataract Creek at low flow (Nimick and Cleasby, this volume, fig. 3). The enrichment of deposit-related trace elements in the streambed sediment of Uncle Sam Gulch upstream from the confluence with Cataract Creek at site 57S is as follows: copper, 72; lead, 26; and zinc, 25; and arsenic, 37 times the geochemical baseline (table 1). Suspended-sediment concentrations collected from site 57S (river mi 12.5) exceeded the concentrations of deposit-related trace elements in streambed sediment with enrichment factors of 93 for copper, 24 for lead, 32 for zinc, and 49 for arsenic relative to the geochemical baseline (table 1). Suspended-sediment concentrations decreased by a factor of 2 to 3.5 at site 57S. Enrichment factors in the streambed sediment at site 53S are as follows: copper, 14 fold; lead, 13 fold; zinc, 6.7 fold; and arsenic, 17 fold. Relative to the suspended-sediment concentrations at site 53S, the concentrations in the suspended sediment were similar for lead, arsenic, and silver, but enriched by a factor of 2 for copper, a factor of 3 for zinc, and a factor of 3.5 for cadmium. These enrichment factors indicate that differential transport of these three deposit-related trace elements occurred in the suspended-sediment load.

The streambed sediment contributed by Uncle Sam Gulch increased the concentrations of deposit-related trace elements in streambed sediment in Cataract Creek downstream from the confluence (site 50S, river mi 12.6). Copper was enriched from 6 to 20, lead from 7 to 14, zinc from 4 to 15, and arsenic from 4 to 16 times the geochemical baseline (table 1). Deposit-related trace-element concentrations in suspended sediment at site 50S were substantially elevated upstream from the concentrations in streambed sediment, which indicated that much of the deposit-related trace-element load was transported in the suspended sediment as colloids. Little change was evident in the concentrations of copper (420 ppm, a 13-fold enrichment), lead (320 ppm, a 9-fold enrichment), zinc (1,450 ppm, a 10-fold enrichment) and arsenic (460 ppm, a 13-fold enrichment) in streambed sediment in Cataract Creek between Uncle Sam Gulch (site 50S) and the Boulder River (site 53S). We interpret these data to indicate that the Crystal mine site on Uncle Sam Gulch was the major source of contaminants in Cataract Creek. Results from the metal-loading study (Cleasby and others, 2000; Kimball and others, this volume) showed that Uncle Sam Gulch was the source of 92 percent of the zinc load and 66 percent of the copper load in Cataract Creek.

### High Ore Creek

The major source of deposit-related trace elements in streambed sediment of High Ore Creek was the Comet mine (Fey and Church, 1998), an open-pit mine with extensive underground workings located near the headwaters (fig. 2). A tailings dam constructed across the drainage adjacent to the Comet mine was breached (Gelinias and Tupling, this volume). Mill tailings had washed downstream from the mine site, contaminating the High Ore Creek watershed (river mi 16; Rich and others, this volume). The tailings in the breached

impoundment were removed in 1998 by the Montana Department of Environmental Quality and stored in the open pit at the Comet mine. The downstream fluvial tailings were removed by the U.S. Bureau of Land Management during the course of this study (Gelinias and Tupling, this volume). Downstream of the breached tailings dam, streambed sediment had deposit-related trace-element concentrations of 2,000 ppm copper, 5,700 ppm lead, 17,000 ppm zinc, 8,100 ppm arsenic, 52 ppm silver, and 150 ppm cadmium (site 59S, river mi 20; fig. 13). Enrichment relative to the geochemical baseline values (table 1) was: copper, more than 60-fold; zinc, more than 110-fold; lead, more than 160-fold, and arsenic, cadmium, and silver by more than 200-fold. Sediment from Bishop Creek, the major tributary entering High Ore Creek between sites 60S and 61S (river mi 17), resulted in some dilution of the deposit-related trace elements in streambed sediment of High Ore Creek. Deposit-related trace-element concentrations in streambed sediment at the mouth of High Ore Creek (site 63S, river mi 21) were reduced to about 740 ppm copper, 1,600 ppm lead, 10,000 ppm zinc, 4,300 ppm arsenic, 34 ppm silver, and 69 ppm cadmium in October 1996 when High Ore Creek was first sampled. In general, copper was diluted by a factor of 2.7, lead by a factor of 3.6, zinc by a factor of 1.7, and arsenic by a factor of 1.9. Overbank deposits of fluvial tailings from the Comet mine, identified on the basis of the lead isotopic signature (Rich and others, this volume), were found on a low terrace at site 14S on the Boulder River. These deposits probably formed during the breach of the mill tailings dam at the Comet mine site. High Ore Creek was a minor source of streambed sediment, but it was a major source of deposit-related trace-element contaminants to the streambed sediment of the Boulder River.

### Boulder River

Streambed-sediment samples were collected systematically at sites along the Boulder River upstream, through, and downstream of the Basin and Boulder mining districts, about 100 ft upstream and downstream from the confluences of Basin, Cataract, and High Ore Creeks. At sites 5S, 6S, 8S, 9S, 11S, 12S, and 13S, samples were collected from both the north and south sides of the Boulder River. Only the average values from these sites are shown in figure 14A. The objective of this sampling plan was to evaluate the efficiency of mixing of sediment from the major tributaries and the effect of flow and velocity on the accumulation of colloidal material on the streambed of the Boulder River. Samples from the north and south sides of the Boulder River had major differences in concentrations: higher concentrations of leachable iron and deposit-related trace elements occurred in streambed sediment deposited on the lower velocity side of the reach where colloidal particles settled. Basin, Cataract, and High Ore Creeks enter the Boulder River from the north. As shown by the data (Rich and others, this volume), mixing in the fluvial system at a distance of 100 ft downstream from the confluence was not complete at that distance from any of the three confluences.

**Figure 13.** Concentrations of copper, lead, zinc, arsenic, silver, cadmium, and antimony determined in the partial digestion of streambed sediment from High Ore Creek and its tributaries, and their effect on streambed sediment of Boulder River. Trace-element concentrations determined for major sources within the watershed are also shown. Data are plotted against distance; upstream always to left regardless of actual direction stream flows. Samples that represent streambed sediment from active stream or river channel are indicated by discrete solid symbols and connected by tie lines. Concentrations of antimony, cadmium, and silver are censored at 2 ppm and arsenic at 5 ppm.

**Figure 14.** Concentration profiles of copper, zinc, lead, and arsenic. *A*, Determined in the total digestion of streambed sediment in Boulder River. Data plotted against distance, upstream always to left. Data for samples from both north and south sides of river at sites *5S*, *6S*, *8S*, *9S*, *11S*, *12S*, and *13S* have been averaged to provide a continuous profile of element concentrations in Boulder River streambed sediment. Concentration data from Basin Creek (site *31S*), Cataract Creek (site *53S*), and High Ore Creek (site *63S*) are shown as diamonds to indicate concentrations of these deposit-related trace elements in streambed sediment that was added by the three major tributaries. Concentrations of arsenic are censored at 5 ppm. *B*, Determined from partial digestion of streambed sediment in Boulder River. Arsenic profile (not shown) closely mimics that of lead.

Concentrations of copper, lead, zinc, and arsenic were not systematically higher on either the north or the south side of the Boulder River.

The distributions of copper, lead, zinc, and arsenic in Boulder River streambed sediment showed similar abundance patterns; concentrations increased downstream from each of the confluences (fig. 14A). Variation between sites downstream of the confluences was within the variation we would expect from stream-sediment sampling. The increase in concentrations at site 5S, upstream from the confluence of Basin Creek, can be explained by contributions from the Jib Mill site and several small prospects in the area between sites 4S and 5S (fig. 1). Downstream from the confluence with Basin Creek (site 6S), the deposit-related trace-element concentrations decreased slightly. This is reasonable in view of the fact that the deposit-related trace-element concentrations in Basin Creek at site 31S were similar for arsenic and zinc and lower for copper than those in the Boulder River at site 5S (fig. 14A). Only lead appeared to be significantly enriched in Basin Creek relative to the Boulder River. Downstream from the Basin Creek confluence, deposit-related trace-element concentrations in Boulder River streambed sediment decreased by more than a factor of two (except lead) at site 7S (river mi 16.2). Samples from site 7S were collected in 1997 from a deep pool that had accumulated significantly more detrital sediment relative to other sites sampled on the Boulder River. Thus, the decrease in deposit-related trace-element concentrations at this site was atypical of the other sites used for comparison. A minor increase in deposit-related trace-element concentrations occurred between sites 6S and 8S; it was not significant.

Deposit-related trace-element enrichment between sites 10S and 11S (both upstream from High Ore Creek) appears to be confined primarily to copper and zinc. The downstream enrichment of the more soluble metals suggested that the enrichment at site 11S was most likely due to sedimentation of colloidal particles and sorption processes within the Boulder River rather than enrichment from an outside source. Samples from site 10S were collected in 1997.

Deposit-related trace-element concentrations increased dramatically immediately downstream from High Ore Creek (site 12S, fig. 14A) and continued to increase for at least 0.5 mile to site 13S (river mi 20.7). Deposit-related trace-element concentrations then decreased significantly at site 14S (1997 data; river mi 21.7), but increased at site 15S (river mi 23). We had difficulty in obtaining sample material at site 14S, which was on the outside of a meander where streambed sediment did not tend to accumulate. The data between sites 13S and 15S showed a gradual decrease in concentration; these data were used to define the concentration trend for the ribbon maps (figs. 4–9).

The effect of historical mining within the Basin mining district on the concentrations of copper, lead, and zinc in streambed sediment of the Boulder River is clear from fig. 14B. Note the substantial increase in concentrations of these deposit-related trace elements in the streambed sediment of the Boulder River as it flowed through the Basin and

Boulder mining districts. Note also that lead concentrations were diluted as a function of distance downstream from the mining districts (that is, downstream from river mi 40). Arsenic also showed the same trend as lead but is not plotted in figure 14B. Concentrations of both copper and zinc increased downstream, albeit at different rates. Both metals have been shown to be toxic to fish in the watershed (Farang and others, this volume). This phenomenon also was observed in the Animas River watershed (Church and others, 1997) and in the Arkansas River watershed (Church and others, 1993; Kimball and others, 1995); it reflects the transport, sorption, and subsequent deposition of colloidal particles from the water column to the streambed sediment. The effect of historical mining activity on aquatic habitat may extend for many river miles downstream from a historical mining district.

## Summary

One of the primary goals of this study was to characterize the deposit-related trace-element distributions and show the impact of historical mining on streambed sediment in the Boulder River watershed study area. The data presented clearly indicate significant enrichment of the deposit-related trace elements copper, lead, zinc, arsenic, silver, cadmium, and antimony in streambed sediment in the major tributary streams downstream from historical mine sites. We have identified the major sources of the deposit-related contaminants: Jack Creek downstream from the Bullion mine and upper Basin Creek downstream from the Buckeye mine are the most severely affected reaches in the Basin Creek basin. Uncle Sam Gulch immediately downstream from the Crystal mine is the most severely affected tributary on Cataract Creek, and it affected Cataract Creek from the confluence with Uncle Sam Gulch to the Boulder River. High Ore Creek is severely affected from the Comet mine to its confluence with the Boulder River. The Boulder River has been impacted by streambed sediment from all three of the major tributaries as well as by milling of ore at the Jib Mill site on the Boulder River near the Basin Creek confluence. Thus we have identified the major point sources of contamination within the Boulder River watershed and fulfilled the second goal of this study. Differential transport of copper and zinc in the suspended sediment and deposition of colloids in the low-velocity zones of the Boulder River have resulted in irregularly dispersed deposits of contaminated streambed sediment in the Boulder River downstream from the confluences of the three major tributaries.

## Premining Geochemical Baseline

Determination of the sources of deposit-related trace elements in the streambed sediment and terrace deposits requires careful evaluation of all possible sources. In addition to those identified at some historical mine sites as just described, these other sources include the unaltered rocks in the Boulder River

watershed study area, the altered areas in the Butte pluton, and the unmined vein deposits that still exist within the study area. Of these, only the hydrothermally altered zones have not been discussed. The geologic character of hydrothermal alteration in the Butte pluton clearly indicates that unmined sources of elevated deposit-related trace-element concentrations are limited. O'Neill and others (this volume) summarize alteration studies of earlier workers. Polymetallic veins were emplaced along shear zones subsequent to cooling of the Butte pluton. The total width of the veins and the alteration zones is measured in terms of a few feet (maximum width about 50 ft). Argillic and sericitic alteration occurred on the outer fringes of the veins where chlorite replaces mafic minerals in the pluton. Silica replacement and deposition were characteristic along vein walls, and sulfide minerals were restricted to the mineralized veins. Becraft and others (1963) defined areas of alteration in the Butte pluton that were not associated with the mineralization that produced the polymetallic vein deposits. McCafferty and others (this volume) mapped the distribution of the chlorite-rich, magnetite-poor altered rocks in the pluton and showed that they parallel known structural features in the Boulder batholith (O'Neill and others, this volume; McDougal and others, this volume, Chapter D9). Sources of deposit-related trace elements, other than the veins exploited by historical mining, were therefore largely restricted to those mineralized veins that had not been mined. Because of the limited extent of geologic sources for elevated concentrations of deposit-related trace elements, the most logical sources of contamination are the fluvial deposits of postmining age along stream reaches in the watershed. Therefore, minimum values were used when the depth profile plots of the geochemical data from stream terrace deposits suggested that the samples might have been contaminated by postmining fluvial processes.

Determination of the premining geochemical baseline in the historical mining districts within the study area was a necessary goal of this project so that we could define minimum target concentrations for the deposit-related trace elements that feasible remediation efforts might be expected to achieve. Elevated deposit-related trace-element concentrations in mining districts commonly are found in soils and streambed deposits prior to mining. The fundamental and difficult question to answer in historical mining districts is: What were these baseline concentrations of the deposit-related trace elements prior to mining? To evaluate the data collected from these localities (fig. 2), concentration profiles of eight major and trace elements (iron, manganese, copper, lead, zinc, arsenic, silver, and cadmium) were graphed, and the concentration-versus-depth profiles examined and interpreted from sample descriptions of sediment grains (Unruh and others, 2000; Rich and others, this volume). Depth profile plots of the data for six of these elements from several of the sites studied appear as figures 15–18 together with plots of the enrichment ratio for copper, lead, zinc, and arsenic (that is, the observed concentration of the deposit-related trace element divided by the geochemical baseline value for the trace element; data

from table 1). Site descriptions, age control, and premining geochemical baseline data for six deposit-related trace elements are summarized in table 3. Identification and interpretation of the geochemical data from premining terraces that contained streambed sediment unaffected by either subsequent erosion and deposition, ground-water movement, or infiltration of contaminated surface waters in the streams resulted in the following general observations:

1. Gravels sampled from terraces that have no vegetation or established soil profile are young, that is, postmining (circa 1870; Ruppel, 1963), and have consistently proven to be contaminated by deposit-related trace elements. These included samples from sites *2B* and *3B* on the Boulder River, site *11B* on Basin Creek, site *13B* on Jack Creek, site *16B* on Uncle Sam Gulch, and sites *18B* and *19B* on High Ore Creek (fig. 2).

2. Samples from other terraces showed evidence of contamination, either from onlap deposition of sediment on the terrace, or by infiltration of contaminated surface waters in the streams. In this case, the data showed distinct trends of deposit-related trace-element enrichment as a function of depth. As one approached the low-flow-water-level depth in the core, concentrations of the deposit-related trace elements increased (for example, see site *2B*, fig. 18).

3. Ground-water movement may also have caused changes in deposit-related trace-element concentrations that vary as a function of element mobility. The deposit-related trace elements are listed in table 3 in inferred increasing element mobility from left to right (Fey and Desborough, this volume). Iron and manganese profiles with depth were used as a qualitative measure of ground-water movement of deposit-related trace elements in the cores (figs. 15–18). Precipitation of iron-oxide coatings on grain surfaces was used as an independent indicator of this process and was also indicated in the figures (for example, site *7B*, fig. 15). Ribbon maps (figs. 19–22) show premining concentrations of copper, lead, zinc, and arsenic in streambed sediment for the major tributaries and the Boulder River. Stream reaches with no data are also indicated on the maps. Premining geochemical background concentrations for both silver and cadmium in streambed sediment were below the limit of detection (< 2 ppm) everywhere within the study area.

## Basin Creek

Premining geochemical baseline data for the deposit-related trace elements in streambed sediment were determined successfully at sites *7B* through *10B* (figs. 2 and 15). Additional data determined from streambed sediment that underlies the mill tailings at the Buckeye mine site on upper Basin Creek were also used to determine the premining geochemical baseline (Rich and others, this volume; Cannon and others, this volume). At site *7B*, ground-water movement in the upper 2 ft of the core had resulted in movement of the deposit-related trace elements. Only those data from samples below 2.5 ft in depth showed a consistent pattern and were used to

**Table 3.** Descriptions of sites sampled for possible premining geochemical baseline, age control, and determination of premining concentrations of selected deposit-related trace elements at those sites.

[Site localities in figure 2; LFWL = low-flow water level in adjacent stream; age data from Laboratory for Tree-ring Research, Univ. of Arizona, Tucson, Ariz., reported in Unruh and others (2000); nd, no data; description of Mazama ash at site B-7 in O'Neill and others, this volume, plate 2]



**Table 3.** Descriptions of sites sampled for possible premining geochemical baseline, age control, and determination of premining concentrations of selected deposit-related trace elements at those sites.—Continued

determine the premining geochemical baseline values at this site. The enrichment ratio did not exceed 3.5 in this section of the core for any of the deposit-related trace elements. At about 4 ft depth at this site in a separate core, we encountered Mazama ash, which was dated at 6,845 years B.P. (O'Neill and others, this volume, pl. 2). The montaine basin where this sample was taken was dammed by a terminal glacial moraine downstream from the Buckeye mill tailings site and the basin filled with postglacial sediment. Downstream on the South Fork of Basin Creek at site *8B*, none of the deposit-related trace elements exceeded an enrichment ratio of two and all data were used (not shown in fig. 15). At site *9B*, on the main channel of Basin Creek upstream from the confluence with the South Fork of Basin Creek, we found an abrupt transition between sediment indicating premining geochemical baseline and sediment that had been contaminated by historical mining. Samples from below 2.7 ft depth were used to indicate premining geochemical baseline values and had enrichment ratios of 2 or less. In contrast, sediment from above 2.5 ft depth showed evidence of ground-water movement of the deposit-related trace elements; copper, lead, arsenic, and cadmium were generally enriched in the sediment in this upper section of the core by a factor of more than 5. Zinc, which was relatively more mobile, and to some extent copper, have been leached out of the core particularly at the upper level above 1 ft depth. At site *10B*, on Basin Creek downstream from the confluence with Jack Creek, all the data from the terrace deposits at this site were used. Profile plots of deposit-related trace-element concentrations were relatively constant in spite of the fact that we observed iron-oxide coatings on the grains below 2.5 ft and manganese had moved in this terrace deposit. At site *10B*,

enrichment factors were always less than 2. Site *11B* was from a low terrace gravel with no vegetative cover. All data indicate that the streambed sediment from this terrace was contaminated and postmining in age. Because site *11B* was the farthest downstream site on Basin Creek, we used the data from site *10B* for the premining geochemical baseline in streambed sediment for the reach downstream from site *10B* when preparing the premining geochemical ribbon maps (figs. 19–22).

On Jack Creek, we investigated terrace deposits at sites *12B* through *15B* (fig. 2). We also obtained data from the cores taken through the tailings below the Bullion mine site (Rich and others, this volume). At site *12B*, we sampled contaminated fluvial sediment that overlies uncontaminated streambed sediment (fig. 16). Enrichment factors for the deposit-related trace elements in the lower section of the core below 6 in. did not exceed 2, whereas above that depth in the core, they were highly variable, approaching 4 to 5 for the more mobile deposit-related trace elements copper and zinc. The mill tailings dam at the Bullion mine site was breached and flotation mill tailings flushed downstream in an event of unknown age. Fluvial tailings deposits exposed along Bullion Mine tributary have had much of the original content of copper and zinc leached out (Rich and others, this volume). The core from site *12B* was one locality where these metals have been sorbed by the older sediment. Site *13B* (not shown in fig. 16) was in a young terrace with no vegetation on the surface of the terrace. All the streambed sediment in this terrace was deposited after the onset of mining and was contaminated. At site *14B*, we cored beneath the dam of an abandoned beaver pond that had been flooded during the breach of the mill tailings dam (fig. 3B). The minimum age of the premining streambed

**Figure 15.** Plots of geochemical data for the elements copper, lead, zinc, arsenic, iron, and manganese from cores taken at sites *7B*, *9B*, and *10B* (fig. 2) for determination of premining geochemical baseline in streambed sediment from Basin Creek basin. Uppermost soil interval was not analyzed; top is ground surface. Presence of iron-oxide coatings on grains was interpreted to be indicative of ground-water movement of deposit-related trace elements that would compromise geochemical baseline concentration data. Intervals in each core used for determination of the premining geochemical baseline are indicated; data are summarized in table 3. Geochemical data from core at site *8B* were very similar to that from site *10B*. Site *11B* yielded no usable data.

**Figure 16.** Plots of geochemical data for the elements copper, lead, zinc, arsenic, iron, and manganese from cores taken at sites *12B*, *14B*, and *15B* (fig. 2) for determination of premining geochemical baseline in streambed sediment from Jack Creek basin. Uppermost soil interval was not analyzed; top is ground surface. Presence of iron-oxide coatings on grains was interpreted to be indicative of ground-water movement of deposit-related trace elements that would compromise geochemical baseline data. Intervals in each core used for determination of the premining geochemical baseline are indicated; data are summarized in table 3. All data from site *13B* indicated that only contaminated sediment was present in this core. We used only the minimum value from the geochemical data from site *15B*, which should be considered an estimate of the premining geochemical baseline in this reservoir.

sediment in this core below the beaver dam is 99 years on the basis of the tree-ring count of a dead Lodgepole pine(?) growing in and partially buried by the beaver dam. Concentrations of the deposit-related trace elements decrease abruptly at a depth of 1.3 ft. Enrichment ratios in the lower section of the core for copper, lead, and zinc were less than 2 and for arsenic were between 3 and 4. At site *15B*, we sampled streambed sediment trapped in a water reservoir on Jack Creek built in 1903 to supply the Bullion smelter. According to Rossillon and Haynes (1999), the Bullion smelter operated between 1904 and 1906. The sediment sample was taken adjacent to a Douglas-fir stump dated at 251 years. Because the stump was within a few hundred feet of the dam and Douglas-fir are sparse in this Lodgepole pine forest, the tree was probably cut down at the time of construction in 1903 for use in the dam, which was built entirely of Douglas-fir logs. Only the lowermost sample interval was used to estimate the premining geochemical baseline at the site (pre-1652). All other samples in the core through reservoir sediment had elevated enrichment factors for copper, lead, and arsenic that exceeded 5. Zinc was leached out of the sediment in the reservoir impoundment and showed variable enrichment ratios. This reservoir constitutes a large, reversible source of fluvial mine tailings that will contaminate water and streambed sediment in Jack Creek for many decades unless remediated.

### Cataract Creek

The concentrations of deposit-related trace elements in streambed sediment of Cataract Creek upstream from the confluence with Uncle Sam Gulch were not investigated because most of the area is on private property and because data from streambed sediment collected in the stream indicated only a small enrichment in deposit-related trace-element concentrations. One potential source of contaminants, the Eva May mine, had been partially remediated prior to this study. No sites where terrace gravel would accumulate due to the steepness of the gradient of this reach of Cataract Creek were identified downstream from the confluence of Uncle Sam Gulch. In Uncle Sam Gulch, no usable data were obtained from the core from site *16B* (fig. 2). At site *17B*, located in a clear-cut in the flood plain of Uncle Sam Gulch, streambed sediment was cored from between the roots of a 3-ft diameter Ponderosa pine that had been cut down in 1983 (Robert Wintergerst, USDA Forest Service, written commun., 1998). The tree was 252 years old, indicating that the streambed sediment predates the onset of mining by more than a century (circa 1731). Instead of the expected low values, concentrations of copper, lead, zinc, arsenic, and cadmium were elevated and varied with depth (fig. 17). Only silver had a low concentration approaching the local geochemical baseline (table 1). Iron concentrations were constant and were not enriched, whereas manganese concentrations were highly variable and showed enrichment near the top of the core above 1 ft in depth (that is, above the ground-water table). Arsenic and copper were

enriched above 1 ft in depth, whereas zinc was enriched below that zone with enrichment factors exceeding 10. Copper concentrations between 1.5 and 2.3 ft were enriched by factors of 2–4, arsenic and lead by factors of 5–7, and zinc was enriched by about a factor of 7 over three of the cored intervals. These data represented the best estimate of the premining geochemical baseline in Uncle Sam Gulch prior to mining. We interpret these data to indicate that the vein exploited at the Crystal mine probably was exposed at the surface and that deposit-related trace elements were being actively eroded into the stream at the site prior to discovery about 1883 (Rossillon and Haynes, 1999).

### High Ore Creek

The premining geochemical baseline was not successfully determined at either site *18B* or *19B* (fig. 2). At both sites, the terrace gravel had no vegetation cover on the surface and proved to be contaminated young terrace gravel. At site *18B*, we used the minimum concentrations from the base of the core, although these concentrations are merely an estimate of what the premining geochemical baseline might have been (fig. 17). Cadmium and zinc concentrations were clearly contaminated by ground-water movement of these two metals. Additional premining geochemical baseline data were obtained from streambed sediment cored from beneath the fluvial mill tailings below the Comet mine site and are summarized in table 3.

### Boulder River

Six terrace gravel sites were sampled along the Boulder River (sites *1B* through *6B*; fig. 2); the data for three of these sites, *2B*, *4B*, and *6B*, illustrate the results (fig. 18). Site *3B* contained no usable data and was postmining in age. At sites *1B*, *2B*, and *5B*, the lowermost samples had elevated deposit-related trace-element concentrations (fig. 18). Whether this was (1) the result of surficial contamination by young sediment with the existing sand and gravel on the banks, which were not removed because we failed to dig back far enough into the gravel deposit, or (2) the result of movement of metals and colloids into the gravel deposits from the contaminated surface waters was not tested. At sites *1B*, *2B*, and *5B*, only the data from the least contaminated interval were used. This was the top interval at sites *1B* and *5B*, and the middle interval at site *2B* (fig. 18). Site *2B* is located immediately downstream from the Jib Mill site (fig. 2) and likely contained overbank deposits contaminated by mill tailings on top of the terrace gravel. As will be shown in "Lead Isotopic Results," lead isotope data from site *2B* prove the value of this approach. The concentrations of the deposit-related trace elements in the upper intervals from sites *1B* and *5B* were very similar to those from site *6B* and are not shown in figure 18. Sites *4B* and *6B* were both large, vegetated terrace deposits that gave very consistent results. The terrace at site *6B* is a minimum

**Figure 17.** Plots of geochemical data for the elements copper, lead, zinc, arsenic, iron, and manganese from cores taken at site *17B* (fig. 2) for determination of premining geochemical baseline in streambed sediment from Uncle Sam Gulch basin, and at sites *18B* and *19B* in High Ore Creek basin. Uppermost soil interval was not analyzed; top is ground surface. Presence of iron-oxide coatings on grains was interpreted to be indicative of ground-water movement of deposit-related trace elements that would compromise geochemical baseline data. Intervals in each core used for determination of the premining geochemical baseline are indicated on the figures; data are summarized in table 3. Samples for site *16B* were contaminated. No convincing evidence for a premining baseline was determined in High Ore Creek basin from cores taken at sites *18B* and *19B*.

**Figure 18.** Plots of geochemical data for the elements copper, lead, zinc, arsenic, iron, and manganese from cores taken at sites *2B*, *4B*, and *6B* (fig. 2) for determination of premining geochemical baseline in streambed sediment from Boulder River watershed in the Basin and Boulder mining districts. Uppermost soil interval was not analyzed; top is ground surface. Presence of iron-oxide coatings on grains was interpreted to be indicative of ground-water movement of deposit-related trace elements that would compromise geochemical baseline data. Intervals in each core used for determination of premining geochemical baseline are indicated on the figures; data are summarized in table 3. All samples from site *3B* were contaminated.

of 60 years old, on the basis of dendrochronological age of a large cottonwood tree that was growing on the terrace deposit. Samples were taken from the exposed root zone in the terrace cut bank. The uppermost interval was composed of a silt layer and may represent a flood deposit rather than local terrace gravel. Including the data from the silt layer does not significantly affect the premining geochemical baseline ribbon maps of figures 19–22.

## Boulder River Watershed

Ribbon maps of the premining geochemical baseline for the watershed are shown in figures 19–22. The data used are both in table 3 and taken from the current geochemical maps in areas where past mining had little effect (figs. 4–7). The same concentration intervals were used as in the previous maps to facilitate comparisons of the conditions in the Boulder River watershed today with those prior to mining (Rich and others, this volume). Premining geochemical baselines for all the deposit-related trace elements were in the lowest two concentration ranges everywhere except downstream from the Crystal mine site in Uncle Sam Gulch.

In contrast to the data from unmined and probably unmineralized tributaries in table 1, the premining geochemical baseline determined from terrace deposits in the Basin and Boulder mining districts was higher than reported in table 1. Premining geochemical baseline concentrations for copper ranged from 19 to 150 ppm with a median value of 53 ppm; lead ranged from 34 to 220 ppm with a median value of 60 ppm; zinc ranged from 100 to 250 ppm with a median value of 160 ppm; arsenic ranged from 23 to 220 with a median value of 46 ppm (35 ppm in table 1); silver was always < 2 ppm; and cadmium ranged from <2 to 2 ppm with a consensus value of <2 ppm. These median values are 65 percent higher for copper, 60 percent higher for lead, 30 percent higher for arsenic, but only 6 percent higher for zinc than those given in table 1. The agreement between the two methods for determination of the premining geochemical baseline is remarkable. Use of either set of geochemical baseline values would make little difference in terms of evaluating the toxic effect of historical mining on aquatic life in the three major tributaries in the Boulder River watershed study area. The data demonstrate the feasibility of using terrace deposits of premining age to determine streambed-sediment geochemistry prior to the onset of mining in a historical mining district. The independent determination of premining geochemical baseline from premining terrace deposits fulfills the third goal of this study. The two methods for the determination of premining geochemical baselines, that is, the use of premining sediments preserved in terrace deposits, and the use of stream sediment from unaffected tributaries in a historical mining district, provide compelling evidence that the watershed would have supported aquatic life prior to mining.

## Lead Isotopic Results

Lead isotopic analyses of all streambed sediment, sediment cores, and selected premining terrace sediment were completed to determine if metals in the present-day streambed-sediment samples were derived from past mining activities. Four isotopes of lead exist in nature, three of which change directly as a function of time through the radioactive decay of uranium and thorium:  $^{206}\text{Pb}$  is the daughter product of decay of  $^{238}\text{U}$ ,  $^{207}\text{Pb}$  is the daughter product of decay of  $^{235}\text{U}$ , and  $^{208}\text{Pb}$  is the daughter product of decay of  $^{232}\text{Th}$ . However,  $^{204}\text{Pb}$  has no radioactive parent. Thus, the isotopic composition of lead in rocks in the Earth's crust (that is,  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$ , and  $^{208}\text{Pb}/^{204}\text{Pb}$ ) changes regularly with time as uranium and thorium undergo radioactive decay. When mineral deposits are formed, lead is separated from the parent uranium and thorium isotopes and the lead isotopic composition of the hydrothermal fluid is "frozen" into the sulfide minerals, usually in galena, within the mineral deposit. This mineral deposit lead isotope signature will then differ from that of the host rocks underlying a watershed because the lead in the host rocks continues to change with time whereas the lead in the mineral deposit remains fixed.

The isotopic composition of lead in streambed sediment reflects mixtures of lead from many discrete sources: the mineral deposits, unmined altered rock surrounding those deposits, the unmineralized rocks underlying the watershed, mine-waste dumps near mine adits, and mill tailings produced during the processing of ore. Physical transport of detrital material derived from erosion and mixing of all these materials combine to make up the streambed sediment. In addition, aqueous or colloidal transport of deposit-related trace elements from mined sites to the stream, and precipitation by mixing, sorption to the colloids and grain coatings, and subsequent settling of the colloids to the streambed also contribute deposit-related trace elements to the streambed.

In order for the lead isotopic data to be useful, it must be possible (1) to measure the isotopic compositions of all suspected sources of lead as well as the premining geochemical baseline, and (2) to determine the lead isotopic composition of the contaminant. Moreover, (3) the lead-isotopic composition of the contaminants must be distinct from that of uncontaminated or premining geochemical baseline (Church and others, 1997).

The lead isotopic values in the present study area form single arrays on lead isotopic correlation plots (that is,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  versus  $^{208}\text{Pb}/^{204}\text{Pb}$  plots). This was because the lead in most of the streambed-sediment samples was contained in minerals derived from the Butte pluton of the Boulder batholith or the associated Elkhorn Mountains Volcanics. The variations observed among the samples reflect variations in U/Pb among the different rocks and ores, which were derived from a common source during melting that formed the batholith and subsequent mineralization (O'Neill and others, this volume; Lund and others,



**Figure 19.** Concentrations of copper (ppm) in premining streambed sediment (solid dot) of Boulder River watershed study area. Stream reaches shown in gray, no data. Concentration intervals are same as in figure 4. Note that all stream reaches where we determined premining geochemical baseline have concentrations of copper below 200 ppm, that is, less than six times baseline value of 32 ppm (table 1). Dark-red square, Jib Mill site.

**Figure 20.** Concentrations of lead (ppm) in premining streambed sediment (solid dot) of Boulder River watershed study area. Stream reaches shown in gray, no data. Concentration intervals are same as in figure 5. Note that many stream reaches where we have been able to determine premining geochemical baseline have concentrations of lead below 80 ppm, that is, about twice the baseline value of 35 ppm (table 1), with the exception of the reach downstream from Crystal mine in Uncle Sam Gulch at site 17B. Dark-red square, Jib Mill site.

**Figure 21.** Concentrations of zinc (ppm) in premining streambed sediment (solid dot) of Boulder River watershed study area. Stream reaches shown in gray, no data. Concentration intervals are same as in figure 6. Note that many stream reaches where we have been able to determine premining geochemical baseline have concentrations of zinc below 200 ppm, that is, less than 1.5 times the baseline value of 150 ppm (table 1), with the exception of the reach downstream from Crystal mine in Uncle Sam Gulch at site 17B. Dark-red square, Jib Mill site.

**Figure 22.** Concentrations of arsenic (ppm) in premining streambed sediment (solid dot) of Boulder River watershed study area. Reaches shown in gray, no data. Concentration intervals the same as in figure 7. Note that many stream reaches where we have been able to determine premining geochemical baseline have concentrations of arsenic below 50 ppm (table 1; arsenic has a median value of 35 ppm). However, downstream from Bullion and Crystal mines, arsenic concentrations were elevated. Dark-red square, Jib Mill site.

2002). Consequently, the lead isotopic data will be represented exclusively using  $^{206}\text{Pb}/^{204}\text{Pb}$  values throughout the ensuing discussion.

Lead isotopic data showed an inverse relationship with lead concentrations (fig. 23). The highest  $^{206}\text{Pb}/^{204}\text{Pb}$  values from drainage basins underlain largely by rocks of the Butte pluton of the Boulder batholith (18.1–18.2) and lowest lead concentration values (<60 ppm) were found among some of the premining streambed-sediment samples collected either from tributaries upstream from major mines or from the Boulder River upstream from Basin Creek. Streambed-sediment samples from sites 3S and 4S (between river miles 12.5 and 14.5, fig. 24A) along the Boulder River showed anomalously high  $^{206}\text{Pb}/^{204}\text{Pb}$  values of 18.3–18.4. These streambed-sediment samples were collected downstream from where the Boulder River cuts through a large dike of Eocene Lowland Creek Volcanics (O'Neill and others, this volume, pl. 1). These Eocene rocks are younger than and have a different source than the Boulder batholith. As a result, they had a more radiogenic lead isotopic composition; that is, they had a higher  $^{206}\text{Pb}/^{204}\text{Pb}$  value than the rocks that make up the majority of the Boulder River watershed study area. Lead isotopic data from these two sites were used as an estimate of the uncontaminated streambed sediment in the Boulder River immediately upstream from the Jib Mill and Basin Creek, but they were not used to calculate average premining baseline lead isotopic values in streambed sediment anywhere else within the study area (table 4).

The lead data in figure 23 clearly indicated two principal sources of deposit-related lead. Streambed-sediment samples containing high concentrations of lead (for example, samples from High Ore Creek with lead concentrations >1,000 ppm) showed a relatively constant  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 18.06. We interpret this value to represent the  $^{206}\text{Pb}/^{204}\text{Pb}$  value of deposit-related contaminant lead from the Comet mine in this drainage. In contrast, the highest concentrations of lead in the Basin and Cataract Creek basins were characterized by a  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 17.90–17.93. Because sampling was limited at each of the mines in the Basin and Cataract Creek basins, we used the average of the highest lead samples (that is, lead concentrations greater than 1,000 ppm and  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 17.91) collected from these two basins to represent the lead isotopic composition of the contaminant lead for both the Basin and Cataract Creek basins (fig. 23, table 4). Comparison of the deposit lead signatures from the mining districts with the data from the geochemical baseline site 2B downstream from the Jib Mill ( $^{206}\text{Pb}/^{204}\text{Pb}$  value of 17.73) is clear evidence that the low lead isotopic value from this site is not from mines in the Basin and Boulder mining districts.

One unfortunate aspect of the relationship among virtually all samples to a common source is that the total range of  $^{206}\text{Pb}/^{204}\text{Pb}$  values among the samples was only about 1.7 percent, varying from  $^{206}\text{Pb}/^{204}\text{Pb}$  of 17.9 to 18.2 (fig. 23, excluding the streambed sediment apparently derived from the Eocene Lowland Creek Volcanics). This means that, when even comparatively small amounts of deposit-related lead are

added to the streambed sediment, the  $^{206}\text{Pb}/^{204}\text{Pb}$  value of the streambed sediment will rapidly approach that of the deposit lead. Consequently, we were not able to resolve the small isotopic differences created by the addition of deposit lead from other downstream sources within the study area.

Lead isotopic data from modern streambed-sediment samples and from the premining terrace appear as figures 24–27; data are in the database (Rich and others, this volume). Individual mine localities are indicated in the figures, plotted by distance (river mi).

## Basin Creek

The lead isotopic compositions of streambed sediment from Basin Creek are compared with those of the Boulder River in figure 24A. All Basin Creek streambed-sediment samples had lower  $^{206}\text{Pb}/^{204}\text{Pb}$  values than those of the Boulder River upstream from the Basin mining district. As Basin Creek flowed past the Buckeye mine, the  $^{206}\text{Pb}/^{204}\text{Pb}$  value decreased from 18.0 to 17.9. The  $^{206}\text{Pb}/^{204}\text{Pb}$  progressively increased downstream as a result of both settling out of colloidal phases rich in deposit-related trace elements and dilution by streambed sediment derived from nonmineralized rock in the Basin Creek basin. At the confluence with Jack Creek, the  $^{206}\text{Pb}/^{204}\text{Pb}$  value decreased from 18.0 to 17.92 as a result of contaminant lead contributed by Jack Creek. Downstream of this confluence to the confluence of Basin Creek with the Boulder River, the  $^{206}\text{Pb}/^{204}\text{Pb}$  value progressively increased as a result of dilution by streambed sediment from unmineralized subbasins drained by other tributaries to Basin Creek (fig. 24A, B).

The effects of the Buckeye and Bullion mines on the  $^{206}\text{Pb}/^{204}\text{Pb}$  value and the lead concentrations in the streambed sediment of upper Basin Creek and the Bullion Mine tributary, respectively, are readily apparent (fig. 24B, C). Lead isotopic values decreased and lead concentrations increased significantly as the streams flowed past these mine sites. The lead concentration and isotopic values in streambed sediment upstream from these mines (sites 20S and 32S) were similar to those found in premining streambed sediment from terrace samples collected along these streams.

In contrast, the streambed-sediment samples from Jack Creek collected upstream from the confluence with the Bullion Mine tributary (site 38S) had elevated lead concentrations and comparatively low  $^{206}\text{Pb}/^{204}\text{Pb}$  values. These results suggest that either historical mining activity or exposed mineralized rock also influenced the deposit-related trace-element concentrations and lead isotopic characteristics of upper Jack Creek. In any case, the  $^{206}\text{Pb}/^{204}\text{Pb}$  value of streambed sediment in Jack Creek was already so similar to those of the contaminant sources ( $^{206}\text{Pb}/^{204}\text{Pb}$  of 17.91–17.92) upstream from the confluence with the Bullion Mine tributary that the addition of streambed sediment from the Bullion Mine tributary was not discernible in the lead isotopic data (fig. 24B). However, the addition of leachable lead from the Bullion Mine tributary to Jack Creek had a large effect on the concentration of lead as

**Table 4.** Estimates of contaminant and premining baseline lead isotopic compositions from Boulder River watershed study area.

[Data are from Fey, Unruh, and Church (1999) and Unruh and others (2000); data are in database, Rich and others, this volume]

well as other deposit-related trace elements in streambed sediment downstream from the confluence with the Bullion Mine tributary (fig. 11).

With the exception of the two most-upstream samples (sites 20S and 32S), the streambed-sediment samples from both Jack and Basin Creeks showed elevated lead concentrations and low  $^{206}\text{Pb}/^{204}\text{Pb}$  relative to streambed sediment from

premining terraces (fig. 24B, C). Although the  $^{206}\text{Pb}/^{204}\text{Pb}$  value and lead concentration in streambed sediment from Basin Creek progressively approached those of the premining samples as a function of distance downstream, the contaminants in Basin Creek still exerted a significant influence on streambed-sediment geochemistry at the confluence with the Boulder River (river mi 15, fig. 24A).

**Figure 23.** Plot of concentration of lead versus isotopic composition of lead ( $^{206}\text{Pb}/^{204}\text{Pb}$ ) showing the dominant effect of mixing of contaminant lead derived from mining on isotopic composition of leachable lead in streambed sediment. Analytical error for lead isotopic data is smaller than the symbol. Note limited range in lead isotopic compositions.

## Cataract Creek

The  $^{206}\text{Pb}/^{204}\text{Pb}$  values in Cataract Creek streambed sediment decreased progressively downstream from premining baseline values at river mi 6 (fig. 25A, site 44S) to essentially contaminant values at the confluence with Uncle Sam Gulch (river mi 13, sites 49S and 50S). Deposit-related trace-element-rich streambed sediment derived from tributaries such as Hoodoo and Rocker Creeks and mines such as the Eva May, Cataract, and Hattie Ferguson in upper Cataract Creek (Martin, this volume) contributed to the deposit-like lead isotopic signature in the streambed sediment at site 49S (river mi 12.5). Consequently, the effect of streambed sediment derived from Uncle Sam Gulch on the  $^{206}\text{Pb}/^{204}\text{Pb}$  value downstream from the confluence with Cataract Creek was nearly undiscernible in the lead isotope data. Only a slight decrease in the  $^{206}\text{Pb}/^{204}\text{Pb}$  value and an increase in lead concentration in streambed sediment were observed downstream from the confluence (fig. 25B, C). The interpretation of the data from site 50S

was further complicated by the fact that mine waste from the Morning Glory was in and along Cataract Creek over an extended area upstream and downstream from the confluence with Uncle Sam Gulch (Martin, this volume).

The influence from the Crystal mine on the deposit-related trace-element load in the streambed sediment of Uncle Sam Gulch is clearly evident in figure 25B, C. The lead concentration increased from 34 ppm upstream from the Crystal mine to 1,900 ppm downstream, whereas  $^{206}\text{Pb}/^{204}\text{Pb}$  value decreased from 18.06 to 17.92. The  $^{206}\text{Pb}/^{204}\text{Pb}$  value remained relatively constant all the way downstream to the confluence with Cataract Creek and lead concentrations decreased by about a factor of 2. Downstream from the confluence with Uncle Sam Gulch, lead in the streambed sediment of Cataract Creek decreased only slightly toward premining baseline values; the  $^{206}\text{Pb}/^{204}\text{Pb}$  value increased to 17.95 whereas lead concentrations decreased to 310 ppm upstream from the confluence of Cataract Creek with the Boulder River. Although the lead isotopic composition of deposit lead in Cataract Creek

**Figure 24.** Profile plots of lead isotopic composition (*A*, *B*) and lead concentration (*C*) determined in streambed sediment. *A*,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus distance on Boulder River and Basin Creek. *B*,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus distance on Basin Creek, Jack Creek, and the Bullion Mine tributary. *C*, Concentration of lead in streambed sediment on Basin Creek, Jack Creek, and the Bullion Mine tributary versus distance.

**Figure 25.** Profile plots of lead isotopic composition (*A*, *B*) and lead concentration (*C*) determined in streambed sediment. *A*,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus distance on Boulder River and Cataract Creek. *B*,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus distance on Cataract Creek and Uncle Sam Gulch. *C*, Concentration of lead in streambed sediment of Cataract Creek and Uncle Sam Gulch versus distance. Note small difference in lead isotopic composition versus the great difference in lead concentration in premining versus modern streambed sediment in Uncle Sam Gulch.



near the Eva May mine site and in Hoodoo Creek was identical to that from the Crystal mine, the very large increase in lead concentration in streambed sediment today downstream from the confluence with Uncle Sam Gulch indicated that the Crystal mine was the major source of contaminants in the Cataract Creek basin.

As mentioned previously, we were not able to obtain any premining stream-terrace samples from Cataract Creek. Lead isotopic data obtained from a single premining terrace sample (17B) on Uncle Sam Gulch are shown in figure 25B, C. The lower than normal  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 17.99 was in accord with higher than normal deposit-related trace-element concentrations observed at this site (fig. 17). The data indicate that a significant amount of lead was in the streambed sediment prior to mining if the sample from the base of the core at site 17B was not contaminated by past mining.

### High Ore Creek

The Comet mine site on High Ore Creek (river mi 15.9) contributed the bulk of the deposit-related trace elements to streambed sediment in this basin. The  $^{206}\text{Pb}/^{204}\text{Pb}$  value decreased markedly from 18.23 in streambed sediment upstream to 18.07 downstream from the mine (fig. 26A, B). Lead concentrations (fig. 26C) increased dramatically from about 30 ppm to 5,700 ppm over this same interval. Downstream from the Comet mine, the  $^{206}\text{Pb}/^{204}\text{Pb}$  value remained relatively constant at 18.06–18.07 to the confluence with the Boulder River. Lead concentrations decreased from 1,600 to 1,000 ppm but were still strongly elevated relative to premining concentrations (table 1). Note that the composition of contaminant deposit lead from the Basin and Cataract Creeks was lower than that from the Comet mine, so the lead isotopic composition of streambed sediment in the Boulder River increased to the deposit-lead value at the Comet mine (table 4, fig. 23) downstream from the confluence with High Ore Creek.

Samples from two of the cores that penetrated through the fluvial tailings immediately downstream from the Comet mine (fig. 2) have been used to estimate premining baseline values for streambed sediment in High Ore Creek. One of the samples had a  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 18.10 and contained 33 ppm lead, very similar to premining baseline values throughout the study area. The other had an elevated lead concentration (110 ppm) and somewhat lower  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 18.08. Because these samples were overlain by tailings, the possibility that lead migration through the sediment column may have affected even the sample with the lowest lead concentration must be considered. In any case, present-day lead concentrations in streambed sediment in High Ore Creek prior to the removal actions, which began in 1997, appeared to be 30–150 times those in streambed sediment prior to mining (tables 1 and 4).

### Boulder River

Lead isotopic data for the entire 70-mile segment of the Boulder River are summarized in figure 27A. The  $^{206}\text{Pb}/^{204}\text{Pb}$  values were lowest through the historical mining district and progressively increased downstream from the district. At a distance of approximately 45 miles downstream from the Basin and Boulder mining districts (site 18S; river mi 68), the  $^{206}\text{Pb}/^{204}\text{Pb}$  finally approached the baseline value at site 1S in the Boulder River (river mi 0.5). However, if the  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 18.27 in streambed sediment from the Little Boulder River was a reasonable indication of sediment unaffected by mining activity (site 19S, river mi 30), then we would conclude that the contribution of deposit lead was still evident at site 18S, forty-five miles downstream from the Basin and Boulder mining districts near the confluence with the Jefferson River (fig. 27).

The effects of each of the tributaries on the  $^{206}\text{Pb}/^{204}\text{Pb}$  value and lead concentration of Boulder River streambed sediment can be evaluated from figure 27. Lead derived from the Jib Mill (and associated tailings) and Basin Creek caused a pronounced decrease in the  $^{206}\text{Pb}/^{204}\text{Pb}$  value and an increase in lead concentration in Boulder River streambed sediment. It was not possible to isolate the contributions from these two sources because mill tailings apparently derived from the Jib Mill were found downstream of the confluence of Basin Creek and the Boulder River. Furthermore, numerous small prospects in the area, as well as construction debris from a railroad grade and interstate highway, have all caused at least some disruption to the normal sedimentation processes, if not a direct contribution to the sediment load in the Boulder River. Lead isotope data from site 2B (fig. 2) demonstrated that the use of the minimum concentration from the core at this site was the correct approach to determination of the uncontaminated geochemical baseline in stream-terrace deposits. Geochemical data from the site (fig. 18) indicate a minimum in all deposit-related trace-element concentrations at a depth of 2.6 ft. The  $^{206}\text{Pb}/^{204}\text{Pb}$  from the three lowest sampled intervals was 17.726, which plotted below the field of the deposit leads from the Basin and Boulder mining districts (fig. 23), indicating an extraneous source of lead and copper associated with the Jib Mill. In contrast, the sample from the 2.6 ft depth had a concentration of 34 ppm and a  $^{206}\text{Pb}/^{204}\text{Pb}$  value of 18.123, which plots in the field of uncontaminated sediment from the study area (fig. 23).

Streambed sediment derived from Cataract Creek caused an abrupt increase in both the  $^{206}\text{Pb}/^{204}\text{Pb}$  and lead concentration in the streambed-sediment sample collected immediately downstream (site 9S, fig. 1, river mi 17) of the confluence of Cataract Creek with the Boulder River. The lead concentration in the Boulder River streambed sediment decreased at site 10S (river mi 17.5) to values close to those obtained just upstream from the confluence (site 8S).

**Figure 26.** Profile plots of lead isotopic composition (*A, B*) and lead concentration (*C*) determined in streambed sediment. *A*,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus distance on Boulder River and High Ore Creek. *B*,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus distance on High Ore Creek. *C*, Concentration of lead in streambed sediment from High Ore Creek versus distance. Note small difference in lead isotopic composition relative to the large difference in lead concentration in premining versus modern streambed sediment in High Ore Creek.

**Figure 27.** Profile plots of lead isotopic composition (*A*, *B*) and lead concentration (*C*) determined in streambed sediment. *A*,  $^{206}\text{Pb}/^{204}\text{Pb}$  versus distance on Boulder River. *B*,  $^{206}\text{Pb}/^{204}\text{Pb}$  at larger-scale intervals for streambed sediment on Boulder River and premining terrace deposits (sites in fig. 18). *C*, Concentration of lead in streambed sediment today and in streambed sediment from premining terrace samples versus distance on Boulder River.

At the confluence with High Ore Creek, lead concentrations in Boulder River streambed sediment increased by more than a factor of two and remained elevated through river mi 28 (fig. 27C). The  $^{206}\text{Pb}/^{204}\text{Pb}$  values increased slightly from 18.02 to 18.05 and remained relatively constant at the latter value through river mi 28, indicating a predominance of the lead from the Comet mine in the streambed sediment of the Boulder River downstream from the confluence with High Ore Creek.

Throughout the Basin and Boulder mining districts, all  $^{206}\text{Pb}/^{204}\text{Pb}$  values in modern streambed sediment were uniformly lower than those from the streambed sediment from premining terraces (fig. 27B), probably because of contamination from historical mines, mills, and smelters in the mining districts. This is in spite of the fact that the lead concentrations, at least upstream from High Ore Creek, were quite similar between the premining and present-day data sets (fig. 27C). Significant increases in lead concentrations in present-day streambed sediment in the Boulder River were apparent downstream from the confluence of all three tributary streams, but were most pronounced downstream from the confluence with High Ore Creek (fig. 27C).

## Calculation of the Effect of Historical Mining on the Streambed Sediment in the Boulder River

Bulk mixing calculations were used to estimate the contribution of contaminated streambed sediment from each of the three basins to the streambed sediment of the Boulder River. These calculations, however, assume uniform, well-mixed end members, which we have shown was not the case from our sampling of the north and south banks of the Boulder River downstream from the confluences of the three principal tributaries. Sampling variability also adds an additional source of error that had not been evaluated because replicate samples were not collected in any one year during this study. Furthermore, the calculation errors associated with the small spread of the entire lead isotopic data set result in some mathematical limitations. However, the calculations are useful to evaluate the scale of the heterogeneity in the sampling and to portray the overwhelming effect that the contamination from past mining in the three basins had on the fine-grained (<150  $\mu\text{m}$ ) streambed sediment and contaminant loads in the Boulder River. Comparisons of the data for copper and zinc, which were transported largely in the dissolved and suspended phases (Nimick and Cleasby, this volume; Kimball and others, this volume), with the data for lead and arsenic, which were transported largely as colloidal components of the streambed sediment and as grain coatings on detritus in the streambed sediment, are useful in our understanding of the transport of contaminants in the suspended- and streambed-sediment loads. The data also provided valuable information on the mixing zones downstream from stream confluences.

The effect of the deposit-related trace elements in the streambed sediment was estimated on the basis of the increase in trace-element concentrations in the streambed sediment of the Boulder River using the following equation, assuming bulk mixing:

$$P_s = [(C_A - C_B) / (C_A - C_C)] \times 100 \quad (1)$$

where  $P_s$  is the percent of the total sediment contributed by tributary  $C$  to the receiving stream at site  $B$ ,

$C_A$  is the concentration of the trace element in streambed sediment in the river upstream from the confluence with the tributary  $C$ ,

$C_B$  is the concentration of the trace element in streambed sediment in the river downstream from the confluence with the tributary and

$C_C$  is the concentration of the trace element in the tributary stream  $C$  at its confluence.

The amount of a deposit-related trace-element contaminant in streambed sediment in the river that was contributed by the tributary was estimated from the following equation, also assuming bulk mixing:

$$P_c = P_s \times C_c / C_B \quad (2)$$

where  $P_c$  is the percent contaminant contributed by the tributary and  $P_s$ ,  $C_c$ , and  $C_B$  are defined as in eq. 1.

An independent method of estimating  $P_c$  for lead was obtained from the lead isotopic data (Church and others, 1997) using the following equation:

$$P_{pb} = [(R_A - R_B) / (R_A - R_C)] \times 100 \quad (3)$$

where  $P_{pb}$  is the percent lead contributed by the tributary  $C$  to the river,

$R_A$  is the  $^{206}\text{Pb}/^{204}\text{Pb}$  in the river upstream of the confluence with tributary  $C$ ,

$R_B$  is the  $^{206}\text{Pb}/^{204}\text{Pb}$  in the river downstream of the confluence with the tributary, and

$R_C$  is the  $^{206}\text{Pb}/^{204}\text{Pb}$  in tributary  $C$  upstream from the confluence.

Values used for  $A$ ,  $B$ , and  $C$  in these equations are indicated in table 5.

Although this method is based on mass and is therefore independent of trace-element concentrations and the mechanisms of transport, estimates may be uncertain as a result of the small isotopic differences found among  $R_A$ ,  $R_B$ , and  $R_C$  relative to the precision of the individual measurements of these lead isotopic ratios. This was especially true for very small contributions (that is,  $R_A \approx R_B$ ) and very large contributions (that is,  $R_B \approx R_C$ ) from  $C$ . It was also true in the situation where contributions of  $C$  to previously contaminated sediment are similar (that is,  $R_A \approx R_B \approx R_C$ ).

Calculations were made, using equations 1, 2, and 3 and the 1996 total-digestion data, to determine the effects of each of the three main tributaries on the streambed-sediment geochemistry of the Boulder River. These results are summarized in table 5. Calculations were made for several site "B"

**Table 5.** Calculated copper, zinc, arsenic, and lead contributions from Basin, Cataract, and High Ore Creeks to Boulder River.

[Total-digestion data are from samples collected in 1996;  $P_s$ ,  $P_c$ , and  $P_{pb}$  are defined from equations 1–3 (in text) and are expressed in percent. Columns in order of element mobility as defined in Fey and Desborough, this volume. Bold type values, good agreement between the different methods of calculation for amount of contaminants contributed by each tributary to Boulder River. Sites are referred to as A, B, or C, as defined in text]

localities to evaluate the effects of the tributaries both immediately downstream from the confluence and farther downstream. We used the concentrations and  $^{206}\text{Pb}/^{204}\text{Pb}$  value of the tributary sample closest to the confluence of the Boulder River as site "C" (sites 31S, 53S, and 63S; figs. 1 and 14).

The choice of sites upstream of the confluence (that is, site "A") for each of the tributaries was somewhat problematic because the downstream concentration profiles (fig. 14B) do not progressively increase in the Boulder River. Whereas it would have been simple to dismiss this irregularity as due to sample heterogeneity, we interpreted the data as a transport phenomenon in the Boulder River. Sediment collected immediately upstream and downstream from the confluences have previously been shown to be quite heterogeneous depending upon the side of the river on which the sample was collected. Also, samples collected midway between tributary confluences generally showed atypically low deposit-related trace-element concentrations that may not be representative of the river segment between the tributaries because these sites were collected in 1997 and 1998, so year-to-year variation was also present in the data set. Consequently, we used the 1996 total-digestion data from the sites immediately upstream of each of the confluences of Cataract and High Ore Creeks as "site A" for these two tributaries (table 5).

The effects of streambed sediment derived from Basin Creek on the Boulder River were distinguished from the effects of mill tailings contributed by the Jib Mill on the basis of the lead isotopic data measured in the terrace at site 2B. However, because the Jib Mill site is private property and was not sampled, we cannot quantitatively separate the contributions from Basin Creek and the Jib Mill site. We have chosen site 4S as site "A" for the calculations for Basin Creek (table 5, fig. 1). The marked increase in deposit-related trace-element concentrations between sites 4S and 5S and the calculations in table 5 suggest that the Jib Mill contributed significant amounts of copper and zinc and more modest amounts of arsenic and lead to the streambed sediment of the Boulder River. This observation from the streambed-sediment data calculations was supported by the analysis of the chemical data from core 2B (fig. 18) sampled downstream from the Jib Mill, which showed increased concentrations of copper and zinc in the lower portions of the core, and by the lead isotopic data from this section of the core, which indicated that ore from outside the Basin and Boulder mining districts was processed at the Jib Mill (fig. 23). The percent sediment contribution (eq. 1) calculated for Basin Creek from the arsenic data agreed well using either site 6S or 8S as the downstream site (48 and 46 percent respectively, table 5) and compared well with calculations using the lead data from site 8S (51 percent). Calculations of the percent contaminant for both lead and arsenic (eq. 2) agreed well using both downstream sites ranging between 74 and 89 percent. These values also agreed well with the calculated percentage of deposit lead (83 and 88 percent) from the lead isotope data (eq. 3). All calculations indicated an unaccounted-for contribution of copper and zinc, which we attribute to the Jib Mill site (see data from site 2B, fig. 18).

Calculations for the percent sediment (eq. 1) and the percent contaminant (eq. 2) using the copper and zinc data were much higher, ranging from about 97 to 120 percent for  $P_C\text{Cu}$  and  $P_C\text{Zn}$ . However, calculated copper contributions ( $P_S\text{Cu}$ ) were very large, ranging from 184 to 265 percent (table 5). We interpret these data to indicate that a large component of copper was being contributed from an unsampled location between 4S and 5S, probably the Jib Mill site. Basin Creek (site 31S) was apparently a lesser contributor of deposit-related trace-element contamination to the Boulder River than the Jib Mill site.

The effects of streambed sediment contributed by Cataract Creek to the Boulder River have been calculated using the data from sites 8S, 9S, and 53S (table 5, fig. 1). Concentrations of all four deposit-related trace elements increased significantly in streambed sediment downstream of the confluence with Cataract Creek at site 9S. Calculations of the percentage of contaminant ( $P_C\text{Pb}$ ) and the percentage of deposit lead ( $P_{Pb}$ ) for site 9S were also in good agreement at 49 and 46 percent respectively. The calculated percent sediment increased using the 1996 total-digestion data for zinc, lead, arsenic, and copper from 19 to 33 percent of the sediment contributed by Cataract Creek (table 5). The calculated percent contaminant increased in a similar fashion ranging from 49 to 67 percent. Higher values for arsenic and copper indicate preferential transport of these two trace elements in the water or suspended sediment of Cataract Creek.

The effects of streambed sediment contributed by High Ore Creek to the Boulder River have been calculated using the data from sites 11S, 12S, and 63S (table 5, fig. 1). Calculations for site 12S, immediately downstream from High Ore Creek (figs. 1 and 14B) suggested that, whereas the percent sediment contributed by High Ore Creek was in the range of 8 to 13 percent using the zinc, arsenic, and lead concentrations ( $P_S\text{Zn}$ ,  $P_S\text{As}$ , and  $P_S\text{Pb}$ ), 51 to 88 percent of the contaminants in streambed sediment of the Boulder River were contributed by the streambed sediment from High Ore Creek (table 5, fig. 1). At site 13S approximately 0.6 mi downstream from High Ore Creek where the differences between concentration and lead isotopic data were reduced between the two different sites from the north and south sides of the river, calculated contaminant contributions from High Ore Creek ranged from 72 to 97 percent for all deposit-related trace elements and 90 percent deposit-lead contaminant. At site 15S, about 3.3 mi downstream, the calculated percentages using the arsenic, lead, and the lead isotopic data were 86, 62, and 76 percent respectively, whereas the calculations for zinc and copper were substantially lower, 52 and 15 percent respectively.

Evidence for preferential transport of copper and zinc relative to lead (shown previously in fig. 14A) and the inconsistent results for these two elements as shown in table 5 indicated that the lead isotopic data generally represented the best estimates of overall deposit-related trace-element contributions to the streambed sediment in the Boulder River. In most instances, the percent contribution calculated from the arsenic and lead concentration data was in reasonably good agreement

with that calculated from the  $^{206}\text{Pb}/^{204}\text{Pb}$  data. Calculations of streambed-sediment contributions from Cataract and High Ore Creeks were probably best estimated from the arsenic and lead data. However, reliable estimates for the Basin Creek contribution cannot be made because of the influence of the Jib Mill at the confluence.

The effects of the three tributaries on the lead in the streambed sediment of the Boulder River are summarized in more detail in figure 28. The effect of past mining on the streambed sediment in the Boulder River increased progressively as the Boulder River flowed through the Basin and Cataract mining districts. It is evident from figures 28 and 29 that High Ore Creek contributed the largest fraction of deposit-related lead to the Boulder River. Downstream from High Ore Creek through site 15S, about 3.3 mi downstream from High Ore Creek, more than 70 percent of the lead in the streambed sediment was traced to deposit lead from historical mining activity in the Boulder River watershed study area.

Estimates of the percentage of deposit-related lead at any site within the area can be made using  $^{206}\text{Pb}/^{204}\text{Pb}$  data and equation 3. The appropriate  $R_A$  and  $R_C$  values are in table 4, and the  $R_B$  values were those measured at the individual sites. The calculated percent deposit-lead values ( $P_{pb}$  values, eq. 3) are shown as a ribbon map, figure 29. Because we expressed the lead isotopic data in terms of percent

contaminant deposit lead, the two different identified isotopic signatures for the deposit leads, one from Basin Creek and Cataract Creek basins, and a second from High Ore Creek basin (fig. 23), were normalized out of the data in figure 28. In using these data, however, we were not able to distinguish between deposit-related lead that had weathered from outcrops of mineralized rock and lead introduced into the stream from historical mining wastes or mill tailings. Consequently, although the calculated  $P_{pb}$  values may closely approximate contaminant lead contributions downstream from major mines, these values are not, in a strict sense, percentages of lead introduced by historical mining. However, in the absence of data indicating a large, undefined source of deposit-related trace elements in the study area, the calculated percentages provided a good estimate of the contaminants introduced into the aquatic habitat today by past mining practices.

The highest percentages of deposit-related lead were found downstream of the major mines in the area. Concentrations of lead in streambed sediment from Basin Creek decreased to some extent as shown by higher  $^{206}\text{Pb}/^{204}\text{Pb}$  values downstream from both the Buckeye mine and the confluence with Jack Creek, but 50–75 percent of the lead present in the streambed sediment of Basin Creek at its confluence with the Boulder River was deposit-related lead.

**Figure 28.** Plot of the calculated percent deposit-lead contamination added to the streambed sediment of the Boulder River by the addition of tailings from the Jib Mill site and streambed sediment from Basin Creek, from streambed sediment from Cataract Creek, and from streambed sediment from High Ore Creek.



**Figure 29.** Ribbon map showing calculated percentages of deposit lead in streambed sediment today (table 5). Dark-red square, Jib Mill site.

The highest proportions of deposit-related lead in the Cataract Creek drainage were found downstream from the Eva May mine site, in Uncle Sam Gulch downstream from the Crystal mine, and in Cataract Creek downstream from Uncle Sam Gulch. The  $^{206}\text{Pb}/^{204}\text{Pb}$  values in streambed sediment downstream from this confluence increased only slightly before Cataract Creek enters the Boulder River.

The Comet mine on High Ore Creek represents the dominant source of deposit-related lead in this basin. The calculated percentages of deposit-related lead remain greater than 90 percent from the Comet mine to the confluence with the Boulder River.

Downstream from site 15S on the Boulder River, calculations become very tentative owing to the lack of data from surrounding rocks or streambed sediment from other tributaries to the Boulder River. The Little Boulder River, a principal tributary that enters the Boulder River just downstream from site 16S (river mi 28) had  $^{206}\text{Pb}/^{204}\text{Pb}$  values similar to or slightly higher than those of premining baseline values estimated in table 4. If we assume that the estimated premining baseline values in table 4 are valid downstream from site 15S and that no other sources of deposit-related lead occur downstream, then calculations can be made as for figures 28 and 29. Results suggest that as much as 80, 50, and 13 percent of the lead in streambed sediment of the Boulder River at sites 16S (river mi 27), 17S (river mi 41), and 18S (river mi 68) respectively is deposit-related lead. Thus, we have quantified the contaminant contributions of the major tributaries to the Boulder River, fulfilling the fourth goal of the study.

### Comparison of the Boulder River Watershed Streambed-Sediment Data with Sediment-Quality Guidelines

Sediment-quality guidelines for trace-element concentrations in streambed sediment have only recently been defined and are not currently regulated. Various measures of biologic response to elevated concentrations of deposit-related trace elements in sediment are summarized in table 6 (Jones and others, 1997; MacDonald and others, 2000). Different definitions are used to define the effect of sediment-borne contaminants on aquatic life (see the footnotes, table 6). For the purposes of this discussion, we adopt the terminology used in MacDonald and others (2000). The Threshold Effect Concentration (TEC) is defined as the “contaminant concentration below which harmful effects on sediment-dwelling organisms were not expected,” whereas the Probable Effect

Concentration (PEC) is defined as the “contaminant concentration above which harmful effects on sediment-dwelling organisms were expected to occur frequently” (MacDonald and others, 2000, p. 21). For the elements antimony and silver, no TEC or PEC values have been determined. For these elements, we use the Screening Level Concentration (SLC) values (table 6), defined as “the highest concentration that can be tolerated by approximately 95 percent of the benthic fauna” (EPA, 1996).

For most of the deposit-related trace elements investigated in this watershed, the ranges of the TEC (or SLC) and PEC concentrations were significantly below those found in the streambed sediment from the Boulder River watershed study area. Leachable concentrations of the potentially toxic trace elements investigated in this study are those concentrations either sorbed or loosely bound in the iron-oxyhydroxide fraction of the streambed sediment. Leachable trace-element concentrations were compared with the sediment-quality guidelines at four sites on the Boulder River, at the mouths of the three major tributaries, and below the major mine sites (table 7). Concentrations of arsenic and lead exceeded the PEC sediment-quality guidelines in streambed sediment throughout the Basin, Cataract, and High Ore Creek basins and in the streambed sediment in the Boulder River immediately downstream from their confluences except at site 6S for lead downstream of the Basin Creek confluence. Copper concentrations exceeded PEC values in Basin Creek below the Bullion Mine tributary, in Uncle Sam Gulch and Cataract Creek downstream to the confluence in the Boulder River, and in the Boulder River downstream from Basin Creek to the confluence with the Little Boulder River (river mi 27). Copper concentrations exceeded the TEC everywhere in the study area downstream from historical mining. Zinc and cadmium concentrations exceeded the PEC in streambed sediment downstream from the Buckeye mine on Basin Creek, and exceeded the TEC elsewhere throughout the Basin Creek basin downstream from historical mining. Zinc and cadmium concentrations in streambed sediment exceeded the PEC everywhere in the Cataract Creek and High Ore Creek basins. Zinc exceeded the PEC and cadmium exceeded the TEC in the streambed sediment of the Boulder River downstream from the confluence with the Little Boulder River because of the sorption of zinc to freshly precipitated colloidal fraction of the streambed sediment (see fig. 14B). Silver and antimony concentrations exceeded the SLC values in streambed sediment everywhere within the study area downstream from historical mining sites where the concentrations in streambed sediment exceed the analytical limits of detection.

**Table 6.** Summary of screening level concentrations proposed as possible measures for sediment-quality guidelines.

[Concentrations in parts per million, ppm; --, no value recommended; bold values are recommended consensus values]

**Table 7.** Sites where the leachable deposit-related trace-element concentrations in streambed sediment from the study area exceed recommended screening levels.

[Concentrations of trace elements copper, lead, zinc, arsenic, and cadmium are in italics where they exceed the TEC and in bold where they exceed the PEC concentration (from table 6, consensus-based values); and for silver and antimony, concentrations are in italics where they exceed the SLC concentration (from table 6, U.S. EPA-IV Screening Level Concentrations)]

## Summary

Assessment of deposit-related and rock-forming trace elements in streambed sediment in the Boulder River watershed has provided the data necessary to delineate stream reaches having elevated contaminant concentrations that exceeded recommended action levels for streambed sediment, to determine anthropogenic sources of deposit-related trace elements that contaminated sediment, to understand the transport of dissolved and particulate trace elements, and to establish the streambed-sediment framework needed to evaluate toxicity to aquatic biota.

Concentrations of the suite of deposit-related trace elements copper, lead, zinc, arsenic, silver, cadmium, and antimony were elevated in modern streambed sediment in the Boulder River downstream from the confluence with Basin, Cataract, and High Ore Creeks. The major sources of these contaminants can be tied directly to historical mining at the Buckeye and Enterprise mines in upper Basin Creek, the Bullion mine on a small tributary of Jack Creek and sediment

trapped in beaver ponds and a small reservoir on Jack Creek, the area of Cataract Creek just upstream from the confluence with Uncle Sam Gulch, the Crystal mine in upper Uncle Sam Gulch, and the Comet mine in upper High Ore Creek. The Jib Mill site immediately upstream from the confluence of Basin Creek with the Boulder River was also implicated as a source of these contaminants, especially of elevated concentrations of copper in the Boulder River at the confluence with Basin Creek.

Downstream from the confluence of Basin Creek, concentrations of leachable arsenic and copper exceeded the probable effect concentration, and lead, zinc, silver, cadmium, and antimony exceeded the threshold effect concentration, in modern streambed sediment of the Boulder River. Downstream from the confluence with Cataract Creek to the confluence with the Little Boulder River, streambed sediment in the Boulder River contained concentrations of copper, lead, zinc, arsenic, and at most sites, cadmium that exceeded the probable effect concentration in streambed sediment. All of the major tributary basins, Basin Creek, Jack Creek, Cataract Creek, Uncle Sam Gulch, and High Ore Creek, also

had concentrations of copper, lead, and arsenic in streambed sediment downstream of these major mines to their confluence that exceeded the probable effects concentration. Everywhere within the three basins downstream from the major mines, the concentrations of all the deposit-related trace elements exceeded the sediment-quality guidelines (table 7).

Comparison of the concentrations of this suite of deposit-related trace elements in streambed sediment today with that in premining streambed sediment from terrace deposits in the flood plains of these streams showed that the concentrations of the deposit-related trace elements were substantially elevated in streambed sediment today, from several to more than 100 times that prior to historical mining activities. Lead isotopic data from these two media indicate that the effect of mineralized rock on the streambed-sediment geochemistry prior to mining was small relative to what we can see today.

Two different sources of deposit lead were defined by the lead isotopic data, one representing the polymetallic vein deposits in both the Basin and Cataract Creek basins, and a second at the Comet mine in the High Ore Creek basin. Calculations of the extent of the contamination caused by historical mining activity using both the arsenic and lead concentration data and the lead isotopic data gave similar results. In contrast, calculations using the copper and zinc data gave higher percentages, some exceeding 100 percent. These results indicate that the copper and zinc were being actively and differentially transported in the suspended-sediment phase and were being precipitated to the streambed sediment as a function of velocity of the stream reach often miles downstream from their source. The contribution of contaminant lead, as shown in figure 28, to streambed sediment of the Boulder River from Basin Creek was about 35 percent and from Cataract Creek about 15 percent. However, the contribution of contaminant lead to streambed sediment of the Boulder River from High Ore Creek was about 50 percent. The contamination from High Ore Creek dominated the concentrations of deposit-related trace elements in stream sediment of the Boulder River below the confluence downstream to the Jefferson River.

## References Cited

- Aamodt, P.L., 1978, Uranium hydrogeochemical and stream sediment pilot study of the Boulder batholith, Montana: Grand Junction, Colo., U.S. Dept. of Energy, GJBX-56(78), 118 p.
- Becraft, G.E., Pinckney, D.M., and Rosenblum, Sam, 1963, Geology and mineral deposits of the Jefferson City Quadrangle, Jefferson and Lewis and Clark Counties, Montana: U.S. Geological Survey Professional Paper 428, 101 p.
- Bigham, J.M., Schwertmann, U., Traina, S.J., Winland, R.L., and Wolf, M., 1996, Schwertmannite and the chemical modeling of iron in acid sulfate waters: *Geochemica et Cosmochimica Acta*, v. 60, p. 2111–2121.
- Briggs, P.H., 1996, Forty elements by inductively coupled plasma-atomic emission spectroscopy, in Arbogast, B.F., ed., Analytical methods manual for the Mineral Resources Program, U.S. Geological Survey: U.S. Geological Survey Open-File Report 96–525, p. 77–94.
- Broxton, W.W., 1980, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Butte NTMS quadrangle, Montana, including concentrations of forty-two additional elements: Grand Junction, Colo., U.S. Dept. of Energy, GJBX-129(80), 207 p.
- Church, S.E., 1981, Multielement analysis of fifty-four geochemical reference samples using inductively coupled plasma-atomic emission spectrometry: *Geostandards Newsletter*, v. 5, p. 133–160.
- Church, S.E., Holmes, C.E., Briggs, P.H., Vaughn, R.B., Cathcart, James, and Marot, Margaret, 1993, Geochemical and lead-isotope data from stream and lake sediments, and cores from the upper Arkansas River drainage—Effects of mining at Leadville, Colorado, on heavy-metal concentrations in the Arkansas River: U.S. Geological Survey Open-File Report 93–534, 61 p.
- Church, S.E., Kimball, B.A., Fey, D.L., Ferderer, D.A., Yager, T.J., and Vaughn, R.B., 1997, Source, transport, and partitioning of metals between water, colloids, and bed sediments of the Animas River, Colorado: U.S. Geological Survey Open-File Report 97–151, 136 p.
- Cleasby, T.E., Nimick, D.A., and Kimball, B.A., 2000, Quantification of metal loads by tracer-injection and synoptic-sampling methods in Cataract Creek, Jefferson County, Montana, August 1997: U.S. Geological Survey Water-Resources Investigations Report 00–4237, 39 p.
- Desborough, G.A., Leinz, Reinhardt, Sutley, Stephen, Briggs, P.H., Swayze, G.A., Smith, K.S., and Breit, George, 2000, Leaching studies of schwertmannite-rich precipitates from the Animas River headwaters, Colorado and Boulder River headwaters, Montana: U.S. Geological Survey Open-File Report 00–004, 16 p.
- Elliott, J.E., Loen, J.S., Wise, K.K., and Blaskowski, M.J., 1992, Maps showing locations of mines and prospects in the Butte 1° × 2° quadrangle, western Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I–2050–C, 147 p., 2 sheets, scale 1:250,000.
- Fey, D.L., and Church, S.E., 1998, Analytical results for 42 fluvial tailings cores and 7 stream-sediment samples from High Ore Creek, northern Jefferson County, Montana: U.S. Geological Survey Open-File Report 98–215, 49 p.

- Fey, D.L., Church, S.E., and Finney, C.A., 1999, Analytical results for 35 mine-waste tailings cores and six stream-sediment samples, and an estimate of the volume of contaminated material at the Buckeye meadow on upper Basin Creek, northern Jefferson County, Montana: U.S. Geological Survey Open-File Report 99-537, 59 p.
- Fey, D.L., Church, S.E., and Finney, C.A., 2000, Analytical results for Bullion mine and Crystal mine waste samples and bed sediments from a small tributary to Jack Creek and from Uncle Sam Gulch, Boulder River watershed, Montana: U.S. Geological Survey Open-File Report 00-031, 63 p.
- Fey, D.L., Unruh, D.M., and Church, S.E., 1999, Chemical data and lead isotopic compositions in stream-sediment samples from the Boulder River watershed, Jefferson County, Montana: U.S. Geological Survey Open-File Report 99-575, 147 p.
- Fortescue, J.A.C., 1992, Landscape geochemistry: retrospect and prospect—1990: *Applied Geochemistry*, v. 7, p. 1-53.
- Jones, D.S., Suter, G.W., II, and Hull, R.N., 1997, Toxicological benchmarks for screening contaminants of potential concern for effects on sediment-associated biota; 1997 revision: Department of Energy Report ES/ER/TM-95/R4, 30 p., unpaginated appendices.
- Kimball, B.A., Callendar, E., and Axtmann, E.V., 1995, Effects of colloids on metal transport in a river receiving acid mine drainage, upper Arkansas River, Colorado, U.S.A.: *Applied Geochemistry*, v. 10, p. 285-306.
- Lund, Karen, Aleinikoff, J.N., Kunk, M.J., Unruh, D.M., Zeihen, G.D., Hodges, W.C., duBray, E.A., and O'Neill, J.M., 2002, SHRIMP U-Pb and  $^{40}\text{Ar}/^{39}\text{Ar}$  age constraints for relating plutonism and mineralization in the Boulder batholith region, Montana: *Economic Geology*, v. 97, p. 241-267.
- MacDonald, D.D., Ingersoll, C.G., and Berger, T.A., 2000, Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems: *Archives of Environmental Contamination and Toxicology*, v. 39, p. 20-31.
- McDanal, S.K., Campbell, W.L., Fox, J.P., and Lee, G.K., 1985, Magnetic tape containing analytical results for rocks, soils, stream sediments, and heavy-mineral concentrate samples: U.S. Geological Survey Report USGS-GD-85-006; available from U.S. Department of Commerce, National Technical Information Service, Springfield, Virginia 22151.
- Metesh, J.J., Lonn, J.D., Duaine, T.E., and Wintergerst, Robert, 1994, Abandoned-inactive mines program, Deerlodge National Forest—Volume I, Basin Creek Drainage: Montana Bureau of Mines and Geology Open-File Report 321, 131 p.
- Metesh, J.J., Lonn, J.D., Duaine, T.E., and Wintergerst, Robert, 1995, Abandoned-inactive mines program, Deerlodge National Forest—Volume II, Cataract Creek Drainage: Montana Bureau of Mines and Geology Open-File Report 344, 201 p.
- Nimick, D.A., and Cleasby, T.E., 2000, Water-quality data for streams in the Boulder River watershed, Jefferson County, Montana: U.S. Geological Survey Open-File Report 00-99, 70 p.
- Nordstrom, D.K., and Alpers, C.N., 1999, Geochemistry of mine waters, *in* Plumlee, G.S., and Logsdon, M.J., eds., *The environmental geochemistry of mineral deposits—Part A, Processes, techniques, and health issues: Society of Economic Geologists, Reviews in Economic Geology*, v. 6A, p. 133-160.
- OSWER (Office of Solid Waste and Emergency Response, Environmental Protection Agency), 1996, Ecotox thresholds: *ECO Update*, v. 3, p. 1-12.
- Persuad, D., Jaaugmagi, R., and Hayton, A., 1993, Guidelines for the protection and management of aquatic sediment quality in Ontario: Ontario Ministry of the Environment and Energy, 30 p.
- Rossillon, Mitzi, and Haynes, Tom, 1999, Basin Creek mine reclamation heritage resource inventory 1998, unpublished report prepared for the Beaverhead-Deerlodge National Forest, Dillon, Mont., 126 p.
- Ruppel, E.T., 1963, geology of the Basin quadrangle, Jefferson, Lewis and Clark, and Powell Counties, Montana: U.S. Geological Survey Bulletin 1151, 121 p.
- Schemel, L.E., Kimball, B.A., and Bencala, K.E., 2000, Colloid formation and metal transport through two mixing zones affected by acid mine drainage near Silverton, Colorado: *Applied Geochemistry*, v. 15, p. 1003-1018.
- Smith, K.S., 1999, Metal sorption on mineral surfaces—An overview with examples relating to mineral deposits, *in* Plumlee, G.S., and Logsdon, M.J., eds., *The environmental geochemistry of mineral deposits—Part A, Processes, techniques, and health issues: Society of Economic Geologists, Reviews in Economic Geology*, v. 6A, p. 161-182.
- Smith, S.M., 1994, Geochemical maps of copper, lead, and zinc, upper Arkansas River drainage basin, Colorado: U.S. Geological Survey Open-File Report 94-408, 15 p.
- Smith, S.M., Church, S.E., and Green, G.N., 1997, Effects of geology and mining activity on sediment geochemistry of the Arkansas River drainage basin, Colorado: *Explore*, no. 96, p. 6-10, 14.

- Unruh, D.M., Fey, D.L., and Church, S.E., 2000, Chemical data and lead isotopic compositions of geochemical baseline samples from streambed sediments and smelter slag, lead isotopic compositions in fluvial tailings, and dendrochronology results from the Boulder River watershed, Jefferson County, Montana: U.S. Geological Survey Open-File Report 00-38, 75 p.
- U.S. Environmental Protection Agency, 1995, National sediment inventory; Documentation of derivation of freshwater sediment quality: Washington, D.C., Office of Water, EPA Report.
- U.S. Environmental Protection Agency, 1996, Calculation and evaluation of sediment effect concentrations for the amphipod *Hyalella azteca* and the midge *Chironomus riparius*: Chicago, Ill., Great Lakes National Program Office, EPA Report 905-R96-008.
- Van Eeckhout, E.M., 1981, Utilizing the geochemical data from the National Uranium Resource Evaluation (NURE) Program; an evaluation of the Butte Montana quadrangle, Montana: Grand Junction, Colo., U.S. Dept. of Energy, GJBX-58(81), 67 p.
- Wallace, C.A., 1987, Generalized geologic map of the Butte 1°× 2° quadrangle, Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF-1925, scale 1:250,000.