

Leaching, Transport, and Methylation of Mercury in and around Abandoned Mercury Mines in the Humboldt River Basin and Surrounding Areas, Nevada

By John E. Gray



U.S. Geological Survey Bulletin 2210-C

Version 1.0 2003

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

Leaching, Transport, and Methylation of Mercury in and around Abandoned Mercury Mines in the Humboldt River Basin and Surrounding Areas, Nevada

By John E. Gray

Chapter C of

Geoenvironmental Investigations of the Humboldt River Basin, Northern Nevada

Edited by Lisa L. Stillings

U.S. Geological Survey Bulletin 2210-C

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

Posted online September 2003, version 1.0

This publication is only available online at:
<http://geology.cr.usgs.gov/pub/bulletins/b2210-c/>

Any use of trade, product, or firm names in this publication
is for descriptive purposes only and does not
imply endorsement by the U.S. Government

Preface

Northern Nevada is one of the world's foremost regions of gold production. The Humboldt River Basin (HRB) covers 43,500 km² in northern Nevada (Crompton, 1995), and it is home to approximately 18 active gold and silver mines (Driesner and Coyner, 2001) among at least 55 significant metallic mineral deposits (Long and others, 1998). Many of the gold mines are along the Carlin trend in the east-central portion of the HRB, and together they have produced 50 million ounces of gold from 1962 (when the Carlin mine first opened) through April 2002 (Nevada Mining Association, 2002). Mining is not new to the region, however. Beginning in 1849, mining has taken place in numerous districts that cover 39 percent of the land area in the HRB (Tingley, 1998). In addition to gold and silver, As, Ba, Cu, Fe, Hg, Li, Mn, Mo, Pb, S, Sb, V, W, Zn, and industrial commodities such as barite, limestone, fluorite, sand and gravel, gypsum, gemstones, pumice, zeolites, and building stone, have been extracted from the HRB (McFaul and others, 2000).

Due to the large amount of historical and recent mining in the HRB, the Bureau of Land Management (BLM) in Nevada asked the U.S. Geological Survey (USGS) Mineral Resources Program to conduct a series of mineral-deposit-related environmental studies in the HRB. BLM required data and geoenvironmental interpretations regarding (1) the chemical composition of water, soil, sediment, and mine waste in the HRB, (2) the natural background chemistry of these materials, and (3) how mining activities may have altered their chemistry. The paper that follows describes one of the studies conducted by the USGS Minerals Program to answer these and similar questions.

All papers within this series of investigations can be found as lettered chapters of USGS Bulletin 2210, *Geoenvironmental Investigations of the Humboldt River Basin, Northern Nevada*. Each chapter is available separately online.

References Cited

- Crompton, E.J., 1995, Potential hydrologic effects of mining in the Humboldt River Basin, northern Nevada: U.S. Geological Survey Water Resources Investigations Report 94-4233, 2 sheets.
- Driesner, D., and Coyner, A., 2001, Major mines of Nevada 2000: Mineral industries in Nevada's economy: Nevada Bureau of Mines and Geology Special Publication P-12, 28 p.
- Long, K.R., DeYoung, J.H., Jr., and Ludington, S.D., 1998, Significant deposits of gold, silver, copper, lead, and zinc in the United States: U.S. Geological Survey Open-File Report 98-206A, 33 p. [USGS Open-File Report 98-206B contains one 3.5-inch diskette].
- McFaul, E.J., Mason G.T., Jr., Ferguson, W.B., and Lipin, B.R., 2000, U.S. Geological Survey mineral databases—MRDS and MAS/MILS: U.S. Geological Survey Digital Data Series DDS-52, two CD-ROMs.
- Nevada Mining Association, 2002, Industry to celebrate 50 millionth ounce of gold: Nevada Mining Association News Release, April 11, 2002.
- Tingley, J.V., 1998, Mining districts of Nevada (2nd ed.): Nevada Bureau of Mines and Geology Report 47d, one CD-ROM.

Contents

Preface	III
Abstract.....	1
Introduction	1
Study Area Description.....	3
Uses of Mercury and the Mercury Mining Process	4
Methods	5
Field Studies and Sample Collection	5
Chemical Analysis	6
Results	6
Ore and Mine Wastes	6
Stream- and Lake-Sediment Samples.....	10
Stream- and Lake-Water Samples.....	11
Water-Leach Studies.....	11
Discussion.....	12
Summary	14
References.....	14

Figures

1. Map showing location of mercury mines studied and sample locations from the Humboldt River, Rye Patch Reservoir, and Rock Creek.....	2
2. Location map and plan-view sketch map of the Cahill mine.....	3
3. Photographs of the Humboldt River basin and the Rye Patch Reservoir from the Eldorado mine, cinnabar in silicified sandstone from the Cahill mine, and the Cahill mine in the Poverty Peaks district.....	4
4. Graph of mercury versus methylmercury concentration in mine-waste calcine, mine-drainage sediments, and Humboldt River sediment samples	10
5. Graphs of mercury in sediments versus distance from mines for all mine drainages, the Eldorado mine, and the Mt. Tobin mine	11
6. Graph of mercury versus methylmercury concentration in unfiltered water samples collected downstream from the Eldorado and Mt. Tobin mines, and from the Humboldt River.....	12
7. Graph of mercury concentration versus pH in filtered water samples of leachates from mine-waste calcine and filtered water samples collected from the Humboldt River, Rye Patch Reservoir, and mine drainages	12

Tables

1. Description and production of mercury mines studied.....	5
2. Mercury data for mine-waste calcines and sediment samples collected from selected mercury mines, the Humboldt River, Rye Patch Reservoir, and Rock Creek.....	7
3. Geochemical data for water samples collected from two mercury mines, the Humboldt River, Rye Patch Reservoir, and Rock Creek.....	9
4. Geochemical data for filtered water leachates of mine-waste samples collected from several mercury mines	13

Leaching, Transport, and Methylation of Mercury in and around Abandoned Mercury Mines in the Humboldt River Basin and Surrounding Areas, Nevada

By John E. Gray¹

Abstract

Mercury and methylmercury concentrations were measured in mine wastes, stream sediments, and stream waters collected both proximal and distal from abandoned mercury mines to evaluate mercury contamination and mercury methylation in the Humboldt River system. The climate in the study area is arid, and due to the lack of mine-water runoff, water-leaching laboratory experiments were used to evaluate the potential of mine wastes to release mercury. Mine-waste calcine contains mercury concentrations as high as 14,000 $\mu\text{g/g}$. Stream-sediment samples collected within 1 km of the mercury mines studied contain mercury concentrations as high as 170 $\mu\text{g/g}$, but sediments collected from the Humboldt River and regional baseline sites have much lower mercury contents, less than 0.44 $\mu\text{g/g}$. Similarly, methylmercury concentrations in mine-waste calcine are locally as high as 96 ng/g , but methylmercury contents in stream sediments collected downstream from the mines and from the Humboldt River are lower ($<0.05\text{--}0.95$ ng/g). Stream-water samples collected below two mines studied contain mercury concentrations ranging from 6 to 2,000 ng/L , whereas mercury contents in Humboldt River and Rye Patch Reservoir water were generally lower, ranging from 2.1 to 9.0 ng/L . Methylmercury concentrations in Humboldt River system water were the lowest in this study ($<0.02\text{--}0.27$ ng/L). Although mercury and methylmercury concentrations were elevated in some mine-waste calcine and mercury concentrations were locally high in mine-waste leachate samples, data show significant dilution of mercury and lower mercury methylation down gradient from the mines, especially in the sediments and water collected from the Humboldt River, which is more than 8 km from any mercury mines. Data show only minor, local transference of mercury and methylmercury from mine-waste calcine to stream sediment, and then onto the water column, and indicate little transference of mercury from the mine sites to the Humboldt River system.

¹ U.S. Geological Survey, Box 25046, Federal Center, Mail Stop 973, Denver, CO 80225 USA; email: jgray@usgs.gov.

Introduction

This study is part of a larger project conducted by the U.S. Geological Survey (USGS) to evaluate the geology, mineral resources, and environmental geochemistry of the Humboldt River basin (HRB), which is the longest river system in Nevada and an important ecosystem (fig. 1). Nevada is one of the world's largest regions of gold production, and the HRB—covering about 43,500 km^2 in northern Nevada—contains at least 18 major gold and silver mines. At least 1,400 t (50 million oz) of gold was produced between 1962 and 2002 in the HRB, as well as significant As, Ba, Cu, F, Fe, Li, Mn, Pb, S, V, W, and Zn. Due to the large amount of metallic and nonmetallic mineral resources in the HRB, the U.S. Bureau of Land Management (BLM) asked the USGS Mineral Resources Program to conduct several environmental studies in the region; this report is one product of these investigations. The BLM was interested in obtaining data on the chemical composition of water, soil, sediment, and mine wastes in the HRB; the natural background chemistry of geologic materials in the region; and how mining activities may have altered the local and regional geochemistry.

In addition to the large amount of precious-metal resources produced in Nevada, abundant mercury was also recovered in this region from the early 1900s until the early 1990s. Historical production from mercury mines in western and central Nevada exceeds 10,000 t (Willden, 1964; Johnson, 1977; Noble and others, 1988), making Nevada the second largest mercury-producing region in the United States, ranking only behind the California Coast Ranges (Peabody, 1993). Many of the mercury mines in this region are located in the HRB, and because of the toxic nature of mercury, the presence of these mercury mines is a potential hazard to residents and wildlife when drainage from the mines enters local streams and rivers, and potentially the HRB (fig. 2). Thus, this study was undertaken to determine if weathering of mercury mines in this region has resulted in any significant erosion and transport of mercury to surrounding ecosystems, specifically the HRB (fig. 3A).

Mercury is a heavy metal of environmental concern

2 Geoenvironmental Investigations of the Humboldt River Basin, Northern Nevada

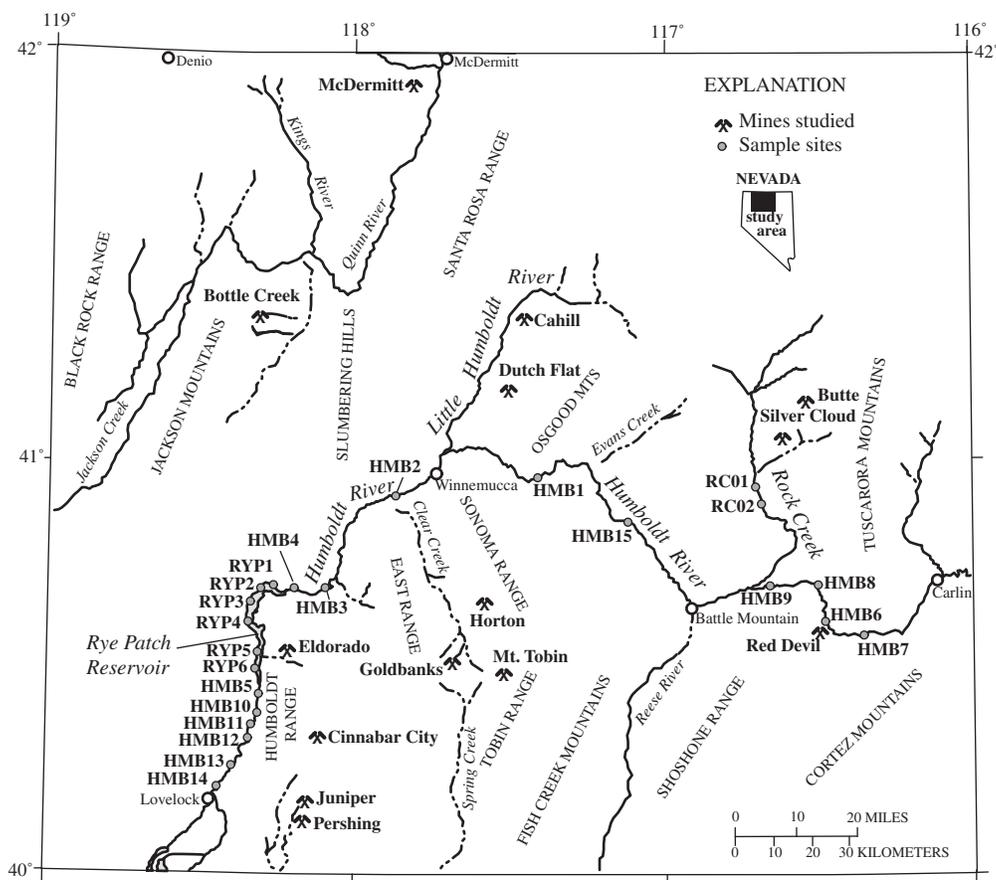


Figure 1. Location of mercury mines studied and sample locations from the Humboldt River, Rye Patch Reservoir, and Rock Creek.

because it is toxic to all organisms, including humans. The most problematic forms are organic mercury compounds, which are the most toxic, water and lipid soluble, and can biomagnify with increasing trophic position in the food chain. Under certain conditions, some inorganic mercury (such as elemental mercury, Hg^0) that remains in mine wastes may be converted to organic mercury (most commonly, methylmercury, CH_3Hg^+). Mercury mine wastes are known to contain a number of mercury byproducts (Biester and others, 1999; Kim and others, 2000), and potentially the most problematic is Hg^0 that can oxidize to Hg^{2+} , which becomes available for microbial methylation, subsequently forming bioavailable compounds such as methylmercury. Mercury methylation is primarily a result of anaerobic microbial activity in sediments, which is typically enhanced in environments with high concentrations of organic matter (Compeau and Bartha, 1985).

To evaluate the distribution of mercury and mercury methylation in and around these mines, the concentration of mercury and (or) methylmercury was measured in samples of (1) ore, mine-waste calcine (roasted ore), stream sediment,

and water collected near and downstream from several of the mines, and (2) stream sediment and water collected from the Humboldt River and in Rye Patch Reservoir. Sediment and water samples were also collected from two sites on Rock Creek, which is one of the larger watersheds in the region and one of the few where flowing water was observed in June 2000. The sample sites on Rock Creek were more than 15 km below the Silver Cloud mine and, thus, are likely representative of the regional geochemical baseline. Due to the abundance of mines and associated downstream transport of mercury in this region, there are probably no true background sites (i.e., areas without anthropogenic mercury contributions). As a result of funding limitations, only a subset of the collected samples were analyzed for methylmercury, but these results are critical for evaluating mercury methylation near the mercury mines, as well as in the HRB. During this study, mine-water runoff was rarely observed (only two localities) due to the arid climate in this region. Therefore, laboratory water-leaching studies of mine-waste calcine were conducted to simulate mine-water runoff and to evaluate the capacity of the mine wastes to release mercury.

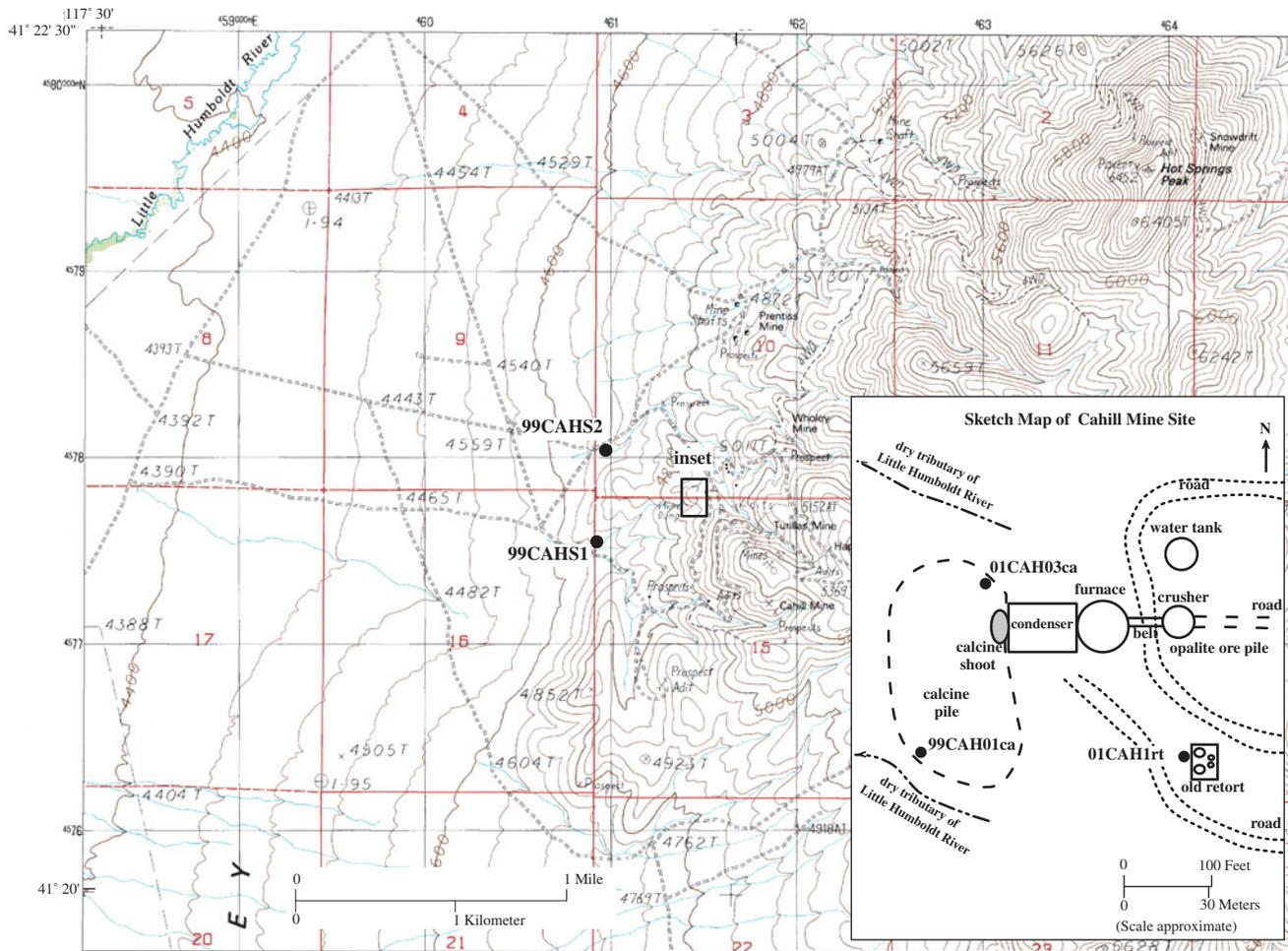


Figure 2. Location and plan-view sketch map of the Cahill mine, which outlines the sources of mercury in and around the mercury mines studied. Mercury remaining in ore, mine-waste calcine, and retorts and furnaces can be released down gradient from the mines into stream drainages. Location of samples for some of the data in table 2 is also shown.

Study Area Description

The mercury mines studied (fig. 1) are part of a mercury belt that consists of numerous deposits found in a broad region in western and central Nevada. This mercury belt was first suggested to extend from McDermitt to Beatty, Nev., by Bailey and Phoenix (1944), who also divided these deposits into eight different types based on geologic bedrock associations. These mercury deposits are found in a wide variety of lithologies including sandstone, limestone, chert, granitic rocks, diabase dikes, rhyolitic tuffs and flows, andesites, and metamorphic rocks such as schists and phyllite (Bailey and Phoenix, 1944; Willden, 1964; Johnson, 1977). Ore and gangue minerals are commonly found in highly silicified rocks, veins, and vein breccias. “Opalite” is a common host rock, which is typically volcanic rock that is altered to amorphous and cryptocrystalline quartz, including opal. Silicified veins, and siliceous-sinter deposits formed by the

surface deposition of hot-spring fluids, are also common host rocks of mercury ore. The dominant ore mineral is cinnabar (HgS , hexagonal) (fig. 3B), but minor metacinnabar (HgS , cubic, dimorphous with cinnabar), native mercury (Hg^0), calomel (Hg_2Cl_2), and mercury oxychlorides (e.g., Hg_2ClO and $\text{Hg}_4\text{Cl}_2\text{O}$) are found in some deposits; pyrite (FeS_2), marcasite (FeS_2), sphalerite ($(\text{Zn}, \text{Fe})\text{S}$), and stibnite (Sb_2S_3) are rare (Bailey and Phoenix, 1944). Gangue is most commonly quartz and calcite, with subordinate barite, muscovite, alunite, jarosite, and clay minerals (Bailey and Phoenix, 1944). The mercury deposits in Nevada are generally of Miocene age, but some are possibly younger, and their formation has been interpreted to be related to extensional tectonics and related magmatism (Bailey and Phoenix, 1944; Noble and others, 1988).

Mercury mines in Nevada operated between about 1907 and 1991, when the McDermitt mine closed. Mercury mines throughout the United States are not presently operating

4 Geoenvironmental Investigations of the Humboldt River Basin, Northern Nevada

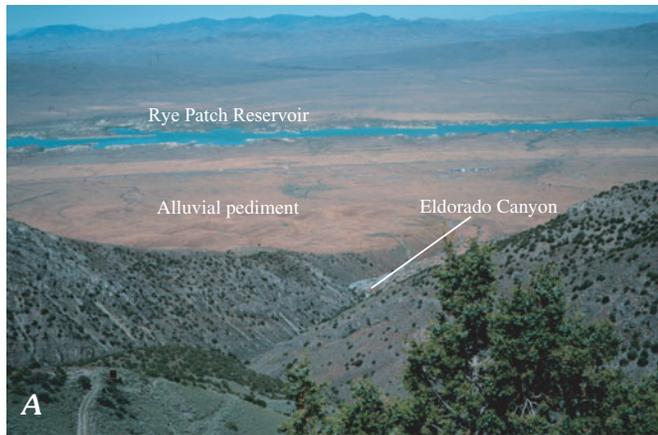


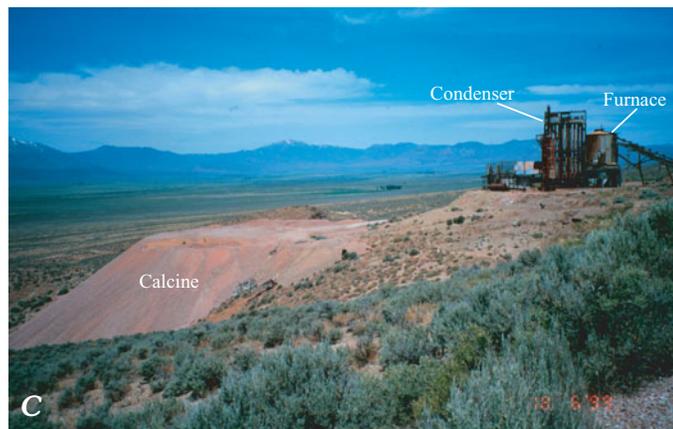
Figure 3 (facing column). *A*, View of the Humboldt River basin and the Rye Patch Reservoir from the Eldorado mercury mine in the Humboldt Range. This photograph shows that sediment or water runoff from the mines is transported and diluted through a large volume of alluvial pediment before it reaches Rye Patch Reservoir, which is part of the Humboldt River system. The Eldorado mine is one of the closest mines to the Humboldt River system and is located about 8 km from Rye Patch Reservoir. *B*, Cinnabar (red mineral) in silicified sandstone from the Cahill mine. *C*, Photograph of the Cahill mine in the Poverty Peaks district. A calcine pile (left foreground) is representative of the majority of mercury-bearing waste rock at the mines studied in Nevada. The rotary furnace and condensation unit (far right) is where mercury ore was burned, generating elemental mercury that was condensed and collected.



Uses of Mercury and the Mercury Mining Process

Mercury has many diverse properties and has been used historically in many products. Mercury is a liquid at room temperature that responds to changes in temperature, which has resulted in its well-known use in thermometers. Mercury also is used in navigational instruments to measure changes in temperature and pressure. Mercury is a good metallic conductor with a low electrical resistivity, and it has been used in electrical products including electrical wiring and switches, fluorescent lamps, mercury batteries, and thermostats (Eisler, 1987). In the medical field, mercury is used as a component in dental fillings and as a preservative in many pharmaceutical products. Mercury has been used in industrial and agricultural applications such as in the production of chlorine and caustic soda, in nuclear reactors, in plastic production, as a fungicide in seeds and bulbs, and as an antifouling agent in paper, paper pulp, and paint (Eisler, 1987). Mercury fulminate is used in munitions, such as blasting-cap detonators. Liquid mercury has the unique property of combining or amalgamating with precious metals, and therefore, it has been used for centuries for the extraction of gold and silver during mining (Lacerda and Salomons, 1998).

The recovery of mercury from its ore is a relatively simple process and is generally inexpensive, and as a result, mercury mining has been conducted for several centuries (Bailey and Phoenix, 1944; Lacerda and Salomons, 1998). As a result of its simple and inexpensive recovery, mercury was typically produced at the site of mining. Cinnabar is the most common mercury ore mineral worldwide, and cinnabar-bearing ore is simply crushed and burned at a temperature of 600°–700°C, which exceeds the stability of cinnabar, releasing mercury as vapor. The mercury vapor is then condensed by air- or water-cooling to form liquid mercury (also known as quicksilver). Lime (CaO) is typically added prior to ore roasting to remove sulfur gas (SO₂), which is also released during the heating process. The ore is typically burned in either a retort (a small, externally



because of low prices and low demand, although some minor byproduct mercury is recovered from a few precious-metal mines. As previously mentioned, mercury production in Nevada exceeds 10,000 t (approximately 300,000 flasks; 1 flask = 76 lb), about 90 percent of which came from the McDermitt mine (Willden, 1964; Johnson, 1977; Noble and others, 1988). Geologic characteristics and mercury production of the districts studied are shown in table 1.

Table 1. Description and production of mercury mines studied.

District	Mines studied	Geology	Approximate mercury production (flasks/district)
Dutch Flat	Dutch Flat	Veins in Paleozoic schist and phyllite cut by Tertiary granodiorite	90 ^{1,2}
Beowawe	Red Devil (Beowawe)	Veins in Paleozoic(?) limestone conglomerate overlain by Tertiary andesite	150 ¹
Spring Valley	Cinnabar City	Veins in Triassic limestone and Quaternary volcanic tuff and basalt	500 ³
Sonoma	Horton	Veins in altered Paleozoic greenstone	500 ³
Poverty Peaks	Cahill	Veins in Paleozoic and Triassic limestone and sandstone, and Tertiary opalite	1,000 ²
Imlay	Eldorado (Blackjack)	Veins in Triassic limestone and shale	1,000 ¹
Mt. Tobin	Mt. Tobin	Silicified Tertiary rhyolite and tuff and pre-Tertiary conglomerate and shale	1,500 ^{1,3}
Ivanhoe	Silver Cloud, Butte	Opalite altered Tertiary volcanic tuff	>2,000 ¹
Goldbanks	Goldbanks	Opalite altered Tertiary volcanic tuff and breccia	2,700 ³
Bottle Creek	White Peaks (Bottle Creek)	Veins in Paleozoic and Triassic tuffs and sandstone and Tertiary diabase dikes	4,500 ¹
Antelope Springs	Pershing, Juniper	Veins in Triassic limestone, dolomite, conglomerate, and shale	12,500 ³
Opalite	McDermitt	Opalite altered Tertiary volcanic tuffs	270,000 ⁴

¹Bailey and Phoenix (1944), ²Willden (1964), ³Johnson (1977), ⁴Noble and others (1988).

heated, oven-like furnace) or in a large rotary furnace (fig. 3C) in which ore is heated internally and continuously rotated. In Nevada, retorts generally processed as much as a few tons of ore daily and were generally used at smaller mines, whereas rotary furnaces processed larger volumes of ore, as much as 100 t of ore daily (Bailey and Phoenix, 1944). At the larger mines in Nevada, both retorts and rotary furnaces are found, and retorts were often used to recover mercury from smaller volumes of high-grade ore or from mercury-rich soot that typically collected in condensers (Bailey and Phoenix, 1944). This method of heating ore to vaporize mercury is a type of calcination process, and thus, resultant mercury mine wastes are termed calcine or mine-waste calcine.

Mercury mine-waste calcine is typically red-brown in color (fig. 3), which results from the burning and oxidation of iron-sulfide minerals typically contained in the ore. Following ore roasting, mine wastes are discarded on the ground, generally at the mine site. However, the roasting process to remove mercury at mines worldwide is not totally efficient and is often incomplete, and thus, mine-waste calcine contains elemental Hg, elemental mercury sorbed onto particulates, cinnabar, metacinnabar, and several water-soluble mercury compounds such as sulfates, chlorides, and oxychlorides, which are present even after many years following cessation of mining (Biesler and others, 1999; Kim and others, 2000). Due to the presence of elemental mercury and soluble mercury compounds, mine-waste calcine is not an appropriate construction material,

especially for public roads. Furthermore, studies have shown elevated mercury gas emissions from mercury mines in Nevada and California (Gustin and others, 2000), indicating that extended human exposure to mercury mine calcine is not advisable (i.e., building houses on abandoned mercury mine sites should be avoided).

Methods

Field Studies and Sample Collection

The 14 mercury mines studied are located in 12 districts (fig. 1) and represent a range in deposit size (mercury production) and geological characteristics (table 1). Most of the sites studied were within the HRB including the Eldorado, Dutch Flat, Cahill, Cinnabar City, Goldbanks, Silver Cloud, Butte, Mt. Tobin, Red Devil, and Horton mines, which were studied to evaluate any adverse influence of mercury to the HRB. In addition, localities outside of the HRB such as the McDermitt, Bottle Creek, Juniper, and Pershing mines were studied as analogs for mercury-transport processes within the HRB. The most important mine studied outside of the Humboldt River basin was McDermitt, the largest mercury mine in Nevada.

Stream-sediment samples consisted of channel-bed

alluvium. Lake-sediment samples were collected along the shoreline below the waterline of Rye Patch Reservoir. Sediment samples were composited by collecting and mixing representative material from several localities at each site. Mine-waste calcine was collected as grab samples. Sediment and mine-waste samples were air-dried and ground prior to analysis. Unfiltered water samples for mercury and methylmercury analysis were collected in precleaned Teflon bottles and were shipped within 48 hours to a commercial laboratory for analysis; at the laboratory, samples were acidified with ultrapure hydrochloric acid. An additional set of filtered and unfiltered water samples were collected at each locality for mercury analysis; these samples were collected to compare suspended (unfiltered) and dissolved (filtered) mercury concentrations in water. This set of water samples was collected in precleaned glass bottles and preserved with ultrapure nitric acid saturated with sodium dichromate; samples were subsequently analyzed by the USGS. All filtered water samples were passed through a 0.45- μm sterile membrane. Stream-water characteristics such as pH, conductivity, alkalinity, turbidity, temperature, Fe^{2+} , and dissolved oxygen were measured in the field at each sample site.

Laboratory water-leaching studies were conducted on samples of mine-waste calcine using a modified version of the U.S. Environmental Protection Agency (EPA) 1312 synthetic precipitation leaching procedure (U.S. Environmental Protection Agency, 1986). Twenty-two mine-waste samples were air-dried and sieved to minus 9.5 mm prior to laboratory water-leaching studies. Following the EPA-1312 method, 2 L of deionized water acidified to pH 4.2 was added to 100 g of sample; these samples were leached as they were rotated at 28 rpm for 18 hours. The only modification to the EPA-1312 method was that the leachate was extracted and filtered at 0.45 μm , rather than with a 0.7- μm filter. This procedural modification was made so that the same filtration method was used for both leachates and surface-water samples collected in the field. Conductivity, pH, Fe^{2+} , and alkalinity were also measured in leachates.

Chemical Analysis

Measurement of mercury followed EPA method 1631, and EPA method 1630 for analysis of methylmercury (Bloom 1989). The concentration of mercury was determined in the mine-waste, sediment, water, and leachate samples using cold-vapor atomic absorption spectrophotometry (CVAAS) methods modified from Kennedy and Crock (1987), or by a cold-vapor atomic fluorescence spectrometry (CVAFS) technique developed by Bloom and Fitzgerald (1988). Methylmercury was determined in samples using CVAFS (Bloom, 1989). During methylmercury analysis, sediment and mine-waste samples were extracted into methylene chloride during digestion to avoid possible methylation artifact effects (Bloom and others, 1997). Quality control for mercury and methylmercury analysis was addressed with field blanks, method blanks, blank

spikes, matrix spikes, certified reference materials, and sample duplicates. Recoveries on blank and matrix spikes were 80–120 percent, and the relative standard deviation was <15 percent on reference standards. Method blanks were below the limits of determination. Sample duplicates are shown in tables 2 and 3. The sediment and water samples were analyzed for additional major and trace elements using several methods, but these results are not discussed in this paper. These additional geochemical data are available in Gray and others (1999).

Results

Ore and Mine Wastes

Significant mine stockpiles of unprocessed ore were not found, and only minor fragments of mineralized rock containing cinnabar were observed near shafts or adits, indicating that ore was efficiently mined and processed at the sites studied. At the Silver Cloud, Cahill, Butte, Goldbanks, and McDermitt mines, finely disseminated cinnabar was found in bedded opalite in open cuts and rock fragments. In addition, metacinnabar was observed in opalite ore from the Silver Cloud mine, and a probable mercury oxychloride (a bright-yellow mineral that darkened upon exposure to sunlight) was found along with vein cinnabar at the Cahill mine. Mercury concentrations in grab samples of ore varied widely from a low of 20 $\mu\text{g/g}$ (Dutch Flat mine) to cinnabar-rich samples containing as much as 6.9 percent (McDermitt mine) (Gray and others, 1999). The mean mercury concentration of ores collected in this study was about 1.4 percent, which is similar to the average content of mercury ore mined throughout Nevada (Bailey and Phoenix, 1944; Willden, 1964; Johnson, 1977).

Mine-waste calcine observed at most of the mines studied in Nevada is similar to calcine found worldwide, which is typically red-brown due to the presence of fine-grained iron oxide and minor cinnabar. However, where opalite was the dominant host rock of ore (e.g., the Silver Cloud mine), mine wastes are bleached white or light pink, which is consistent with the silica-rich nature of opalite at such sites. Mercury concentrations are highly variable in samples of mine-waste calcine collected from various mines. For example, calcine collected from the Eldorado mine contains mercury concentrations varying from 25 to 1,300 $\mu\text{g/g}$, whereas calcine from the Silver Cloud mine contains mercury ranging from 3.0 to 180 $\mu\text{g/g}$ (table 2). Methylmercury concentrations in mine-waste calcine collected from the mines studied also vary widely—from <0.05 to 96 ng/g (table 2, fig. 4).

In addition to measuring the concentration of mercury in the mine-waste calcine, the volume of calcine at the sites studied was also estimated in the field using compass and tape mapping. The amount of calcine remaining at these mercury mines is variable but is consistent with the general size and mercury production as shown in table 1. Calcine was estimated

Table 2. Mercury data for mine-waste calcines and sediment samples collected from selected mercury mines, the Humboldt River, Rye Patch Reservoir, and Rock Creek.[Sample-number prefixes indicate collection date, e.g., 99 = 1999. ^a, replicate analyses; n.a., not analyzed]

Sample number	Location/description	Hg ($\mu\text{g/g}$)	Methyl-Hg (ng/g)
99DFL1ca	Dutch Flat mine-waste calcines	320	n.a.
99DFL2ca	Dutch Flat mine-waste calcines	110	n.a.
99DFL1ca	Dutch Flat mine-waste calcines inside small retort	680	n.a.
00RD1ca	Red Devil mine-waste calcines	26	n.a.
00RD1ca	Red Devil mine-waste calcines	320	n.a.
00RD1ca	Red Devil mine-waste calcines	2.4	n.a.
00RD1s	Red Devil mine, stream sediment 300 m below mine	0.21	n.a.
00RD2s	Red Devil mine, stream sediment 500 m below mine	0.80	n.a.
00RD3s	Red Devil mine, stream sediment 1,000 m below mine	0.23	n.a.
00CC1ca	Cinnabar City mine-waste calcines	12	n.a.
00CC2ca	Cinnabar City mine-waste calcines	1.3	n.a.
00CC3ca	Cinnabar City mine-waste calcines	6.2	n.a.
00CC1s	Cinnabar City mine, stream sediment 100 m below mine	7.8	n.a.
00CC2s	Cinnabar City mine, stream sediment 300 m below mine	3.5	n.a.
00CC3s	Cinnabar City mine, stream sediment 1,500 m below mine	0.8	n.a.
00HN03ca	Horton mine-waste calcines	610	n.a.
01HN1ca	Horton mine-waste calcines	380	0.80
01HN2ca	Horton mine-waste calcines	220	0.99
00HN01s	Horton mine, stream sediment 300 m below mine	0.90	n.a.
00HN02s	Horton mine, stream sediment 800 m below mine	0.90	n.a.
00HN03s	Horton mine, stream sediment 5,000 m below mine	0.17	n.a.
99CAH01ca	Cahill mine-waste calcines	680	n.a.
01CAH1rt	Cahill mine-waste calcines inside small retort	27, 28 ^a	0.87
01CAH03ca	Cahill mine-waste calcines	64, 62 ^a	0.31
99CAH1s	Cahill mine, stream sediment 500 m below mine	170	n.a.
99CAH2s	Cahill mine, stream sediment 800 m below mine	2.0	n.a.
00BJK01ca	Eldorado mine-waste calcines	1,000	7.7
00BJK02ca	Eldorado mine-waste calcines	25	< 0.05
01BJK01ca	Eldorado mine-waste calcines	1,300, 1,200 ^a	3.5, 4.2 ^a
00BJK01s	Eldorado mine, stream sediment 100 m below mine	1.7	0.95
00BJK02s	Eldorado mine, stream sediment 500 m below mine	1.4	0.26
00BJK03s	Eldorado mine, stream sediment 2000 m below mine	0.87	0.23
01TB01ca	Mt. Tobin mine-waste calcines	520, 540 ^a	0.073
01TB02ca	Mt. Tobin mine-waste calcines	290	< 0.05
01TB03ca	Mt. Tobin mine-waste calcines	1,200	2.9
00TB01s	Mt. Tobin mine, stream sediment 50 m below mine	40	0.18
00TB02s	Mt. Tobin mine, stream sediment 400 m below mine	60	0.21
00TB03s	Mt. Tobin mine, stream sediment 1,500 m below mine	22	0.12
00TB04s	Mt. Tobin mine, stream sediment 6,000 m below mine	0.16	n.a.
00TB05s	Mt. Tobin mine, stream sediment 8,000 m below mine	0.23	n.a.
99SLV1ca	Silver Cloud mine-waste calcines	3.0	n.a.
99SLV2ca	Silver Cloud mine-waste calcines	17	n.a.
99SLV1rt	Silver Cloud mine-waste calcines inside small retort	180	n.a.
99SLV01s	Silver Cloud mine, stream sediment 150 m below mine	18	n.a.
99SLV01s	Silver Cloud mine, stream sediment 2,000 m below mine	8.8	n.a.
00BU01ca	Butte mine-waste calcines	79	0.07
00BU02ca	Butte mine-waste calcines	14	< 0.05
00BU03ca	Butte mine-waste calcines	45	n.a.

Table 2. Mercury data for mine-waste calcines and sediment samples collected from selected mercury mines, the Humboldt River, Rye Patch Reservoir, and Rock Creek—*Continued*.

Sample number	Location/description	Hg ($\mu\text{g/g}$)	Methyl-Hg (ng/g)
99GLB1ca	Goldbanks mine-waste calcines	2.5	n.a.
99GLB2ca	Goldbanks mine-waste calcines	10	n.a.
99GLB1s	Goldbanks mine, stream sediment 300 m below mine	2.6	n.a.
99GLB2s	Goldbanks mine, stream sediment 1,000 m below mine	2.2	n.a.
99GLB3s	Goldbanks mine, stream sediment 4,000 m below mine	0.24	n.a.
99GLB4s	Goldbanks mine, stream sediment 5,000 m below mine	0.60	n.a.
99BCK1ca	Bottle Creek mine-waste calcines	7.8	n.a.
99BCK2ca	Bottle Creek mine-waste calcines	5.4	n.a.
99BCK3ca	Bottle Creek mine-waste calcines	210	n.a.
99PER1ca	Pershing mine-waste calcines	11	n.a.
99PER2ca	Pershing mine-waste calcines	9.3	n.a.
99PER3ca	Pershing mine-waste calcines	13	n.a.
99PER1rt	Pershing mine-waste calcines	310	n.a.
99ANT1ca	Juniper mine-waste calcines	3.6	n.a.
99ANT2ca	Juniper mine-waste calcines	43	n.a.
99ANT2ca	Juniper mine-waste calcines	100	n.a.
00McD1ca	McDermitt mine-waste calcines	1,200	88, 92, 96 ^a
00McD2ca	McDermitt mine-waste calcines	40	6.8, 6.0 ^a
00McD3ca	McDermitt mine-waste calcines	1,400	0.58
01McD1ca	McDermitt mine-waste calcines	1,400	19
01McD2ca	McDermitt mine-waste calcines	200	0.88
01McD3ca	McDermitt mine-waste calcines	330	0.19
01McD4rt	McDermitt mine-waste calcines inside small retort	14,000	4.3
01HMB1	Humboldt River, stream sediment	0.008	0.072
01HMB2	Humboldt River, stream sediment	0.05	n.a.
01HMB3	Humboldt River, stream sediment	0.05	n.a.
01HMB4	Humboldt River, stream sediment	0.01	n.a.
01HMB5	Humboldt River, stream sediment	0.01	n.a.
00HMB6	Humboldt River, stream sediment	0.017	< 0.05
00HMB7	Humboldt River, stream sediment	0.014	< 0.05
00HMB8	Humboldt River, stream sediment	0.016	0.077
00HMB9	Humboldt River, stream sediment	0.080	n.a.
00HMB10	Humboldt River, stream sediment	0.010	< 0.05
00HMB11	Humboldt River, stream sediment	0.017	< 0.05
00HMB12	Humboldt River, stream sediment	0.019	< 0.05, < 0.05 ^a
01HMB13	Humboldt River, stream sediment	0.10	n.a.
00HMB14	Humboldt River, stream sediment	0.28	n.a.
00HMB15	Humboldt River, stream sediment	0.021	< 0.05
99RYP1	Rye Patch Reservoir, lake sediment	0.15	n.a.
99RYP2	Rye Patch Reservoir, lake sediment	0.05	n.a.
99RYP3	Rye Patch Reservoir, lake sediment	0.07	n.a.
99RYP4	Rye Patch Reservoir, lake sediment	0.09	n.a.
99RYP5	Rye Patch Reservoir, lake sediment	0.09	n.a.
01RYP6	Rye Patch Reservoir, lake sediment	0.004	0.090
00RC01	Rock Creek, baseline stream sediment	0.44	n.a.
00RC02	Rock Creek, baseline stream sediment	0.27	n.a.

Table 3. Geochemical data for water samples collected from two mercury mines, the Humboldt River, Rye Patch Reservoir, and Rock Creek.[Sample-number prefixes indicate collection date, e.g., 99 = 1999. NTU, nephelometric turbidity units; n.a., not analyzed; ^a, replicate analyses]

Sample number	Location/description	Hg (ng/L)	Methyl-Hg (ng/L)	pH	Conductivity (μ S/cm)	Turbidity (NTU)
99BJK1	Eldorado mine, unfiltered stream water 100 m below mine	8.0	n.a.	8.6	350	5
99BJK2	Eldorado mine, unfiltered stream water 500 m below mine	6.0	n.a.	8.7	330	8
01BJK1	Eldorado mine, unfiltered stream water above mine	3.1	0.039	8.3	350	10
01BJK2	Eldorado mine, unfiltered stream water 100 m below mine	13	0.11	8.6	350	10
01BJK3	Eldorado mine, unfiltered stream water 500 m below mine	8.7	0.89	8.7	380	10
99BJK1	Eldorado mine, filtered stream water 100 m below mine	< 5.0	n.a.	8.6	n.a.	n.a.
99BJK2	Eldorado mine, filtered stream water 500 m below mine	< 5.0	n.a.	8.7	n.a.	n.a.
00TB01	Mt. Tobin mine, unfiltered stream water 50 m below mine	80	n.a.	8.5	440	2
00TB02	Mt. Tobin mine, unfiltered stream water 400 m below mine	130	n.a.	8.4	485	5
00TB03	Mt. Tobin mine, unfiltered stream water 1,500 m below mine	120	n.a.	8.6	510	7
01TB01	Mt. Tobin mine, unfiltered stream water 50 m below mine	55	0.20	8.5	440	2
01TB02	Mt. Tobin mine, unfiltered stream water 400 m below mine	388	0.49	8.4	450	5
01TB03	Mt. Tobin mine, unfiltered stream water 1,500 m below mine	330, 305 ^a	0.60	8.6	450	10
01TB04	Mt. Tobin mine, unfiltered stream water 6,000 m below mine	2,000	0.92, 0.89 ^a	8.2	470	20
00TB01	Mt. Tobin mine, filtered stream water 50 m below mine	< 5.0	n.a.	8.5	n.a.	n.a.
00TB02	Mt. Tobin mine, filtered stream water 50 m below mine	< 5.0	n.a.	8.4	n.a.	n.a.
00TB03	Mt. Tobin mine, filtered stream water 50 m below mine	< 5.0	n.a.	8.6	n.a.	n.a.
01HMB1	Humboldt River, unfiltered stream water	6.0	0.19, 0.21 ^a	8.7	550	40
99HMB2	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.2	600	90
99HMB3	Humboldt River, unfiltered stream water	8.0	n.a.	8.4	630	150
99HMB4	Humboldt River, unfiltered stream water	9.0	n.a.	8.3	660	150
99HMB5	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.6	840	50
01HMB6	Humboldt River, unfiltered stream water	5.0	< 0.02	8.5	400	40
00HMB7	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.5	400	50
01HMB8	Humboldt River, unfiltered stream water	2.2, 2.3 ^a	0.19	8.6	480	40
00HMB9	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.5	420	70
01HMB10	Humboldt River, unfiltered stream water	6.9	< 0.02, 0.02 ^a	8.6	1000	150
00HMB11	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.5	810	150
00HMB12	Humboldt River, unfiltered stream water	6.0	n.a.	8.5	800	120
00HMB13	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.6	770	140
00HMB14	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.5	860	150
00HMB15	Humboldt River, unfiltered stream water	< 5.0	n.a.	8.4	490	100
01HMB1	Humboldt River, filtered stream water	< 5.0	n.a.	8.7	n.a.	n.a.
99HMB2	Humboldt River, filtered stream water	< 5.0	n.a.	8.2	n.a.	n.a.
99HMB3	Humboldt River, filtered stream water	< 5.0	n.a.	8.4	n.a.	n.a.
99HMB4	Humboldt River, filtered stream water	< 5.0	n.a.	8.3	n.a.	n.a.
99HMB5	Humboldt River, filtered stream water	< 5.0	n.a.	8.6	n.a.	n.a.
00HMB6	Humboldt River, filtered stream water	< 5.0	n.a.	8.5	n.a.	n.a.
00HMB7	Humboldt River, filtered stream water	< 5.0	n.a.	8.5	n.a.	n.a.
00HMB8	Humboldt River, filtered stream water	< 5.0	n.a.	8.6	n.a.	n.a.
00HMB9	Humboldt River, filtered stream water	< 5.0	n.a.	8.5	n.a.	n.a.
00HMB10	Humboldt River, filtered stream water	< 5.0	n.a.	8.6	n.a.	n.a.
00HMB11	Humboldt River, filtered stream water	< 5.0	n.a.	8.5	n.a.	n.a.
00HMB12	Humboldt River, filtered stream water	< 5.0	n.a.	8.5	n.a.	n.a.
00HMB13	Humboldt River, filtered stream water	< 5.0	n.a.	8.6	n.a.	n.a.
00HMB14	Humboldt River, filtered stream water	< 5.0	n.a.	8.5	n.a.	n.a.
00HMB15	Humboldt River, filtered stream water	< 5.0	n.a.	8.4	n.a.	n.a.
99RYP1	Rye Patch Reservoir, unfiltered lake water	8.0	n.a.	8.5	730	140
99RYP2	Rye Patch Reservoir, unfiltered lake water	8.0	n.a.	8.5	730	140
99RYP3	Rye Patch Reservoir, unfiltered lake water	5.0	n.a.	8.6	740	80
99RYP4	Rye Patch Reservoir, unfiltered lake water	< 5.0	n.a.	8.6	780	40
99RYP5	Rye Patch Reservoir, unfiltered lake water	< 5.0	n.a.	8.6	820	50
00RYP6	Rye Patch Reservoir, unfiltered lake water	5.5	< 0.02	8.6	800	100

Table 3. Geochemical data for water samples collected from two mercury mines, the Humboldt River, Rye Patch Reservoir, and Rock Creek—*Continued.*

Sample number	Location/description	Hg (ng/L)	Methyl-Hg (ng/L)	pH	Conductivity (μS/cm)	Turbidity (NTU)
01RYP6	Rye Patch Reservoir, unfiltered lake water	2.1	0.27	8.6	780	80
99RYP1	Rye Patch Reservoir, filtered lake water	5.0	n.a.	8.5	n.a.	n.a.
99RYP2	Rye Patch Reservoir, filtered lake water	< 5.0	n.a.	8.5	n.a.	n.a.
99RYP3	Rye Patch Reservoir, filtered lake water	< 5.0	n.a.	8.6	n.a.	n.a.
99RYP4	Rye Patch Reservoir, filtered lake water	< 5.0	n.a.	8.6	n.a.	n.a.
99RYP5	Rye Patch Reservoir, filtered lake water	< 5.0	n.a.	8.6	n.a.	n.a.
00RC01	Rock Creek baseline, unfiltered stream water	< 5.0	n.a.	9.4	350	5
00RC02	Rock Creek baseline, unfiltered stream water	< 5.0	n.a.	9.8	360	5

to vary from approximately 300 m³ (at Dutch Flat, the smallest mine studied) to greater than 1,000,000 m³ (at McDermitt, the largest mine studied). Using these volumes and the mercury concentrations determined in samples of calcine collected from the mines, there is about 1 t of mercury remaining in the calcine at the Dutch Flat mine, and greater than 1,000 t of mercury in calcine at the McDermitt mine. Thus, there is a large amount of mercury remaining in the mine-waste piles that is potentially available for leaching, downstream transport, and possible conversion to other forms of mercury.

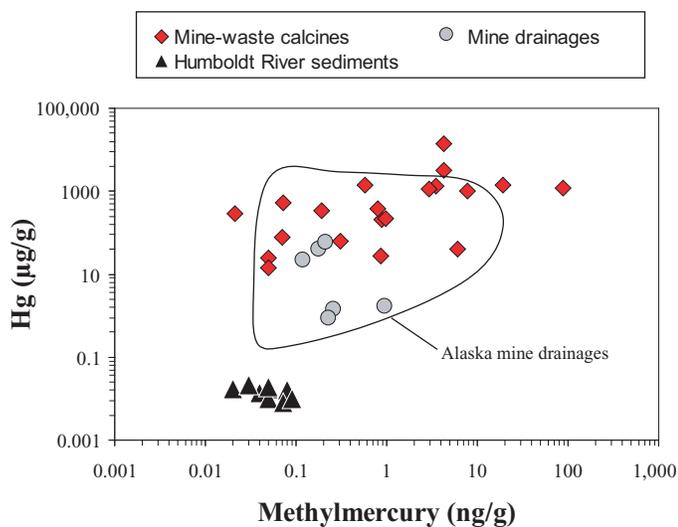


Figure 4. Mercury versus methylmercury concentration in mine-waste calcine, mine-drainage sediments, and Humboldt River sediment samples. The range of data for mine-drainage sediments collected from mercury mines in Alaska (Gray and others, 2000) are shown for reference.

Stream- and Lake-Sediment Samples

Stream-sediment samples collected within 1 km of the mines studied contain mercury concentrations as high as 170 μg/g (Cahill mine, table 2). Such samples are highly elevated in mercury when compared to stream sediments collected distant from the mines (several kilometers), such as the Rock Creek regional geochemical baseline site and the Humboldt River, both of which have mercury concentrations of less than 0.44 μg/g (table 2, fig. 5A). Few structures were observed to keep on-site mine-waste materials from eroding down gradient, and as a result, calcine and ore-bearing detritus were visible in streambeds below most mines. However, the concentration of mercury in stream sediments collected below the mines is generally lower than that in calcine material from the corresponding mine. For example, although calcine material from the Eldorado mine contains as much as 1,300 μg/g mercury, stream sediment collected about 100 m downstream from the mine contains only 1.7 μg/g mercury, and sediment collected about 2 km below the mine contains 0.87 μg/g mercury (table 2, fig. 5B). The Eldorado mine is located about midway along Eldorado Creek, which is a large drainage basin with a stream length of about 10 km. Thus, sediment transported downstream from the Eldorado mine is significantly diluted by barren (unmineralized) detritus in this large drainage basin, as evidenced by the mercury data for stream-sediment samples collected from Eldorado Creek. Stream-sediment samples collected downstream from the Mt. Tobin mine show a similar pattern (fig. 5C). Perhaps most importantly, sediment samples collected from the Humboldt River and Rye Patch Reservoir contain mercury concentrations of less than 0.28 μg/g (table 2). These results are not overly surprising because the mercury mines are located more than 8 km from the Humboldt River and Rye Patch Reservoir, and as a result, mercury is dispersed and significantly diluted before it reaches the Humboldt River system.

Methylmercury contents in sediment samples show a pattern similar to that of mercury in sediments. The only

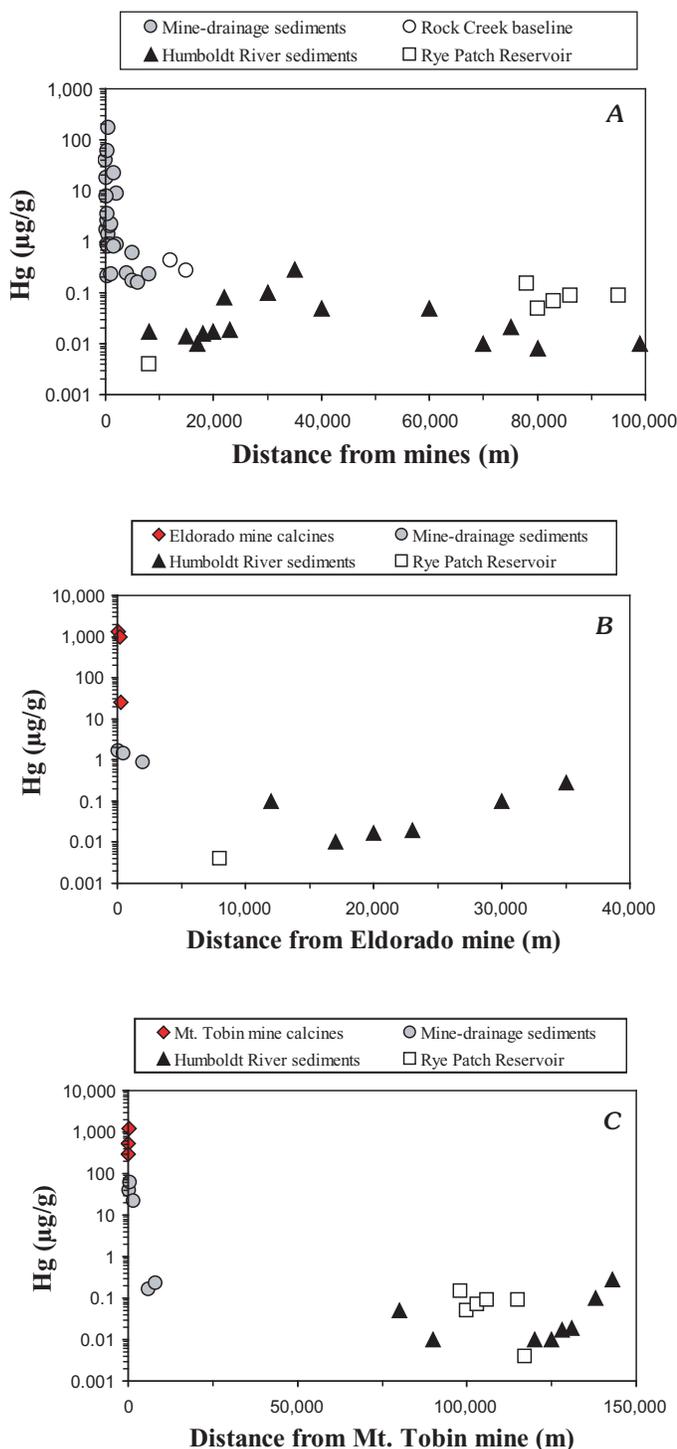


Figure 5. Mercury in sediments versus distance from mines for A, all mine drainages; B, the Eldorado mine; and C, the Mt. Tobin mine. The distance plotted in A for samples collected from the Humboldt River and Rye Patch Reservoir is that to the nearest upstream mercury mine. These data document dilution of mercury below the mercury mines in this study.

mine-drainage sediments analyzed for methylmercury were those collected from the Eldorado and Mt. Tobin mines, but methylmercury content in these samples are generally lower (0.12 to 0.95 ng/g) than that found in the upstream mine-waste calcine (<0.05–7.7 ng/g). Sediment samples collected from the Humboldt River and Rye Patch Reservoir generally contain the lowest methylmercury contents (<0.05–0.090 ng/g) of the sediments collected in this study.

Stream- and Lake-Water Samples

Stream water was found flowing at only the Eldorado and Mt. Tobin mine sites. During fieldwork in the summers of 1999–2001, Eldorado Creek was dry about 1 km below the mine, whereas water flowed for about 6 km downstream from the Mt. Tobin mine. Mercury concentrations in unfiltered water collected downstream from these mines range from 6.0 to 2,000 ng/L; all filtered mine-water samples have mercury contents of ≤ 5.0 ng/L (table 3). These results suggest transport of mercury primarily as finely suspended matter (probably finely particulate cinnabar or mercury adsorbed to suspended matter) downstream from these mines for short distances until the water flow dissipates. Mercury contents actually increase in unfiltered water collected downstream from the Mt. Tobin mine, which is probably due to abundant domestic animal activity (grazing livestock) in this area, resulting in significant disruption of the stream bed, more suspended organic particulates, and an increase in downstream water turbidity. Mercury concentrations in all of the unfiltered stream- and lake-water samples collected from the Humboldt River system were generally lower (≤ 5.0 to 9.0 ng/L) than those in the mine waters (fig. 6); all filtered water samples collected from the Humboldt River system had mercury concentrations of less than 5.0 ng/L. Unfiltered water samples collected from the Rock Creek baseline sites had mercury contents of less than 5.0 ng/L (table 3).

Methylmercury concentrations in unfiltered water collected downstream from the Eldorado and Mt. Tobin mines varied from 0.11 to 0.92 ng/L (table 3, fig. 6). Methylmercury concentrations in unfiltered water samples collected from the Humboldt River and Rye Patch Reservoir ranged from <0.02 to 0.27 ng/L; these concentrations are generally lower than those observed in water collected downstream from the mercury mines studied.

Water-Leach Studies

Highly variable and elevated concentrations of mercury were found in some of the leachates obtained from the mine-waste calcine samples (fig. 7). For example, three leachates of calcine samples obtained from the Silver Cloud mine contained from 0.2 to 1,500 $\mu\text{g/L}$ mercury—this represents leachates with the highest and one of the lowest mercury concentrations determined in this study (table 4). Leachates obtained from three calcine samples collected from the McDermitt mine

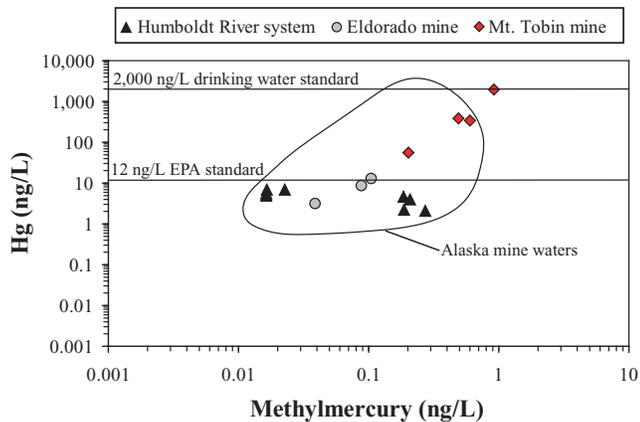


Figure 6. Mercury versus methylmercury concentration in unfiltered water samples collected downstream from the Eldorado and Mt. Tobin mines, and from the Humboldt River and Rye Patch Reservoir. The range of data for unfiltered water samples collected from mercury mines in Alaska (Gray and others, 2000), the State of Nevada drinking-water standard, and the EPA criterion continuous-concentration standard established to protect against *chronic* effects of mercury to aquatic wildlife are shown for reference.

contained somewhat lower mercury concentrations (0.2–21 $\mu\text{g/L}$). The concentration of mercury in these leachates is highly elevated when compared to that found in the natural surface waters examined in this study. There is no consistent correlation between leachate mercury concentrations and mercury contents in the corresponding calcine leached, or between leachate mercury concentrations and the type of ore processed from the various mines (Gray and others, 2002). Leaching of soluble mercury from these mine-waste calcines is most likely due to the presence of soluble mercury salts, which were reported in previous studies that identified mercury chlorides and oxychlorides at several mines in this region (Bailey and Phoenix, 1944).

Conductivity (25–3,800 $\mu\text{S/cm}$) and pH (3.2–9.9) measured in the leachates also varied widely (table 4). Although the two leachates with the highest conductivities, 3,800 and 3,400 $\mu\text{S/cm}$, also contain high mercury concentrations (1,500 and 81 $\mu\text{g/L}$, respectively) the overall correlation between high conductivity and mercury concentration is weak (table 4). There is also a poor correlation between leachate mercury concentration and pH (fig. 7), indicating that mercury concentration is not solely controlled by the capacity of the calcine samples to generate acid.

Discussion

The primary environmental concerns regarding mercury mines in Nevada are downstream transport of mercury and conversion of mercury to water soluble, bioavailable forms such as

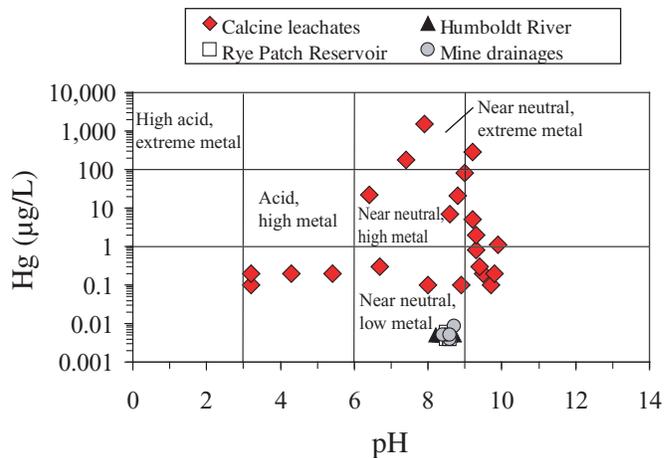


Figure 7. Mercury concentration versus pH in filtered water samples of leachates from mine-waste calcine and filtered water samples collected from the Humboldt River, Rye Patch Reservoir, and mine drainages. Mercury concentrations in the leachates are highly variable; some plot in the near-neutral, extreme-metal field. All natural surface-water samples collected plot in the near-neutral, low-metal field.

methylmercury. At the mines studied, there is minor cinnabar visible in the area of the open-pit cuts, adits, trenches, in a few outcrops, and in mine-waste calcine. Fine-grained and encapsulated cinnabar observed in many of the calcine piles, and the high variability of mercury within samples of calcine from individual mines, probably indicates that retorting was not totally or uniformly efficient and that mercury byproduct compounds are present in calcine. Detrital cinnabar and mine-waste calcine are clearly visible in stream drainages below the mines, indicating that mercury is eroding downstream from the mines. Mercury concentrations in stream-sediment samples were significantly lower than those in mine-waste calcine collected from the corresponding mine, and thus, sediments show substantial dispersion of mercury downstream from the mines. Although mercury contents in mine-waste calcine (as much as 14,000 $\mu\text{g/g}$) and stream-sediment samples (as much as 170 $\mu\text{g/g}$) collected at or near the mines are highly elevated, the dominant form of the mercury is cinnabar (HgS), which is generally resistant to chemical and physical weathering (Gray and others, 2000). In addition, acid-water-generating sulfide minerals, such as pyrite, are rare in the mercury ores and mine wastes. Thus, the potential for acid-water generation near these mines is minimal even during high-flow runoff, which is important because cinnabar is more soluble in acidic conditions (Gray and others, 2003). During this study, elemental mercury, which is more chemically reactive than cinnabar, was not observed around retorts or rotary furnaces at any of the mines studied. The absence of elemental mercury at these sites may be related to the hot, arid climate and relative age of these mines (i.e., most of these mines have been inactive for several decades), and thus, elemental mercury may have evaporated over time.

Table 4. Geochemical data for filtered water leachates of mine-waste samples collected from several mercury mines.

Sample number	Location/description	Hg ($\mu\text{g/L}$)	pH	Conductivity ($\mu\text{S/cm}$)
99DFL1ca	Dutch Flat mine-waste calcines, leachate	175	7.4	270
99DFL1rt	Dutch Flat mine-waste calcines inside small retort, leachate	0.10	3.2	1,500
99CAH1ca	Cahill mine-waste calcines, leachate	0.10	9.7	160
99CAH3ca	Cahill mine-waste calcines, leachate	0.30	9.4	100
99CAH1rt	Cahill mine-waste calcines inside small retort, leachate	2.0	9.3	1,700
99BJK1ca	Eldorado mine-waste calcines, leachate	5.0	9.2	130
99BJK2ca	Eldorado mine-waste calcines, leachate	0.10	8.9	70
99BJK1rt	Eldorado mine-waste calcines inside small retort, leachate	0.30	9.2	390
99SLV1ca	Silver Cloud mine-waste calcines, leachate	0.20	5.4	25
99SLV2ca	Silver Cloud mine-waste calcines, leachate	0.80	9.3	40
99SLV1rt	Silver Cloud mine-waste calcines inside small retort, leachate	1,500	7.9	3,800
99GLB1ca	Goldbanks mine-waste calcines, leachate	0.20	9.5	85
99GLB2ca	Goldbanks mine-waste calcines, leachate	0.10	8.0	80
99BCK1ca	Bottle Creek mine-waste calcines, leachate	7.0	7.8	95
99BCK3ca	Bottle Creek mine-waste calcines, leachate	290	9.2	80
99PER1ca	Pershing mine-waste calcines, leachate	0.20	9.8	290
99PER1rt	Pershing mine-waste calcines inside small retort, leachate	81	9.0	3,400
99ANT1ca	Juniper mine-waste calcines, leachate	1.1	9.9	940
99ANT3ca	Juniper mine-waste calcines, leachate	22	6.4	2,100
99MCD1ca	McDermitt mine-waste calcines, leachate	21	8.8	65
99MCD2ca	McDermitt mine-waste calcines, leachate	0.20	4.3	190
99MCD3ca	McDermitt mine-waste calcines, leachate	0.20	3.2	1,700

Methylmercury concentrations in mine waste, water, and sediment collected from in and around the mines are more environmentally important than total mercury contents because methylmercury is highly toxic to organisms (National Academy of Sciences, 1978; Eisler, 1987; U.S. Environmental Protection Agency, 2001). Similar to the results for mercury, methylmercury contents in stream sediments collected downstream from mines are generally lower than methylmercury in corresponding mine-waste calcine (table 2). More importantly, methylmercury contents in sediments collected from the Humboldt River were the lowest found in the study (fig. 4). Methylmercury results for mine-drainage sediment and the Humboldt River indicate significantly lower mercury methylation in stream environments both proximal and distal from the mercury mines when compared to methylmercury in mine-waste calcine.

Mercury concentrations in unfiltered water samples collected from the Humboldt River and Rye Patch Reservoir (2.1–9.0 ng/L) are below several important environmental and health standards including (1) the 2,000-ng/L State of Nevada

drinking-water standard for mercury (Nevada Division of Environmental Protection, 2001), (2) the 2,400-ng/L mercury standard recommended by the EPA to protect against *acute* effects to aquatic wildlife, and (3) the 12-ng/L mercury standard recommended by the EPA to protect against *chronic* effects to aquatic wildlife (U.S. Environmental Protection Agency, 1992) (fig. 6). The concentration of mercury in water samples collected downstream from the Eldorado and Mt. Tobin mercury mines is generally higher than that in the Humboldt River (fig. 6). Mercury concentrations in the mine-water samples was equal to or less than the State of Nevada drinking-water standard and less than the EPA *acute* aquatic-life standard for mercury. However, mercury concentrations in several of the mine-water samples exceed the 12-ng/L EPA mercury standard to protect against *chronic* effects to aquatic wildlife, especially stream water collected from the Mt. Tobin mine (fig. 6). Similarly, leachates obtained from calcine samples contained variable and some highly elevated mercury concentrations (fig. 7), and some of these concentrations are significantly higher than the 2,000 ng/L State of Nevada drinking-water standard for

mercury. The leachate data indicate that there are water-soluble forms of mercury in some mine-waste calcine samples or that finely particulate mercury-bearing material passed through the 0.45- μm filter during leachate filtration. Leachates produced in this study probably represent the maximum mercury concentrations that can be obtained by water leaching of the mine-waste calcine because the EPA-1312 method is a rigorous leaching technique that includes rotation and agitation and a 20:1 water-to-sample ratio.

Methylmercury concentrations in unfiltered water samples collected from the Humboldt River and Rye Patch Reservoir generally had the lowest methylmercury contents in this study (fig. 6). Conversely, results for the sediment and water samples indicate significant local methylation at mine sites. However, downstream transport of methylmercury in this arid region is limited by the lack of mine-water runoff. Of all the mines studied, stream water was observed only at the Eldorado and Mt. Tobin mines, and both of these streams were ephemeral and dry within a few kilometers of these mines. Thus, mine-water runoff is hydrologically disconnected from the Humboldt River system because such water does not flow directly into the Humboldt River. Surface-water runoff from all mercury mines in this region is rapidly diluted and infiltrates into broad areas of desert pediment before reaching the Humboldt River (fig. 3A). This is true even during periods of high precipitation, such as storm events or spring runoff, because the mines are distant from the Humboldt River (fig. 1). In addition, stream water below the mines studied and that from the Humboldt River is alkaline (pH 8.2–8.7), and under such conditions, cinnabar generally has a low solubility. Proximal to most cinnabar-dominant mercury mines, mercury transport is mostly as finely suspended particulate cinnabar (Gray and others, 2000; Gray and others, 2002).

The concentrations of mercury and methylmercury in mine-waste calcine and mine-drainage sediments collected in this study are similar to those found in other mercury mines in the United States, for example in Alaska (Gray and others, 2000), although the methylmercury concentrations in calcine from the McDermitt mine are as much as several times those observed in samples from Alaska. The climatic settings of Nevada and Alaska are clearly different (arid versus subarctic), but the mercury mines in both regions are mineralogically similar because they both are hot-springs mineral deposits where ore is dominantly cinnabar (Gray and others, 1997). High local methylmercury concentrations in mercury-bearing mine wastes in Nevada suggest higher methylation in this climate where annual temperatures are higher, with possibly more microbial activity, resulting in greater methylation. Concentrations of mercury and methylmercury in mine water collected in this study are also comparable to those found in mine waters from Alaska. In Alaska, several of the mercury mines are located proximal to aquatic ecosystems that support freshwater fish and salmon, and in some instances, fish collected from such streams contain elevated concentrations of mercury ($>0.5 \mu\text{g/g}$, Gray and others, 2000). However, in Nevada, streams proximal to the mercury mines studied are small and ephemeral and do not contain fish. Thus, in this region of

Nevada, the transference of significant methylmercury from mine-waste calcine to stream sediments, to stream water, and then to biota such as fish, is unlikely. Presently, there are no advisories for elevated mercury in fish on any water body in the Humboldt River system. Data presented here, which generally show low mercury and methylmercury contents in samples collected from the Humboldt River are consistent with the lack of advisories on the Humboldt River.

Summary

Results in this study indicate minimal adverse environmental effects to the Humboldt River ecosystem from mercury mines in Nevada because

- The primary mercury ore mineral is cinnabar, which is resistant to physical and chemical weathering. Elemental mercury, which is more reactive than cinnabar, was not observed at any of the mines studied.
- The climate in the study area is arid, and there is rarely runoff from the mines. Mine drainage was found at only 2 of the 14 mines studied, and drainage from these mines dissipated a few kilometers downstream.
- Samples of mine-waste calcine contain locally high concentrations of mercury and methylmercury, but stream-sediment samples collected downstream from the mines had generally lower mercury and methylmercury contents; these results indicate only minor, local downstream transference of mercury and methylmercury. Sediments collected from the Humboldt River and Rye Patch Reservoir had the lowest mercury and methylmercury contents in this study.
- Leachates from calcine collected from several of the mines generated variable, but in some instances significant, mercury concentrations (as much as $1,500 \mu\text{g/L}$) during water-leaching experiments. However, natural runoff from the mercury mines has little influence on the major watersheds because mercury concentrations in water samples from the Humboldt River are much lower ($<9.0 \text{ ng/L}$).
- The mines are distant from the Humboldt River, and mine runoff does not flow directly into the Humboldt River. In addition, mercury in water and sediment is transported and diluted through a significant volume of pediment before it reaches the Humboldt River.

References

- Bailey, E.H., and Phoenix, D.A., 1944, Quicksilver deposits in Nevada: Nevada Bureau of Mines, Geology and Mining Series No. 41, 206 p.
- Biester, H., Gosar, M., and Muller, G., 1999, Mercury speciation in tailings of the Idrija mine: *Journal of Geochemical Exploration*, v. 65, p. 195–204.

- Bloom, N.S., 1989, Determination of picogram levels of methylmercury by aqueous phase ethylation, followed by cryogenic gas chromatography with cold vapor atomic fluorescence detection: *Canadian Journal of Fisheries and Aquatic Science*, v. 7, p. 1131–1140.
- Bloom, N.S., Colman, J.A., and Barber, L., 1997, Artifact formation of methylmercury during aqueous distillation and alternative techniques for the extraction of methylmercury for environmental samples: *Fresenius Journal of Analytical Chemistry*, v. 358, p. 371–377.
- Bloom, N.S., and Fitzgerald, W.F., 1988, Determination of volatile mercury species at the picogram level by low-temperature gas chromatography with cold-vapour atomic fluorescence detection: *Analytica Chimica Acta*, v. 208, p. 151–161.
- Compeau, C.C., Bartha, R.A., 1985, Sulfate reducing bacteria: Principal methylators of mercury in anoxic estuarine sediment: *Applied Environmental Microbiology*, v. 50, p. 498–502.
- Eisler, R., 1987, Mercury hazards to fish, wildlife, and invertebrates: A synoptic review: U.S. Fish and Wildlife Service Biological Report 85 (1.10), 90 p.
- Gray, J.E., Adams, M.G., Crock, J.G., and Theodorakos, P.M., 1999, Digital geochemical data for environmental studies of mercury mines in Nevada: U.S. Geological Survey Open-File Report 99-576, CD-ROM, [or at URL <http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-99-0576/>].
- Gray, J.E., Crock, J.G., and Fey, D.L., 2002, Environmental geochemistry of abandoned mercury mines in west-central Nevada, USA: *Applied Geochemistry*, v. 17, p. 1069–1079.
- Gray, J.E., Gent, C.A., Snee, L.W., and Wilson, F.H., 1997, Epithermal mercury-antimony and gold-bearing vein deposits of southwestern Alaska: *Economic Geology Monograph* 9, p. 287–305.
- Gray, J.E., Greaves, I.A., Bustos, D.M., and Krabbenhoft, D.P., 2003, Mercury and methylmercury contents in calcine, water, and sediment collected from the Palawan Quicksilver mine, Palawan, Philippines: *Environmental Geology*, v. 43, p. 298–307.
- Gray, J.E., Theodorakos, P.M., Bailey, E.A., and Turner, R.R., 2000, Distribution, speciation, and transport of mercury in stream sediment, stream water, and fish collected near abandoned mercury mines in southwestern Alaska, USA: *Science of the Total Environment*, v. 260, p. 21–33.
- Gustin, M.S., Lindberg, S.E., Austin, K., Coolbaugh, M., Vette, A., and Zhang, H., 2000, Assessing the contribution of natural sources to regional atmospheric mercury budgets: *Science of the Total Environment*, v. 259, p. 61–71.
- Johnson, M.G., 1977, Geology and mineral deposits of Pershing County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 89, 115 p.
- Kennedy, K.R., and Crock, J.G., 1987, Determination of mercury in geological materials by continuous flow, cold-vapor, atomic-absorption spectrophotometry: *Analytical Letters*, v. 20, p. 899–908.
- Kim, C.S., Brown, G.E., Jr., and Rytuba, J.J., 2000, Characterization and speciation of mercury-bearing mine wastes using X-ray absorption spectroscopy: *Science of the Total Environment*, v. 260, p. 157–168.
- Lacerda, L.D., and Salomons, W., 1998, Mercury from gold and silver mining: A chemical time bomb?: Berlin, Springer-Verlag.
- National Academy of Sciences, 1978, An assessment of mercury in the environment: Washington, D.C., National Academy of Sciences, National Research Council.
- Nevada Division of Environmental Protection, 2001, Water pollution control: Nevada Bureau of Water Quality Planning, Chapter 445A, [URL <http://www.state.nv.us.ndep/bwqp/>].
- Noble, D.C., McCormack, J.K., McKee, E.H., Silberman, M.L., and Wallace, A.B., 1988, Time of mineralization in the evolution of the McDermitt caldera complex, Nevada-Oregon, and the relation of middle Miocene mineralization in the northern Great Basin to coeval regional basaltic magmatic activity: *Economic Geology*, v. 83, p. 859–863.
- Peabody, C.E., 1993, The association of cinnabar and bitumen in mercury deposits in the California Coast Ranges, *in* Parnell, J., Kucha, H., and Landais, P., eds., *Bitumens in ore deposits*: Berlin, Springer-Verlag, p. 179–209.
- U.S. Environmental Protection Agency, 1986, Test methods for evaluating solid waste: v. I and II (SW-846) (3rd ed.) November, 1986, [updates available through revision 2V, April 4, 1995].
- U.S. Environmental Protection Agency, 1992, Water quality standards; establishment of numeric criteria for priority toxic pollutants; states' compliance; final rule: Federal Register, 40 CFR Part 131, v. 57, no. 246, p. 60847–60916.
- U.S. Environmental Protection Agency, 2001, Water quality criterion for the protection of human health: Methylmercury: U.S. Environmental Protection Agency Report EPA-823-R-01-001.
- Willden, Ronald, 1964, Geology and mineral deposits of Humboldt County, Nevada: Nevada Bureau of Mines and Geology Bulletin 59, 154 p.

Manuscript approved for publication June 23, 2003

Published in the Central Region, Denver, Colorado

Editing, page layout, photocomposition—Richard W. Scott, Jr.

Graphics by the author