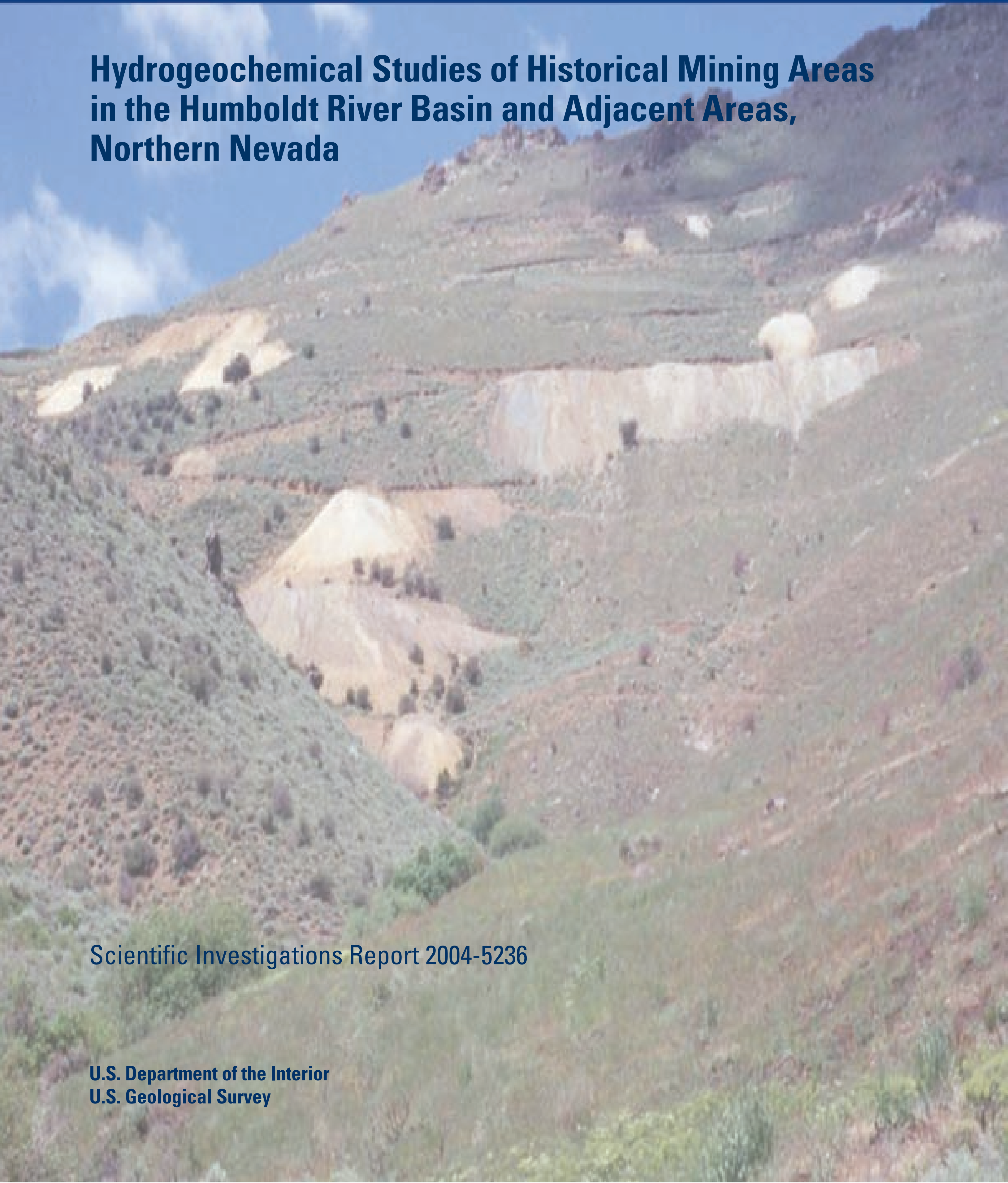

# Hydrogeochemical Studies of Historical Mining Areas in the Humboldt River Basin and Adjacent Areas, Northern Nevada

Scientific Investigations Report 2004-5236

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

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# Hydrogeochemical Studies of Historical Mining Areas in the Humboldt River Basin and Adjacent Areas, Northern Nevada

By J. Thomas Nash

## Abstract

Reconnaissance field studies were made at 50 historical mining districts in northern Nevada to determine the actual or potential contamination of surface or ground water by mine drainage water, mine-waste dumps, and mill tailings. The main focus of this report is on mining areas in the central Humboldt River Basin, from approximately Elko to Winnemucca, with coverage of adjacent or analogous mining areas. More than 650 new chemical analyses of mine water, mine waste and tailings, and leachates of those materials are described and interpreted to provide Federal land-management agencies and the public with concepts regarding sources of mining-related contamination and the extent of contamination. The new observations and geochemical data suggest that contamination is not nearly as common or widespread as postulated by some in the popular press. Out of the tens of thousands of small prospects, small mines, and some large mines on public lands, less than 1 percent of the historical sites pose significant threats to water quality, human health, or wildlife habitat.

Although there are tens of thousands of small prospects in northern Nevada, these small diggings generally release no more contamination than the same rocks prior to mining. Out of the hundreds of small- to medium-sized mines on public lands, only a few release acidic mine drainage or significant concentrations of metal contaminants. Large historical mines generally are on private property (patented mining claims) and were not sampled in this study, but only a small percentage are known to produce significant contamination. The approach in this investigation was to identify the largest accessible historical mine or mines in a district for observation and sampling and to seek the worst case of likely contamination. Field observations suggest that visible indicators of acidic mine drainage (such as red, iron-rich precipitates) are rare, and field measurements of pH and chemical analyses of several kinds of materials (dump rocks, tailings, surface water) indicate that only a few sites release acid or significant concentrations of metals. The most consistent observation at and near mining areas is neutral to weakly alkaline pH values (6.5 to 8.4) and water compositions attesting to significant amounts of carbonate derived from rocks, alluvium, and caliche-bearing soils. The alkalinity of surface water is sufficient to naturally mitigate local sources of acidic water by mixing; the neutralization processes induce reactions that greatly reduce the concentrations of most metals in the evolved water. There are, however, indications of elevated amounts of arsenic, molybdenum, and selenium that are mobile in weakly alkaline water. There is some risk for these elements to be cumulatively enriched in closed basins over many years, but the magnitude of that risk is beyond the scope of this investigation.

Acidic mine water loaded with toxic metals, asserted by the popular press to be common and typical of abandoned mines, actually is rare in northern Nevada. This study over 5 years, including several unusually wet spring seasons, found only 16 draining mine adits, and those had flow rates of less than 1 gallon per minute to about 20 gallons per minute. The small number of draining mine workings and the low flow relative to other mining areas are consistent with the vegetation and precipitation of the mine areas. The relatively low metal concentrations in the evolved mine water, compared to other mining regions, reflects the generally deep oxidation of sulfide minerals and the presence of carbonate minerals in wall rocks and soils that naturally mitigate acids. The findings here are similar to those of Price and others (“Water quality at inactive and abandoned mines in Nevada,” Nevada Bureau of Mines and Geology, Open-File Report 95–4, 1995), who estimated that less than about 0.05 percent of mines in Nevada create acidic, metal-rich drainage. In areas where drainage, ponds, or puddles have a pH of less than 3, the water takes on high to extremely high concentrations of many potentially toxic metals.

Mill tailings are among the largest potential sources of contaminants, in part because they typically were placed in canyons and arroyos where they are vulnerable to storm events. Reconnaissance field studies in and near the Humboldt River Basin have identified 83 mills and associated tailings impoundments related to historical mining. The majority of the mill and tailings sites are not recorded in the literature. All

tailings impoundments show evidence of substantial amounts of erosion. At least 11 tailings dams were breached by floodwater, carrying fluvial tailings 1 to 10 miles down canyons and across alluvial fans. Most of the tailings sites are dry most of the year, but some are near streams. Tailings that are wet part of the year do not appear to be reacting significantly with streamwater because physical factors such as clay layers and hardpan cement appear to limit permeability and release of metals to surface water. The major effect of mill tailings on surface-water quality may be brief flushes of runoff during storms events that carry acid and metals released from soluble mineral crusts. Small ephemeral ponds and puddles that collect in trenches and low areas on tailings impoundments tend to be acidic and extremely enriched in metals, in part through cycles of evaporation. Ponded water that is rich in salts and metals could be acutely toxic to unsuspecting animals. Rare extreme storms have the potential to cause catastrophic failure of tailings impoundments, carry away metals in stormwater, and transport tailings as debris flows for 1 to 10 miles. In most situations these stormwaters and transported tailings would affect wildlife but few or no people or domestic water wells. Because all identified historical tailings sites are several miles or more from the Humboldt River and major tributaries, tailings probably have no measurable effect on water quality in the main stem of the Humboldt River.

The processes that create acidic, metal-rich water in Nevada are the same as for other parts of the world, but the scale of transport and the fate of metals are much more localized because of the ubiquitous presence of caliche soils. The arid climate and associated soils of Nevada minimize the scale of acid-mine drainage that is common in other historical mining areas. Water quality in even the worst cases is naturally attenuated to near or below regulatory standard levels within 1 mile of the source. However, some unconventional processes that operate in Nevada need further study. Brief storms can dissolve mineral crusts on mine waste and tailings to create a "first flush" of runoff that could be harmful to wildlife or livestock. The prevailing alkaline water in this climate is capable of transporting significant concentrations of a suite of metals and metalloids that includes arsenic, molybdenum, selenium, and uranium either into local basins or sinks such as the Humboldt Sink, where they can become concentrated to toxic levels by plants or by evaporation. Careful study is needed of the multiple sources, transport, and fate of these metals.

## Introduction

Mining for more than 140 years in Nevada has produced a rich history of people and towns, bonanzas and busts. One of the legacies is inactive and abandoned mines, estimated to number between 225,000 and 310,000 (Price and others, 1995). Some say that the abandoned mines are the source of many contaminants and leak "poisons into the West's water" (Watkins, 2000), but field investigations indicate that a very small percentage (possibly 0.05 percent, Price and others, 1995) are sources of significant acid-mine drainage and related contaminants. What is the effect of historical mines on the environment, especially on the precious water resources of these arid lands? Reconnaissance geochemical studies of 50 historical mining areas in and near the Humboldt River Basin were undertaken by the author to provide objective information to help guide Federal land management agencies (FLMA's) in their response to requirements of the Clean Water Act and other national laws for water and environmental quality. The goal of this investigation is to use knowledge of mineral resources to predict where geochemical hazards may be caused by historical mining (Plumlee and Nash, 1995; Plumlee and others, 1999); to observe and sample those predicted sites; and to evaluate the new information and chemical results to understand processes that do or do not mobilize metals in the surficial environment. Descriptions of mining districts in this report focus on the central part of the Humboldt River Basin, but discussions later in the report use field observations and geochemical information for other parts of the basin and adjacent mining areas of northern Nevada.

The study area comprises the Humboldt River Basin and adjacent areas (fig. 1), with emphasis on mining areas relatively close to the Humboldt River (fig. 2). The basin comprises about 16,840 $mi^2$ or 10,800,000 acres. The mineral resources of the Humboldt Basin have been investigated by many scientists over the past 100 years, but only recently has our knowledge of regional geology and mine geology been applied to the understanding and evaluation of mining effects on water and environmental quality. The investigations reported here apply some of the techniques and perspectives developed in the Abandoned Mine Lands Initiative (AMLI) of the U.S. Geological Survey (USGS), a program of integrated geological-hydrological-biological-chemical studies underway in the Upper Animas River watershed in Colorado and the Boulder River watershed in, Montana (Buxton and others, 1997; Nimick and von Guerard, 1998). The goal of my studies of sites and districts is to determine the character of mining-related contamination that is actively or potentially a threat to water quality and to estimate the potential for natural attenuation of that contamination. These geology-based studies and recommendations differ in matters of emphasis and data collection from the biology-based assessments that are the cornerstone of environmental regulations. If the reconnaissance studies or interpretations reported here raise questions or concerns, followup work should be done using trace-element sampling protocols and more precise analytical methods. Additional studies, such as biological populations, may also be warranted by my reconnaissance studies.

*Acknowledgments.*—Discussions with the Bureau of Land Management (BLM) staff in district offices of northern Nevada provided helpful guidance regarding priorities on public lands. Steve Brooks, formerly of BLM's Winnemucca

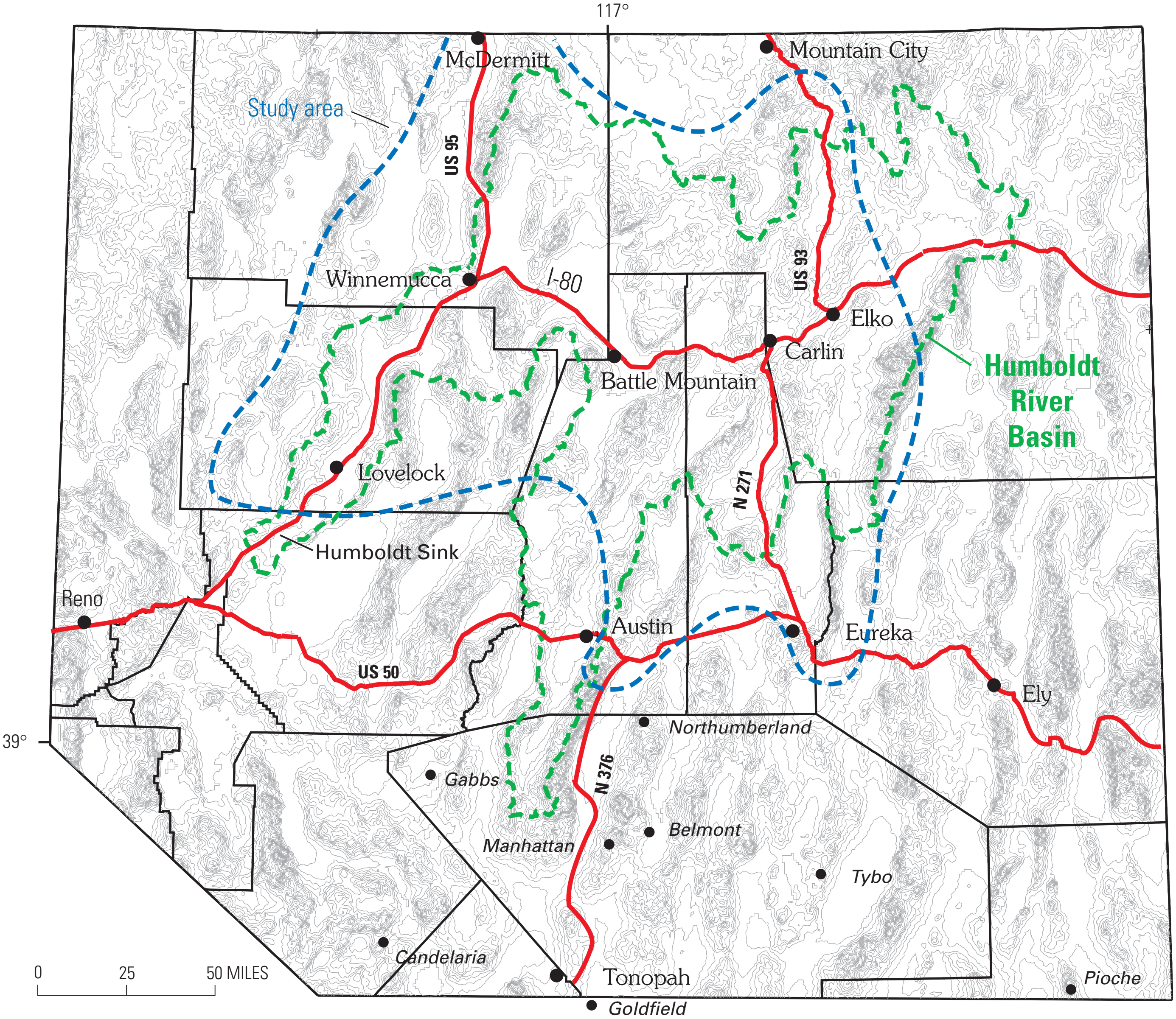

**Figure 1.** Index map of northern Nevada showing major towns and the study area. The Humboldt River Basin is outlined in green; names of mining districts studied in central Nevada are set in italics.

District Office, provided very helpful suggestions and technical information on abandoned mine sites. John Gray, Bill Miller, Lisa Stillings, and Alan Wallace[1] of the USGS offered helpful guidance during this project, and Steve Smith and Helen Folger, USGS, provided very helpful reviews of draft versions of this report. Errors of fact or interpretation that are in this report are the responsibility of the author; comments from persons with new or divergent information will be appreciated at *tnash@usgs.gov*.

## Study Methods

Field work for this study spanned more than 10 visits from September 1995 to June 2000. I also had visited many of the districts in previous years for investigations pertaining to mineral resource assessments. Sites visited and sampled were selected using published information, USGS records in the Mineral Resources Data System (MRDS), information on USGS 1:24,000-scale topographic maps, and by accessibility. Sample localities were recorded on the topographic maps and measured with a conventional GPS instrument having an accuracy of about ±100 to 150 ft based on tests at known sites. Analyzed samples are described in a spreadsheet file (Appendix 1), which also gives locations in latitude and longitude.

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[1] While this report was being prepared for publication an important report on mineral resources and geology was published and is a useful companion to this report: “Assessment of Metallic Resources in the Humboldt River Basin, Northern Nevada” (Wallace and others, 2004).

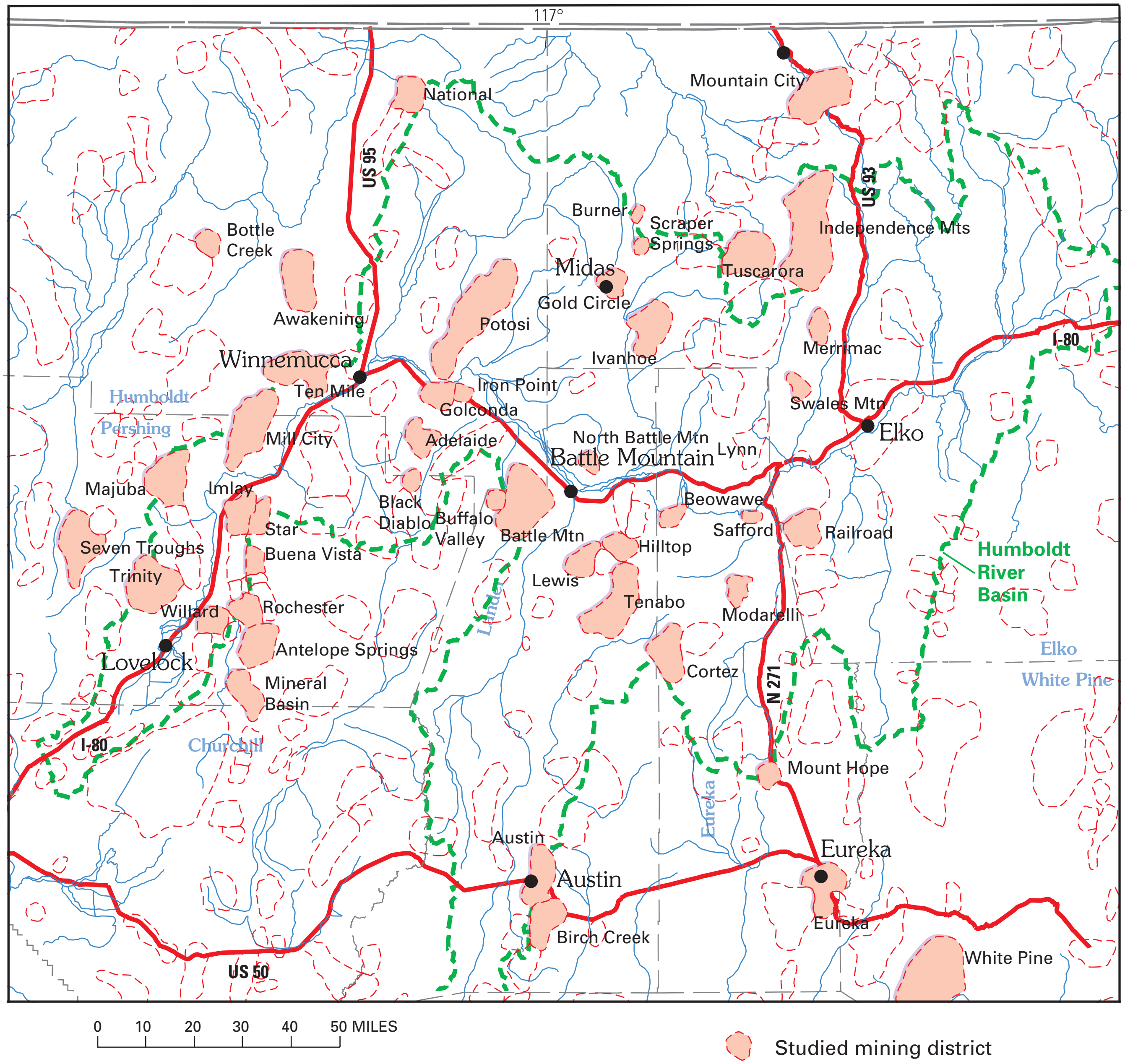

**Figure 2.** Location of historical mining districts in northern Nevada. District outlines are from Tingley (1998); studied districts are colored.

## Solids Chemistry

Solids samples were collected from mine dumps, outcrops, and mill tailings. In most cases the intent was to collect a representative sample, but for some sites a select sample was collected to determine a special property. The most commonly employed sampling method for dumps and tailings involved collecting numerous small portions at 20 to 30 subsites to derive a composite sample. The fraction that passed through a 2-mm stainless steel sieve was retained for analysis. This is the standard protocol developed for USGS-AMLI investigations of mine dumps (Nash, 1999; Fey and others, 2000).

Solids samples were prepared for analysis under the direction of Paul Lechler, Nevada Bureau of Mines and Geology, Reno, and analyzed by two commercial laboratories. In one method the solid samples are dissolved in a mixture of four acids, then the concentrations of 35 major and trace elements are determined using inductively coupled plasma-atomic emission spectrometry (ICP-AES); this is considered a total analysis as the strong acids dissolve all but the most refractory minerals such as zircon. This method is essentially that of Briggs and Fey (1996), although slight variations in method may exist between laboratories. Solid samples were also analyzed by a method that uses weaker acids to dissolve

**Table 1.** Summary of chemical analyses of dump, tailings, slag, and altered rock samples.

[Results are from ICP-AES analyses; for complete analyses see file NHGX.xls; >, greater than; <, less than; wt. %, weight percent; ppm, parts per million]

| Element | Dump (*n*=117) | | Tailings (*n*=45) | | Slag (*n*=5) | | Altered rocks (*n*=43) | |
|---|---|---|---|---|---|---|---|---|
| | Median | Maximum | Median | Maximum | Median | Maximum | Median | Maximum |
| Ag (ppm) | 34 | 1,082 | 37 | 708 | 8.5 | 375 | 0.7 | 14 |
| As (ppm) | 210 | 60,900 | 649 | 6,570 | 67 | 281 | 60 | 7,720 |
| Au (ppm) | 0.02 | 25.1 | 0.21 | 4.4 | 0.47 | 1.7 | 0.03 | 25.8 |
| Bi (ppm) | 1.3 | >9,800 | 0.7 | 982 | 0.4 | 20.6 | 1.4 | 250 |
| Cd (ppm) | 3.8 | 991 | 1.6 | 141 | 0.9 | 42 | 0.5 | 61 |
| Cu (ppm) | 143 | 91,400 | 68 | 3,350 | 500 | 32,400 | 61 | 3,070 |
| Fe (wt.%) | 4.2 | 47.6 | 2.1 | 22.0 | 20.1 | 21.4 | 2.65 | 36.8 |
| Hg (ppm) | 1.5 | 4,930 | 2.3 | 1,160 | <0.1 | 0.2 | 0.2 | 444 |
| Mn (ppm) | 277 | 29,340 | 167 | 5,040 | 1,000 | 7,625 | 166 | 14,300 |
| Mo (ppm) | 5.8 | 1,580 | 5.0 | 121 | 3.0 | 265 | 3.4 | 1,500 |
| Pb (ppm) | 211 | 33,900 | 490 | 42,800 | 50 | 12,200 | 16 | 4,750 |
| Sb (ppm) | 40 | 5,090 | 95 | 8,860 | 5.0 | 606 | 6.0 | 220 |
| Se (ppm) | 4.5 | >98 | 5.6 | 97 | <0.1 | 6.8 | 1.3 | 14 |
| Te (ppm) | 1.1 | 164 | 0.9 | 16 | <0.5 | 3.3 | 0.3 | 9.0 |
| Tl (ppm) | 2.5 | 19.9 | 1.3 | 3.9 | <0.5 | 2.6 | 1.2 | 3.9 |
| Zn (ppm) | 240 | 54,950 | 211 | 28,300 | 3,370 | 37,600 | 63 | 1,270 |

most minerals and then uses an organic reagent to collect 15 metals of interest (Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Pb, Sb, Se, Te, Tl, and Zn). Analysis is by ICP-AES; results are very similar to those of Motooka (1990) but include five additional elements. This second analytical method has lower levels of determination and works well for some elements, such as Hg, Sb, Se, Te, and Tl, that are not effectively determined by the total digestion method. Total sulfur, determined by combustion, was done on some samples but discontinued because the method does not discriminate among forms of sulfur (such as sulfide and sulfate) and thus does not provide as much information as desired for topics such as acid-generating potential. Quality-assurance monitoring by Lechler shows that the precision and accuracy (deviation of the reported concentrations from accepted values) is less than 5 percent for most elements. Analytical results of 232 chemical analyses of solid materials are summarized in table 1; complete results are in a spreadsheet file (Appendix 2) that is included with this report.

The analytical methods just described are useful for characterizing the chemical composition of solid materials, but those analyses generally do not indicate what elements may be soluble (mobile) in the near-surface environment. Another method was used to estimate the mobility of metals, described in the "Leachate Chemistry" section.

## Water Chemistry

Water samples were collected after testing for pH and conductivity with portable instruments. The methods are simplified from those described by Ficklin and Mosier (1999); no chemical determinations were made in the field. The pocket-sized conductivity meter (Corning CD-55), with an upper limit of 2,000 microsiemens per centimeter ($\mu$S/cm), responded consistently and showed no drift after calibration. The pH meter (Orion 250), with built-in temperature electrode, required frequent calibration during the day, and at most sites the calibration was checked on a standard solution after the field measurement. The field standards were buffered solutions of pH 4.0, 7.0, and 10.0. The field measurements of pH are considered to carry an uncertainty of about ±0.1 standard units, even though the meter reports to 0.01 unit. Water samples for chemical analysis were collected by a consistent technique adopted for reconnaissance investigations. The water was collected with a disposable 60-mL syringe, then pushed through a disposable 0.45-micrometer cellulose filter. The syringe and the 60- or 120-mL polyethylene bottle were rinsed twice in the sampled water collection. The filtered sample was acidified to a pH of about 2 at the site with 5 drops of ultrapure 1:1 nitric acid ($HNO_3$) per 60 mL. The acid stabilizes most metals but is not effective for mercury. Regrettably, no reliable mercury determinations can be made with this sampling method because it adsorbs onto the container (J.E. Gray, oral commun., 1997). At selected localities where results for Hg were needed, a special aliquot was collected: filtered into a glass bottle to which had been added an appropriate amount of dichromate solution to stabilize the Hg before analysis (Crock, 1996). At appropriate localities (with pH greater than 4) an unfiltered sample was collected for determination of alkalinity. Laboratory and field blank tests using deionized water indicated that contamination introduced by the sampling procedure and equipment is in the low parts per billion range (1–10 ppb), which is considered adequate in the search for metal concentrations orders of magnitude greater than the sampling error. Because the goals of this reconnaissance were to determine which metals are significantly enriched in surface water far above so-called "trace levels," costly and time-consuming trace-element protocols of the USGS or U.S. Environmental Protection Agency (USEPA) were not followed. The filtered and acidified water samples were analyzed by a commercial laboratory in Denver, Colo., within 20 days of collection, using ICP-MS (inductively coupled plasma-mass spectrometry); the general method is described by Crock and others (1999). Data for more than 60 elements are reported, generally to levels less than 1 ppb, but in this report only 10 to 15 elements of prime environmental concern will be discussed. Quality assurance is described in Nash (2000b). This analytical method is appropriate for determination of many metals of potential concern and expected to have a wide range in concentrations, and the method is especially good for trace elements in water such as As, Cu, Pb, and Zn (Crock and others, 1999). If water compositions reported here are a concern, followup work should be done using trace-element sampling protocols and more precise analytical methods.

Analytical results for surface-water samples were reported previously (Nash, 2000b) and are included in a spreadsheet file in this report (Appendix 3).

A summary of analytical results for 275 surface-water samples collected at 241 sites (table 2) shows the wide range of metal compositions present in samples from the study area. Some surface-water samples from draining mine adits or mill tailings impoundments have extremely high metal concentrations that contrast with most stream-water compositions and are notably higher than concentrations in surface water from areas with little mining (termed background). Acidic water tends to contain high to extremely high concentrations of base metals such as Cd, Cu, Fe, Mn, Pb, and Zn, but other metals such as Al, As, Se, and U can also be enriched. Evaporation causes some elements such as As, Co, Cr, and Ni in some unusual settings to become unusually concentrated. These and other trends in water chemistry are discussed in later sections.

## Leachate Chemistry

The chemical analyses for solids described herein are not always appropriate for environmental characterization because they describe total metal rather than mobile (soluble) metal concentrations. To determine the mobility of metals, as well as the tendency of a material to generate acid, a passive leach test (Nash, 1999; Fey and others, 2000) was used. Solid materials from dumps, mill tailings, and outcrops were processed in the laboratory by a leach method that provides a measure of reactions in nature, such as during weathering or storm events. The method is elegantly simple: 100 g of rock sample is placed in a beaker with 2,000 mL of deionized water, stirred slightly, and an initial pH measured. After about 20 hours, the solution is stirred slightly to mix the leachate solution. At 24 hours the acidity (pH) and conductivity of the leachate are measured, and a 60-mL portion (aliquot) is taken with a syringe and passed through a 0.45-micrometer filter. The sample is acidified with 5 drops of ultrapure 1:1 nitric acid ($HNO_3$) to stabilize metals in the solution chiefly to minimize adsorption on the plastic bottle or formation of precipitates. The leachate is analyzed by the same ICP-MS method as for water samples collected in the field. This analytical method is well suited for these solutions with highly variable composition. The analytical results for 158 leachate samples, summarized in table 3, resemble those for surface water degraded by mine waste. However, unlike the water analyses that show the results of rock interactions, the leachate results show the potential to generate those compositions—actual behavior is more complex and involves factors such as permeability, kinetics, and climate. The methods and applications are described in more detail elsewhere (Nash, 1999; Fey and others, 2000; Nash, 2002a).

Analytical results for the leachate solutions, determined by ICP-MS, are in a spreadsheet file included with this report (Appendix 4).

# Geologic and Geographic Setting

Geology of the region has important ramifications. Carbonate-bearing units (limestone, dolomite, calcareous shale) are common in several mountain ranges in the region. These rocks provide excellent acid-neutralizing capacity, and clasts of these lithologies in stream deposits (alluvium) extend those properties to near-surface materials in contact with surface water. In addition, caliche (a soil component rich in calcium carbonate) is abundant in the matrix and as layers in most alluvium in the region, providing another highly reactive source of acid-neutralizing capacity. Structures, particularly relatively young basin-and-range-type normal faults, have uplifted the mountain blocks, promoting deep oxidation of ore deposits in many places and greatly diminishing the potential for acidic drainage because sulfide minerals were destroyed prior to mining. In a few rare places, the uplift is such that mechanical erosion exceeds chemical weathering, allowing sulfidic rocks to exist near the surface and create acidic drainage. This is perhaps best shown in the National and Hilltop districts described later. Placer deposits of gold in many of the districts demonstrate that gold-bearing deposits were exposed at the surface thousands of years ago, thereby providing one line of evidence for pre-mining conditions in the region. Outcrops of altered rocks, as well as the placer gold deposits, demonstrate that not all acidic, metal-rich surface water is caused by humans and mining.

**Table 2.** Summary of surface-water compositions at 241 sites, northern Nevada.

[Analytical results are from ICP-MS analyses of filtered and acidified samples, in parts per billion; Cond, conductivity in microsiemens per centimeter ($\mu$S/cm); >, greater than]

| Statistic | pH (units) | Cond µS/cm | Al (ppb) | As (ppb) | Cd (ppb) | Co (ppb) | Cr (ppb) | Cu (ppb) | Fe (ppb) | Mn (ppb) |
|---|---|---|---|---|---|---|---|---|---|---|
| Minimum* | 9.7 | 80 | 0.3 | 0.3 | 0.02 | 0.02 | 0.1 | 0.5 | 19 | 0.1 |
| Median | 7.7 | 470 | 26 | 9.4 | 0.6 | 1.2 | 4.0 | 5.0 | 458 | 22 |
| Average | 6.9 | 662 | 39,633 | 17,909 | 452 | 2,826 | 58 | 30,364 | 241,200 | 35,970 |
| Maximum* | 1.7 | 4,590 | 1,800,000 | 3,800,000 | 26,000 | 494,530 | 3,482 | 3,894,600 | >4,000,000 | 3,600,000 |

| Statistic | Mo (ppb) | Ni (ppb) | Pb (ppb) | Sb (ppb) | Se (ppb) | Tl (ppb) | U (ppb) | V (ppb) | Zn (ppb) |
|---|---|---|---|---|---|---|---|---|---|
| Minimum | 0.3 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.04 | 0.1 | 0.5 |
| Median | 3.5 | 7.2 | 0.3 | 0.8 | 2.4 | 0.1 | 2.1 | 2.2 | 20.7 |
| Average | 21 | 1,143 | 51 | 14 | 31 | 0.3 | 19 | 23 | 47,020 |
| Maximum | 583 | 172,030 | 5,800 | 1,660 | 1,340 | 14 | 760 | 2,600 | 2,600,000 |

* Minimum pH is minimum acidity; maximum pH is maximum acidity.

**Table 3.** Summary of leachate chemistry from samples of mine dumps, mill tailings, and altered rocks, northern Nevada.

[Leach tests 24 hours, element concentrations from ICP-MS analyses, in parts per billion (ppb); Cond., conductivity; <, less than]

| | **Mine dumps (*n*=74)** | | **Mill tailings (*n*=67)** | | **Altered rocks (*n*=17)** | |
|---|---|---|---|---|---|---|
| **Element** | **Median** | **Maximum*** | **Median** | **Maximum*** | **Median** | **Maximum*** |
| **pH leachate** | **4.6** | **2.1** | **6.4** | **2.1** | **7.7** | **4.2** |
| Cond. ($\mu$S/cm) | 198 | 1,790 | 164 | 3,080 | 20 | 300 |
| Al (ppb) | 169 | 105,600 | 81 | 63,000 | 23.1 | 226 |
| As (ppb) | 2.8 | 28,700 | 17.5 | 5,300 | 5.8 | 61 |
| Cd (ppb) | 0.8 | 880 | 0.2 | 1,100 | 0.01 | 0.3 |
| Cu (ppb) | 11.8 | 83,200 | 3.0 | 73,700 | 0.6 | 29 |
| Fe (ppb) | 132 | 86,400 | 194 | 180,000 | 13.9 | 53 |
| Mn (ppb) | 63 | 28,000 | 16.0 | 97,000 | 0.7 | 169 |
| Mo (ppb) | 1.2 | 60 | 1.1 | 240 | 1.4 | 7.8 |
| Pb (ppb) | 0.9 | 1,690 | 2.1 | 3,700 | 0.2 | 21 |
| Sb (ppb) | 0.5 | 242 | 4.1 | 1,700 | 0.8 | 9.2 |
| Se (ppb) | 0.8 | 46 | 0.9 | 100 | <0.1 | 1.2 |
| U (ppb) | 0.2 | 135 | 0.1 | 98 | 0.02 | 1.4 |
| Zn (ppb) | 68 | 75,000 | 11.4 | 33,000 | <0.5 | 40 |

Maximum*: for pH, the value is maximum acidity or minimum pH.

Climate and topography are important factors in the development of mine drainage. Three aspects are briefly highlighted herein.

First, mine drainage can only happen where there is enough vertical relief to cause water to flow from mine workings. Precipitation that interacts with mined materials on flat terrain may enter ground water but would not be called mine drainage as defined here. In Nevada, mine drainage is present only in the hilly or mountainous parts of the region where precipitation can enter disturbed lands either directly or through fractures (ground-water flow) and then flow out on the surface. Mine shafts do not create surface drainage, but mine tunnels driven into mountains may collect ground water and carry it to the surface (indeed, many mine tunnels were constructed originally to provide an energy-efficient means of removing water from an underground mine, and after mining ceases these tunnels continue to carry water). Water pumped from mines is geochemically similar to mine drainage but will not be considered here.

Second, precipitation is highly variable across distances as short as a mile in Nevada, and these differences can be seen in the kinds and amount of vegetation (photos 1–6) and in the

**Photograph 1.** The temperate semi-arid climate of northern Nevada is characterized by xerophytic shrubs such as sagebrush. Trees are rare in the basins but can be abundant in the ranges, as seen here in the Cortez Range. Precipitation is the major factor, but rock and soil chemistry also influence vegetation.

**Photograph 2.** Alluvial fans grade into playas, many miles from the mountain ranges. Intermittent streams and arroyos are dry most of the year, but can be sites of violent flash floods. This former railroad bridge was destroyed by a flash flood that carried tailings more than 10 miles west from Tonopah.

amount of water at a mine site. Generalized maps of precipitation in Nevada show the effects of elevation on increased amounts of precipitation, much of that as snow (fig. 3; Houghton and others, 1975). There should be no surprise that there is little or no mine drainage at lower elevations on the flanks of ranges. Evaporation exceeds precipitation in most of the study area, which reduces the magnitude of some hydrogeochemical effects in surface water, but it enhances others. There are two especially noteworthy problems: (1) Evaporation can concentrate some toxic metals to hazardous levels—in this area the elements most prone to this are As, Mo, and Se; (2) orientation also is important because it influences the amount of sun exposure and evaporation. Large differences in precipitation and evaporation can be seen during and shortly after a spring storm. Just as aspen and fir trees tend to develop selectively in north-facing basins, more water is present in mine sites with a northerly aspect. This is evident in the larger amount of water in small creeks and in mine drainage of north-facing areas of the Battle Mountain, Hilltop, and National mining districts.

A third feature related to climate is the development of alkaline water and carbonate-rich aridsols and caliche in arid

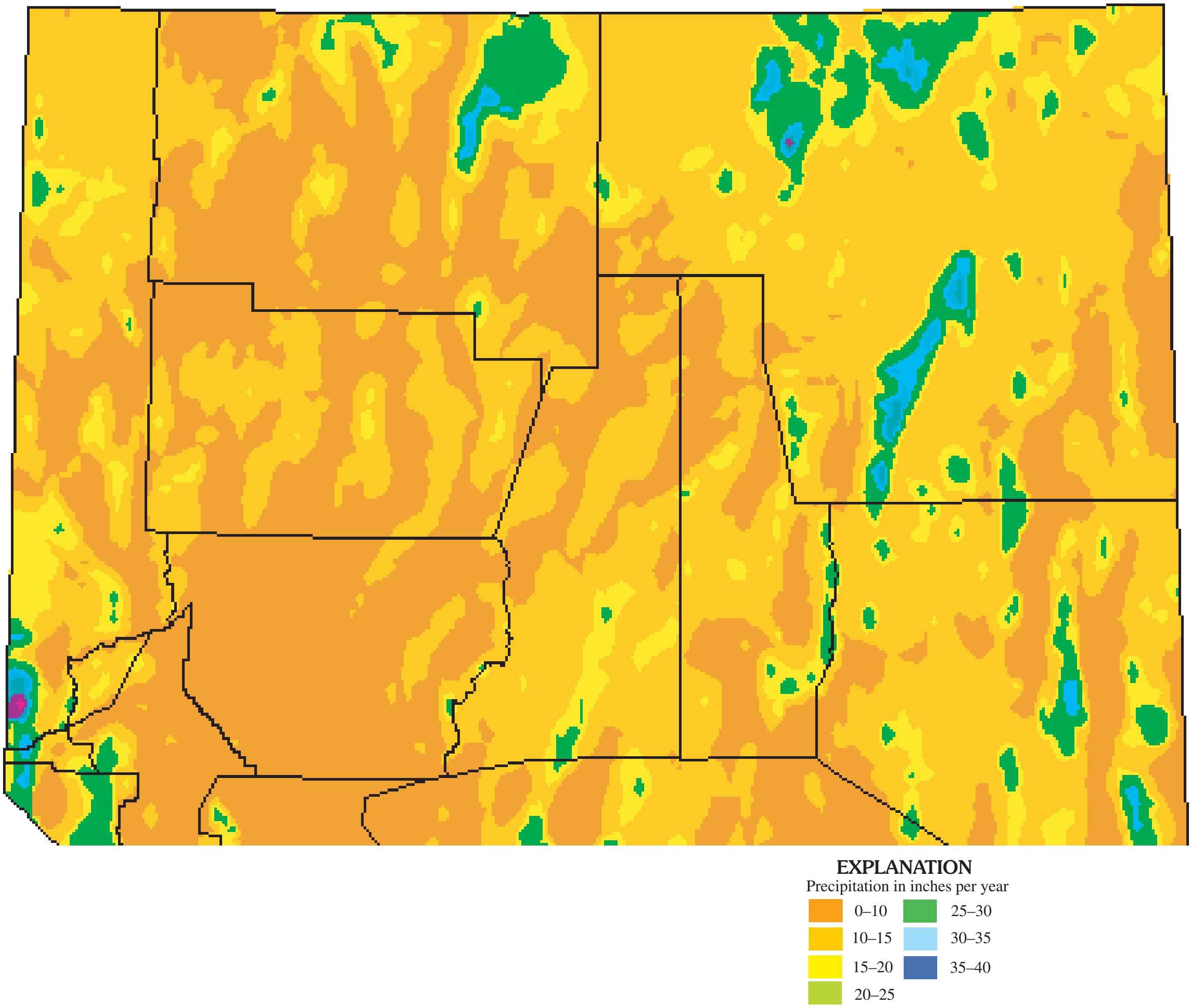

**Figure 3.** Precipitation zones in northern Nevada. From the statewide map prepared by Oregon Climate Service, Oregon State University, from, 1961 to 1990 annual data (see http://ndep.state.nv.us/admin/nvpre.gif).

areas, including Nevada (Southard, 2000). The relationship of these soils to climate was first emphasized by Jenny (1941). Carbonate as caliche is a major constituent in alluvium and soils at lower elevations of the study area. The fine-grained and porous aspects of caliche make the carbonate more reactive and available to ephemeral near-surface water than calcium carbonate in limestone. Two aspects of the caliche may be important in mining areas. One, the surface water has high alkalinity and pH values greater than 8; this water has high acid-neutralizing capacity. Second, acid-mine water that is released during wet periods of the year is effectively neutralized by reactions with caliche as the water infiltrates this alluvium.

A new aspect of water management and water budget in northern Nevada is mine dewatering at more than a dozen major open-pit mines that is unprecedented in magnitude. Numerous issues relating to drawdown, discharge, and water quality are beyond the scope of this report; abundant information can be found in the Web site of Nevada Division of Water Protection (*www.state.nv.us/cnr/ndwp)*, in particular the Humboldt River chronology (Horton, 2001). The magnitude of pumping is difficult for most people to comprehend. Some of the water is put to beneficial uses such as irrigating alfalfa, but much must be discharged into tributaries of the Humboldt River (photo 7). Briefly, individual mines pump more than 50,000 gallons per minute (gpm), and the total discharge into the Humboldt River in the late 1990's was more than 50 percent of the historical flow in the river. Later in this report, adit flows from historical mines will be described as ranging up to about 40 gpm.

Finally, it is important to note that the Humboldt River Basin is a closed internal basin. Metals carried in the river are

**Photograph 3.** Pinyon-juniper forests characterize some mountainous areas where precipitation is higher (more than 16 inches/year), especially as snow. This is a steppe division of the arid regime. (Tochima Range near Manhattan)

**Photograph 4.** The crests of some ranges receive substantial amounts of snow and more rain in summer than lower elevations (total precipitation 16–20 inches year). This severe climate is also highly influenced by wind. Limber pines and mountain mahogany grow east of the crest of the Santa Rosa range, National district, and wildflowers are lush for a few weeks as snow melts.

not flushed out to the Pacific Ocean. The ultimate fate of the Humboldt River water is the Humboldt Sink, where it evaporates (fig. 1). The dynamics of this closed basin are beyond the scope of this report, but unusual geochemical enrichments can occur. For example, there is the potential for relatively soluble metals such as As, Mo, and Se, released in daily amounts that exceed no regulations, to accumulate in both concentration and total mass in the Humboldt Sink.

## Ore Deposit Types and Their Environmental Signatures

Many types of ore deposits have been located or mined in the Humboldt Basin over the past 125 years. Economic geologists use numerous classification systems to compare and summarize geologic and economic attributes of deposits

**Photograph 5.** Headwater streams high in the mountain ranges, fed by springs, create riparian zones containing willows, as here on the east flank of the Toiyabe Range, south of Austin. Mines located in these microareas tend to release contaminated drainage to nearby streams.

**Photograph 6.** Aspen groves flourish in spring-fed headwaters of Dean Creek below Mount Lewis. These local sources of water were used by old mills, and today the waters could leach acid and metals if tailings were placed in the creek.

(Lindgren, 1933; Cox and Singer, 1986; Guilbert and Park, 1986). If one were to use one of these classifications, more than 40 mineral deposit types would be considered. These classifications subdivide deposits according to finer points of geologic age, ore genesis, mineralogy, and additional attributes that specialists need to know to properly evaluate the economic potential (likelihood of occurrence, ore grade, ore tonnage, and ore metallurgy) of a geologic terrain or a prospect. These classifications are too specialized for nongeologists and include much detail that is not necessary for a general understanding of mine-related geochemical effects on the environment. A much simpler system will be used here that emphasizes host rock type (lithology) and ore composition (table 4), both of which play major roles in the generation and dispersion of acidic water and chemical pollutants (Nash, 2001; Nash, 2002a).

## Polymetallic Deposits

Many of the mines and prospects in the Humboldt Basin are of the polymetallic type in which silver was the main economic commodity of interest. These deposits also carry substantial amounts of base-metal sulfide minerals (such as

**Table 4.** Classification of mineral deposits for environmental assessment, Humboldt River Basin, Nevada.

| Type | Geologic setting | Ore controls | Mineralogy | Geochemistry | Examples in area |
|---|---|---|---|---|---|
| 1. **Polymetallic** | In altered igneous, sedimentary rocks, esp. limestone, some volcanic | Faults, veins, replacements | Multiple sulfides: pyrite, chalcopyrite, galena, sphalerite, Ag-minerals, arsenopyrite | High Ag, As, Cd, Cu, Mo, Pb, Zn, with Au, Se, Te | Iron Canyon, Betty O'Neal, Cortez Silver, Dean, Rip Van Winkle Pansey Lee |
| 2. **Skarn** | In or near igneous stocks, mostly calcic sedimentary rocks | Intrusive contact, replaces host rock | Similar to PM, tends to have more Cu and Mo sulfides; Ca-silicate | Similar to PM, tends to have more Cu and Mo, high Bi | Copper Basin, Adelaide, Copper Canyon |
| 3. **Epithermal vein** | Tertiary volcanic tuffs and flows, pre-Tert. sediments | Faults, veins, breccias | Lower sulfide content, low galena, sphalerite, chalcopyrite | High As, Sb, Hg, Ag, Au, Se, Te, ±Cu, Pb, Zn | Sleeper, National, Midas, Mule Canyon Tuscarora |
| 4. **Massive sulfide** | Meta-volcanic or meta-shale | Bedded layers, shears | Very high pyrite, Cu-sulfides, sphalerite, | High S, Cu, Cd, Fe, Zn,±Pb, As, Sb, Ag | Big Mike, Mountain City |
| 5. **Mercury** | Same as epithermal vein | Faults, veins, breccias | Very low sulfide, sparse pyrite, intense silica | High Hg, As, Sb, Se, ±Au | Ivanhoe District, Goldbanks, Buckskin Hg |
| 6. **Uranium vein** | Igneous, sedimentary, or volcanic | Faults, veins, igneous contacts | High pyrite, uraninite, autunite, iron oxides, ± Cu-Pb-Zn sulfides | High U, radionuclides, ± As, Cu, Pb, Se, Zn | Apex (Rundberg), Aurora (McDermitt) |
| 7. **Sed-hosted gold** 'Carlin-type' | Sedimentary rocks, esp. shale, chert, calc-siltite | Faults, veins disseminations | Fine-grained pyrite, gold, ± carbon, realgar, barite | As, Hg, Sb, Se, Tl, Ag, ±Zn | Carlin, Betze-Post, Jerritt Canyon, Twin Creeks, Marigold Pipeline, Rain, Trenton Canyon |
| 8. **Porphyry Cu-Mo** | Igneous stocks, intruded sediments | Contacts, veins stockworks | High pyrite, Cu-sulfides molybdenite, Cu-oxides ±fluorite | As, Cu, Fe, Mo, S, Zn ±Cd, F, Pb, Se, Te, U | Mount Hope, Copper Canyon Buckingham, Majuba(?) |
| 9. **Acid Sulfate** | Volcanic rocks, stocks | Breccias, stockworks | High pyrite, alunite enargite, chalcopyrite, silica rock | Al, As, Cu, Fe, S with Au, Ag, Ba, Pb, Zn | Goldfield |

**Photograph 7.** Mine dewatering at large open-pit mines is a new factor in the water budget of the Humboldt River Basin. These pipes, about 3 feet in diameter, carry water from the Lone Tree mine under Interstate 80 to the Humboldt River. In the late 1990's, mine dewatering discharges into the Humboldt River amounted to more than 50 percent of the historical average flow (Horton, 2001).

galena [PbS], sphalerite [ZnS], and chalcopyrite [$CuFeS_2$]), allowing some of the mines to recover copper, lead, or zinc. Gold was a byproduct in some, and as the price of gold rose in the 1970's some of these deposits became targets for gold exploration. Many of the original mines of the region worked ores of this type, but these have not been of great interest in recent years unless they contain high gold concentrations. Although the polymetallic character is generally similar among this group, economic geologists recognize that there are many differences. Some examples of this type are small, simple veins filled by quartz and sulfide minerals, formerly amenable to mining by small underground operations as in the Tenabo and Battle Mountain districts. A few were larger and deeper vein systems, as at the Pansey Lee mine, described herein. Some are relatively large vein and replacement zones in limestone, as at the original Cortez silver mine or the Arizona mine near Unionville, also described herein. Many of these deposits are part of a larger system of veins related to an intrusive body (or even a porphyry copper-molybdenum system), well illustrated by the Battle Mountain district (Theodore and Blake, 1975) or the Rochester district (Vikre, 1981).

Polymetallic deposits have the potential to create acidic mine or rock drainage from the high amounts of sulfide minerals they contain, and they have the potential to release many toxic heavy metals in those acidic waters (Plumlee and others, 1999; Nash, 2002a). Local factors tend to determine the actual magnitude of contamination from polymetallic deposits; the most important factors are the amount of precipitation, amount of pre-mining oxidation, and the acid-neutralizing capacity of host rocks. Because these factors are highly variable from district to district, or even site to site, predictions based on the polymetallic model tend to be relatively unreliable without field data.

## Skarn Deposits

These deposits have been important sources of tungsten, copper, and molybdenum in Nevada. Recent technologic changes in bulk mining and bulk processing have allowed some deposits to be mined for gold that was considered uneconomic 30 years ago. Chemically and geologically, these deposits have features in common with the polymetallic class, as shown in the Battle Mountain district. They merit consideration as a separate type because many of the historical mines had large production, and current mines tend to be open-pit operations that move even larger amounts of waste rock and ore. Skarn deposits have the potential to create large amounts of metal-rich acidic drainage, but most of this is immediately mitigated by carbonate-bearing host rocks (Hammarstrom and others, 1995). An additional mitigating factor in Nevada is the tendency for mined deposits to be deeply oxidized prior to mining; thus, there is much less sulfide in the mine and in waste dumps to create acid.

Skarn deposits were observed and sampled in the Battle Mountain, Buffalo Valley, Adelaide, Railroad, and Merrimac districts. These examples of skarn deposits are rich in many base metals, especially Cu, Fe, Pb, and Zn; the combination of pre-mining oxidation that destroyed sulfide minerals and abundant carbonate minerals precludes the formation of acidic water.

## Epithermal Vein Deposits

These deposits have been important sources of precious metals in many Nevada districts, including National, Ten Mile, Gold Circle, and Tuscarora. New technology and higher prices for gold have allowed many broad stockwork and breccia zones to be mined by open-pit methods in the 1980's–1990's as at Sleeper, Florida Canyon, and Mule Canyon. These deposits are generally in volcanic rocks of Tertiary age, but some compositionally similar deposits (gold and associated metals) can form in altered sedimentary rocks. Called Comstock-type and hot-spring type by some classifications (Cox and Singer, 1986), these deposits tend to have low concentrations of pyrite and base metals in northern Nevada (Nash and others, 1995), whereas epithermal veins elsewhere can be rich in base metals and grade into the polymetallic class. The metallurgical restrictions of heap-leach technology that is used to process gold ores from most open pits tends to require low pyrite content; thus, most mined deposits are those that have undergone pre-mining weathering and oxidation that destroy pyrite. However, former underground mining and conventional milling of ores could accommodate sulfidic ores, as in the National, Gold Circle, and Tuscarora districts. Sulfidic waste and tailings from the older mines pose substantially greater problems than from the oxidized, low-sulfide, bulk-mined epithermal ores (Nash and Trudel, 1996). Character of wall rock alteration is an important factor in exacerbating or mitigating drainage signatures: green kinds of propylitic alteration provide added acid-neutralizing capacity that helps mitigate any acid produced (Nash, 2002a), whereas most clay-rich (argillic) or acid-sulfate alteration adds acid and metals and there is low acid-neutralizing capacity for natural attenuation of acidity.

Metal mobilities from these deposits vary greatly according to local climate and concentrations of sulfide minerals and base metals (Plumlee and others, 1999). In the San Juan Mountains of Colorado, very acidic, metal-rich mine drainage develops from deposits that were rich in base-metal sulfide minerals and exposed to the moderately wet climate (Nash, 1999; 2002a). Deposits in Nevada have generally lower content of base metals (except for deep parts of the Comstock lode), and in many Nevada deposits deep pre-mining oxidation destroyed most sulfide minerals. Where sulfide minerals are present and buffering capacity is low, as in the National district, highly acidic water develops and carries high concentrations of many metals. In most other Nevada locales, these epithermal deposits create few concerns, as will be described later. Studies of pit lakes in mined-out epithermal gold deposits (Shevenell and Connors, 2000) show near-neutral pH values and generally low metal concentrations, except where concentrated by evaporation.

Examples of epithermal deposits were studied and sampled in the National, Gold Circle, Tuscarora, and Safford districts.

## Mercury Deposits

Deposits of mercury in volcanic or sedimentary rocks have been mined at several districts in northern Nevada. These deposits have many features in common with epithermal veins, described previously, but merit special treatment because of the problems associated with high mercury concentrations. The volcanic-rock-hosted mercury deposits of the Ivanhoe district contain even lower concentrations of Cu, Pb, and Zn than the epithermal veins but similar high concentrations of As, Sb, and Se. Called "hot spring" Hg deposits by some specialists (Rytuba, 1986), these deposits are associated with large amounts of hot-springs silica sinter but relatively low concentrations of pyrite.

Environmental concerns at mercury deposits are numerous and complex (Rytuba and Kleinkopf, 1995; Gray and others, 1999; Gray, 2003). The major concerns at the Nevada mines are (1) elevated Hg in unmined rocks and soils; (2) elevated Hg in soils created by mining and retorting the ore; (3) elevated Hg created by spills at the retort; (4) elevated Hg in the retort tailings (also called calcine); and (5) formation of methyl mercury from inorganic mercury compounds—methyl mercury is extremely toxic (Crock, 1996). Acid drainage is created at some mercury mines but is not known or expected at the northern Nevada sites because sulfide mineral content is low and the mines are not wet.

Mercury mines investigated here do not appear to be releasing metals to the environment beyond the areas of disturbance. The mine workings, dumps, and retort tailings could pose health problems related to dust or ingestion, but formation of highly toxic methylmercury is unlikely at these sites in Nevada (Gray, 2003); such geochemical issues are beyond the scope of this study and specific investigations are recommended to address those questions.

## Sediment-Hosted Gold Deposits

Deposits of gold in sedimentary rocks, often called "Carlin-type" for the first major mine of this kind in the Lynn district (fig. 2), have become the major focus of exploration and mining in northern Nevada. The deposits tend to be mined by large-scale open-pit operations, but in recent years some are mined underground as well. The major gold mines of northern Nevada were not accessible for study and sampling, but the small, mined-out Quito mine near Austin was studied briefly as an analog deposit. Gold is recovered by a variety of highly sophisticated techniques, from cyanide sprayed on heap leaches to complex, high-temperature autoclaves (pressure cookers). Because the mines process large tonnages of ore (several million tons per year), large amounts of waste and processed ore (leach piles or ground tailings) are produced and are subject to close monitoring. Many of the large and deep mines must pump water from the underground or open-pit mines, and that water is handled carefully by the mine operators before release on the surface. Important geoenvironmental aspects (Hofstra and others, 1995; Plumlee and others, 1999; Bowell and others, 2000) include (1) rocks that have moderate to high acid-neutralizing capacity from carbonate minerals; (2) fine-grained pyrite in ore and alteration zones that commonly amounts to 5 percent and locally as much as 50 percent below the weathered zone; and (3) a trace-element suite that includes substantial amounts of As, Hg, Mo, Sb, Se, and Tl, and locally Zn and Cd (but other base metals are low).

Observed waters in these deposits are alkaline, indicating predominance of the acid-neutralizing capacity of carbonates over acid from sulfides, and these waters have the potential to transport the Carlin suite of trace metals, especially the oxyanion forms of As, Mo, and Se.

In the 1990's a new variety of disseminated gold deposit was recognized as having more direct genetic association with a source pluton than the Carlin-type. Called "distal-disseminated gold" (Cox, 1992; Theodore, 1998), these deposits tend to have somewhat higher concentrations of base metals than the Carlin-type, closer to the gold skarn deposits with which they share many genetic similarities. In practice, these distal deposits have weathering and other geochemical properties that are so similar to the Carlin-type that distinction generally is not required. A few examples in the Battle Mountain and Hilltop districts will be mentioned.

Environmental concerns for these deposits are quite different from other deposit types in Nevada. (1) Acid-mine or rock drainage is generally acknowledged to be a minor problem. Although the unweathered rocks contain appreciable amounts of fine-grained pyrite, most acid created during post-mining oxidation is neutralized by nearby carbonate-bearing rocks or by limestone placed below waste dumps. (2) Alkaline mine or rock drainage (pH 6–8) may be a problem at these deposits. Arsenic, Hg, Mo, Sb, Se, and tend to be enriched in these ores, and these metals are relatively soluble under near-neutral pH conditions. Water analyses are sparse for these deposits and available data have been reviewed elsewhere (Hofstra and others, 1995; Plumlee and others, 1999). Zinc is relatively rich in some of these deposits and also can be transported at pH 6–8. (3) Oxidized ores, in which pyrite and other sulfide minerals are destroyed by pre-mining weathering, are amenable to simple cyanide heap leaching because the gold is "free" and potentially toxic trace metals such as arsenic are stable in iron oxide minerals. The oxide ores, as at the Marigold mine, are generally believed to pose no environmental hazards. (4) Pit lakes will form in most of these open-pit mines, some of which will be more than a mile in length and hundreds of feet deep. The nature of water flow into or out of pit lakes and the quality of the water are complex issues.

One example of this type of deposit, the Quito mine, was investigated and is described herein. It is much smaller than the major mining operations to the northeast, in Eureka County, but may provide some useful insights to those mining areas. Mill tailings at analog deposits at Manhattan (White Caps) and Northumberland in central Nevada were described by Nash (2003b).

## Porphyry Cu-Mo Deposits

Porphyry deposits of copper and molybdenum, associated with shallow-level igneous stocks having a characteristic porphyritic texture (large crystals mixed with very fine ones), are the major source of Cu and Mo in the United States and the world. Mines range in size from large to huge (as at Bingham Canyon near Salt Lake City) and commonly are open pits. The geologic aspects with potential environmental implications include (1) large tonnages of rocks with high sulfide mineral and base-metal concentrations; (2) igneous rocks and alteration zones that can have low to moderate acid-neutralizing capacity; and (3) high fracture permeability that promotes percolation of surface water and encourages acid-generating and metal-liberating reaction. These and other aspects of porphyry deposits are reviewed elsewhere (Cox and others, 1995; Ludington and others, 1995). Metals of major concern include As, Cd, Cu, Fe, Mo, Pb, Sb, Te, and Zn from the Cu-Mo deposits. Porphyry deposits may produce a wide range in pH and metal concentrations (Bowell and others, 2000) depending upon degree of oxidation. The Mo-rich variety (termed "Climax-type") have the potential to produce acidic water that is rich in F and U.

Porphyry deposits are known in Nevada; two atypical examples have been mined in the Humboldt Basin at Copper Canyon and Copper Basin (Battle Mountain district) and a few prospects have been drilled. The two Cu-Mo mines in the Battle Mountain district are outside of the source porphyry intrusions and geochemically are more akin to skarn deposits (Doebrich and Theodore, 1996). Significant Mo and Cu porphyry prospects are known at Buckingham, near Battle Mountain (Loucks and Johnson, 1992), and at Mount Hope in southern Eureka County (Westra and Riedell, 1996). Polymetallic vein deposits on the fringe of the Buckingham and Mount Hope Mo-Cu prospects were observed and sampled in this study, but the porphyry parts of these large systems are not exposed at the surface or mined.

## Massive Sulfide Deposits

Only a few massive sulfide deposits have been mined in Nevada, including two examples in the study area and one to the north near Mountain City. These deposits are extremely rich in pyrite and can be mined for their content of sulfur, copper, zinc, or byproduct silver and gold. The deposits occur as layers or lenses of pyritic rock that contain high to very high concentrations of As, Cd, Cu, Fe, Pb, Zn, and other metals. Their chemical and mineralogical composition is similar to polymetallic deposits. The rock units containing these sulfide deposits have been metamorphosed, but their bulk composition has not changed greatly and the newly formed minerals contribute to a generally high acid-neutralizing capacity.

The high concentrations of pyrite and base-metal sulfide minerals in massive sulfide deposits can produce extremely acidic drainage, as in the Shasta district of California (Alpers and Nordstrom, 1991; Taylor and others, 1995; Plumlee and others, 1999). The combination of bad mining practices and wet climate can cause severe environmental degradation, but not all massive sulfides have this effect. The combination of dry climate and deep oxidation in the Basin and Range province of Arizona and Nevada greatly reduces the tendency for acid generation (Nash and others, 1996).

Also, the green propylitic alteration of basaltic host rocks, common in this deposit type, introduces calcite and chlorite that provide high acid-neutralizing capacity. Water draining from many massive sulfide deposits is neutral to weakly alkaline, caused by the beneficial effects of altered wall rocks. Despite geologic differences, massive sulfide deposits have many geochemical features in common with polymetallic deposits: ore compositions alone would suggest huge problems, but natural mitigation by wall rocks can greatly reduce risks in some areas.

The Big Mike deposit, south of Winnemucca, is the largest example of a massive sulfide deposit in the study area (Rye and others, 1984). Other prospects are known, including the Black Beauty, which is probably of this type (LaPointe and others, 1991). The Rio Tinto mine near Mountain City was a major producer (Coats and Stephens, 1968), but it is located north of the Humboldt Basin. The sulfidic mill tailings from the Rio Tinto, near Mountain City (figs. 1 and 2), are a source of contaminants in the Owyhee River Basin; they are a National Priority List caliber site and the subject of ongoing discussion for reclamation under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, commonly called Superfund). The magnitude and extent of contamination from massive sulfide deposits in northern Nevada appear to vary according to local conditions of climate and mining history. Where dry, there are few problems. In Nevada, the mines themselves tend to pose few problems because wall rocks can counter acid production, but waste piles and tailings that are rich in pyrite can generate highly acidic, metal-rich water.

## Acid Sulfate Deposits

Acid sulfate deposits are not known within the Humboldt River Basin, but examples at Goldfield, Nev. (fig. 1), and Summitville, Colo., are prominent in environmental studies of mines because their high sulfide content and lack of rock buffering tend to create extremely acidic drainage water (Plumlee and others, 1999; Nash, 2002a). Brief studies were made of the Goldfield district in 1999 to provide data to compare with deposit types within the study area, particularly the massive sulfide type. The remarkable feature at Goldfield, and elsewhere, is the intense alteration attributed to hot acid sulfate solutions that destroy nearly all minerals originally in wall rocks and leave a sponge-textured rock composed of fine silica, pyrite, and alunite (a potassium-aluminum-sulfate mineral). These altered rocks have the potential to create very acidic drainage water, as observed at Goldfield during an unusually wet June day in 1999, and persistently in the San Juan Mountains of Colorado.

No acid sulfate deposits or prospects are known in the Humboldt River Basin, but prospects in the Scraper Springs district (fig. 2) contain aluminum minerals characteristic of the acid sulfate alteration assemblage. My observations at Scraper Springs, described herein, did not reveal significant amounts of pyrite or other characteristics of the acid sulfate deposit type. My samples from the Goldfield district produced some extreme chemical values, as discussed in later sections.

## Uranium Vein Deposits

Many kinds of uranium deposits in plutonic, volcanic, and sedimentary rocks have been identified in Nevada, but only a few were mined in a significant way (Garside, 1973). The behavior of uranium and associated metals is quite different among the various types of uranium deposits, but many of the potentially toxic metals tend to be mobile in either highly acidic or alkaline water. In the study area, the largest uranium deposits are of the vein-type, located a few miles south of Austin at the Apex mine. Here, and at other uranium vein deposits in Nevada, oxidized and reduced minerals are both present at various depths. The unoxidized, deeper parts having abundant pyrite and marcasite (both are $FeS_2$) have the greatest potential to create acid-mine drainage, which in turn can transport uranium and other metals (Wanty and others, 1999). The waste dumps at the Apex mine share many characteristics with those of the Los Ochos mine in Colorado (Nash, 2002a).

The environmental geochemistry of uranium mines is more complex than for other metal mines because radiation and decay products of uranium, such as radon and radium, also are involved. Regulatory standards are established for uranium and radionuclides in water and in mill tailings but have not been set for mine-waste dumps. Standards for released water and base metals are the same as those for metal mines. Mine reclamation generally focuses on exposure to radiation rather than chemical concentrations of uranium, but release of uranium and radionuclides to surface and ground water also is a concern, and water-quality standards must be met.

# Mill Tailings—Potential Sources of Contaminants

*Introduction.*—Mills in historical mining districts of northern Nevada from about 1870 to about 1970 treated millions of tons of ore to recover metals of value and in doing so created large quantities of waste materials that can release acid or metals to the environment. Although the term "tailings" is often applied to any kind of mined material, regardless of ore grade or amount of processing, the term will be used here only for material that was ground and processed through a mill (photo 8). At most mines, more than 90 percent of the ore-grade material mined was processed, yielding mill tailings with grain size finer than beach sand and containing minerals that either escaped recovery or had too little value to recover. Other recovery methods, such as retorts for mercury or heap-leach pads for precious metals, left piles of crushed rock containing substantial amounts of ore-related metals.[2]

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[2] Metal or metals will be used in this report to describe collectively elements associated with ores including base metals (such as Cu, Fe, Pb, and so forth), metalloids (such as As and Sb), and uranium, in solids or water.

**Photograph 8.** Mill tailings are the fine, sandy material created when the ore is ground to release minerals of value. Mill tailings created 50 or more years ago can be either soft, like sand dunes, or hard from reactions that create hardpan. These tailings below the Cortez silver mill, which was active in the 1920's, are easily eroded by stormwaters.

These processing operations placed the tailings in nearby locations that were convenient but often unstable and subject to episodic contact with surface water. Because most mills used water in their chemical processing of ores, and most tailings emerged as a wet slurry, tailings tended to be placed in arroyos or stream channels that carry water. There were no Federal or State regulations against placing tailings in streams before 1935. The fine grain size of tailings tends to make them more reactive when exposed to water and more vulnerable to erosion than mine waste on dumps that has not been crushed or ground. In some situations mill tailings can be significant sources of pollution to surface and ground water; an extreme example in Nevada is the sulfidic tailings from the Rio Tinto mine that releases acid and metals to a tributary of the Owyhee River.

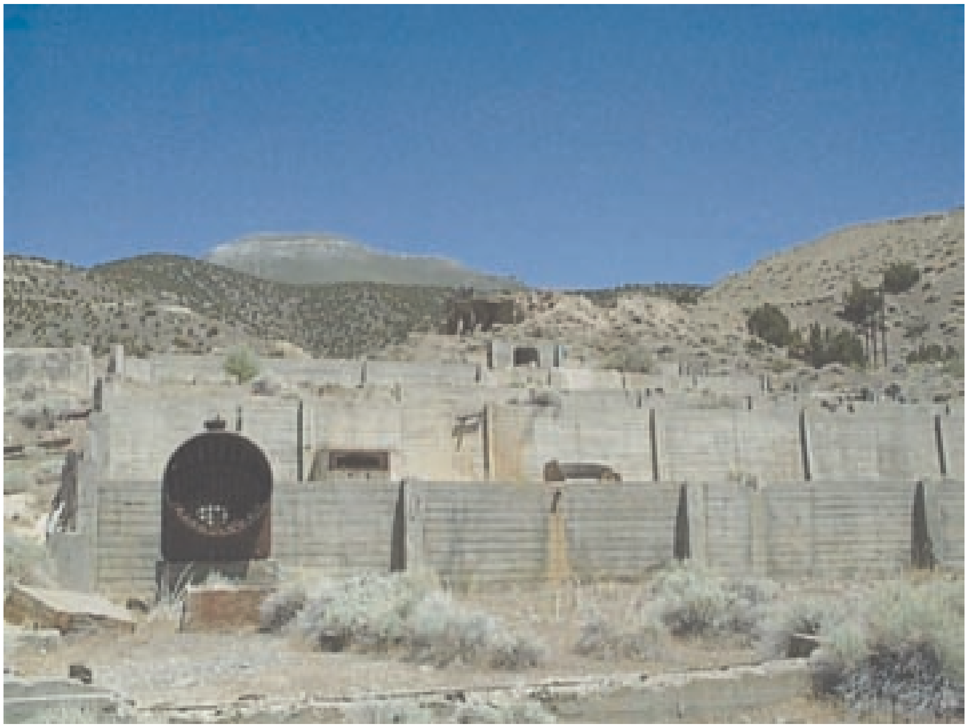
Although mills and tailings are part of abandoned mine lands, they have not received scientific study proportional to their potential effect on the environment: most geologic references and databases include less than 10 percent of mill or tailings sites and even less information on their size, physical situation, and composition. Milling facilities of active or recently active mining operations by major corporations are not included because they are subject to several regulatory processes for operation and closure; a few mill sites that were abandoned without reclamation during the last 10 years are included because they are of interest to land managers. During the course of geochemical studies in northern Nevada from 1995 to 2000, I made special effort to locate mills and tailings because they are inadequately recorded in the literature. I located in the field 83 mills or mill sites and derelict mill-tailings impoundments at 78 sites (Appendix 5). Transported (fluvial) deposits of significant size were observed at 13 sites downstream from mills. Samples from the tailings sites were collected onsite where possible.

The substantial erosion of tailings at many sites indicates that many tailings impoundments are at risk for failure during local extreme storms (flash floods). Tailings dam failures at 11 sites indicate that catastrophic failure of abandoned mill tailings is more common in Nevada than reported in the literature (Nash, 2002b). The chemical and physical consequences of these catastrophic failures exemplify the potential effect of such failures on wildlife and the landscape.

*Properties of mill tailings.*—The engineering aspects of mills and tailings disposal are too complex to be reviewed here; the interested reader can pursue the extensive literature elsewhere. Some useful volumes include the review by Ritcey (1989) and research papers in two special volumes (Jambor and Blowes, 1994; ICARD, 2000). A few aspects can be described briefly for better understanding of general principles. (1) All mills had crushing and grinding equipment to reduce the particle size, which was required to allow contact with milling chemicals; grains typically are finer than beach sand. Stamp mills from the 1880's produced coarse-grained tailings, about 1 mm (0.04 inch) maximum diameter, whereas post-1920 flotation tailings are fine (about 0.25 mm or 0.01 inch) and some are very fine (less than 0.1 mm or 0.004 inch). These grain sizes can influence geochemical reactions and other properties. (2) Processing is specific for metals of interest: many mills focus on gold, whereas some concentrate copper or lead by gravity or flotation; other minerals are not affected and go out in the tailings. Pyrite typically is in the tailings, and some pre-1920 methods did not attempt to remove sphalerite (ZnS) because Zn was not valued. (3) Tailings are handled in many ways, almost always aided by gravity and almost always as thick mixtures with water. The mixtures vary, but those having about 70 percent water resemble wet concrete and can flow through pipes or sluices—this is an advantage to processing the tailings but can lead to problems at the disposal site (pond), including dam failure (Ritcey, 1989). In Nevada, where water generally was in short supply, the water was recovered from tailings in settling tanks, and the semi-solid tailings would be stacked like hay. If wet, the tailings could flow to lowlands or constructed ponds (with dams), whereas the dry variety would accumulate in piles on a slope. These physical differences may explain the location of tailings today, whether it was by design or by convenience at the time.

*Identification of mill and tailings sites.*—Mills vary greatly in size, style of construction, and preservation. The older mills tend to have stone foundations (photo 9), but

**Photograph 9.** This mill at Cortez is typical of the older mills with its stone foundation and three levels. Concrete was used for foundations after about 1900.



**Photograph 10.** As mill technology developed the mills became larger and had six or more levels to accommodate special functions such as cyanide or flotation tanks. This mill in the Rochester district was active from 1915 to 1930.

concrete foundations were used after about 1900 (photo 10). Some mills are as small as a garage, and others are hundreds of feet wide; the larger mills generally have three to six levels up a hillside so that gravity could be used to move the materials from one operation to another. Some mills are remarkably intact and handsome structures, but many burned and have no superstructure. Mills generally were taken apart when the mining ceased, so equipment is rarely present today. Many photographs of mills from Colorado can be seen in another report (Nash, 2002a) as a guide to what the industry used over the past century.

In nearly all cases, mills were placed at a lower elevation than the mine. Some mills in Nevada were served by a gravity-driven tram, but in most cases the ore was delivered by mine car, wagon, or truck. In many cases, the mill was placed at the nearest site having water, but in some districts water was piped in from distant wells. Some mills were several miles from the mine, as in the Tonopah district where mills were sited about 12 miles to the west at Millers to obtain enough water. Some mills serviced just one mine, and others served an entire district. At mercury mines, mills and retorts tend to be small and serve a single mine. At some mill sites there is enough evidence remaining to deduce the kind of milling used, such as the heavy steel rods of the stamp mills at the Looney gold mine (Rochester district), or the cylindrical tanks used for cyanide at the Buckskin mill (National district). In many situations it is easiest to locate the mill and then search for the associated tailings. Identification of mill sites, however, is not the significant issue for land management because it is not the mill itself that causes concerns. Although many mills used cyanide, which is highly toxic, the cyanide is not likely to persist today unless in a sealed container. Cyanide is degraded by many natural processes, including oxidation and biodegradation, and is unlikely to be significant in mills or tailings as old as those under discussion here. This issue will not be considered further, but the concerned reader should see other reports (for example, Smith and Mudder, 1999). Mercury used to recover gold can contaminate mill sites but has not been investigated here.

My reconnaissance studies of the historical mining districts of northern Nevada that are in or near the Humboldt River Basin disclosed 83 mills (or mill sites), 78 tailings impoundments, and 13 fluvial tailings sites (fig. 4). Also identified were 11 smelters (or slag sites). Very few of these tailings or slag sites are mentioned in electronic databases, and there is virtually no database for their size, physical situation, and composition. The sites are briefly described by Nash (2002b) and described later in the descriptions of mining districts. Chemical analyses of tailings and reactions in leach tests are in Nash (2000b).

*Contaminant pathways from tailings.*—Contaminants from mill tailings migrate in the same ways as from mine waste dumps, but some mechanisms differ in detail. Because of the finer grain size of tailings, wind can carry small particles from tailings and has been recognized by the BLM to be a substantial concern at sites near the Getchell mine (Potosi district, fig. 2) and Paradise Peak mine (near Gabbs, fig. 1). I have seen evidence of the windborne particulates as dust clouds (photo 11) and as sand dunes at several localities but did not document the magnitude or areal extent of the contamination. Runoff from tailings will be described later at many sites, and seeps are present at a few sites (see photo 12). Streams also can react with mill tailings, as at the Rio Tinto tailings impoundment (photo 13). In the prevailing arid climate, efflorescent crusts (photo 14) tend to develop on tailings, and these are highly soluble according to leach tests and will create a flush of highly contaminated runoff in the first minutes of a rainstorm. Seeps to the surface are rare, in part because the geometry of most historical tailings piles is such that there is relatively little vertical dimension and thus little tendency for water to seep from the sides or gullies in the piles. Seeps of very acidic and metal-rich water were observed at the Rip Van Winkle tailings, described later. In general, we must assume that seeps can carry acid and metals from tailings after storms or snowmelt, and that infiltrating seepage water probably moves slowly through the pile and into underlying alluvium and ground water. The composition of these seeps is difficult to determine and is best done with wells drilled by machine or hand auger. More work of this type could be done to document the magnitude of this pathway and the composition of the waters that are mixing with shallow ground water.

## Chemical Composition of Dumps, Tailings, and Mineralized Rocks

Metal concentrations in mine-waste dumps, and of mill tailings, vary greatly by deposit type and by style of mining. The previous section described the general compositional trends by deposit type. In chemical terms, the concentrations of metals largely reflect the rarity of the metal, ranging from less than a part per million gold in some gold ores, to more than 40 percent iron in iron ores. Concentrations of metals required to constitute ore are related to their market value: because gold has a high unit value, not much gold is required to make it ore grade, whereas iron or lead, with low unit value, must be present in much higher concentrations. Not intuitive is the abundance of non-ore metals, such as As in any ore or Zn in a gold ore, that are not recovered in mining or milling and which collect on waste piles. Geology determines the concentration of these metals, and their concentrations generally are predictable by geologic setting and deposit type (Plumlee and others, 1999; Nash, 2002a).

Compositions of mined and waste rocks in mining districts reflect mining technology as well as the geologic influences outlined in the previous section. By economic definition, ore-grade rocks have the highest concentrations of metals in a district, whereas altered and mineralized waste rocks (sub-ore grade at the time of mining), having elevated but relatively lower concentrations of ore metals and associated minerals such as pyrite, are placed on dumps. Slightly altered rock, with

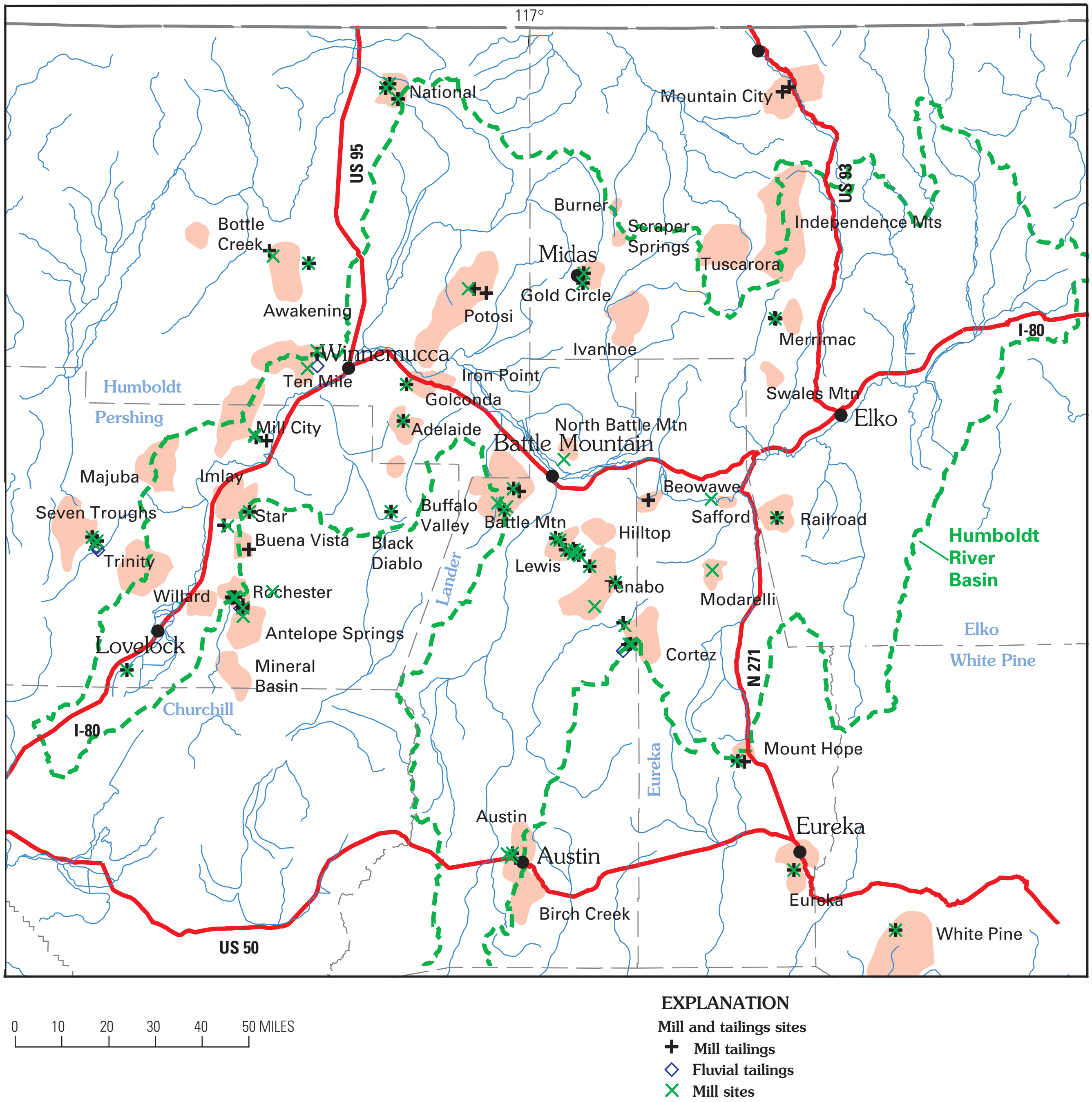


**Figure 4.** Location of mill and tailings sites in northern Nevada. District outlines are from Tingley (1998); only studied districts are shown.

very low (background) concentrations of metals and generally low sulfide content, is removed while gaining access to ores by excavating shafts or tunnels or by stripping in an open-pit mine. In most mines this variety of waste is stacked in piles that are spatially distinct from subeconomic mineralized ones. Stockpiles of ore-grade material are less common, but some are present at prospects and reopened mines that lack a nearby mill to treat the ore.

The composition of mill tailings reflects the ore type milled and varies according to changes in technology. Stamp mills in the 1800's, which used jig tables and mercury amalgamation to concentrate gold, released metal-rich tailings because the base metals were not removed by those milling methods. Zinc was a penalty at smelters until about 1920; thus, old mills did not attempt to concentrate sphalerite (ZnS). Pre-1920 tailings thus tend to be higher in Zn than the same type of ore processed after Zn became valuable. There also can be substantial variation in tailings mineralogy and composition from a given mill, shown in visibly differing colors of layers in the impoundment—reflecting changes in the character

**Photograph 11.** Wind erosion and transport of dust from tailings impoundments can be a concern if the tailings are dry. The Paradise Peak mine area, south of Gabbs, is noted for its high winds and severe dust clouds.

**Photograph 12.** Seepage of surface water through mill tailings can mobilize acid and metals. These tailings at the Morningstar millsite, in the headwaters of Dean Creek, receive more snow and rain than most parts of the study area, saturating the tailings and creating seeps that flow into the nearby creek.

of ore mined (such as oxidized near-surface ore compared to sulfidic ore from deeper zones), variability in ore mined on a custom basis (same mill but ore from different mines), or evolution in mill technique. Generally, lighter tailings color is suggestive of lower concentrations of heavy metals. Rusty coloration by iron oxide and sulfate minerals tends to indicate high metal concentrations, and many of these tailings can create acids when exposed to water. Gray coloration tends to reflect the presence of sulfide minerals, but there can be other geologic associations such as dark-colored host rocks. Most tailings contain only a small percentage of sulfide minerals because most mills were designed to remove these minerals, but even a small amount of sulfide mineral can create acid when exposed to water, and the acids will dissolve and carry base metals that may be present. An extreme example of this in Nevada is the sulfide-rich tailings from the Rio Tinto massive sulfide mine near Mountain City.

Representative samples of dumps, tailings, slag, and unmined altered rocks were collected and chemically analyzed to provide a generalized chemical description of the range in

**Photograph 13.** Mill tailings placed in streams can be significant sources of contamination. Tailings from the Rio Tinto mine near Mountain City fill the valley of Mill Creek and release acid and metals to this tributary of the Owyhee River. Limestone, in the right corner of the view, might have been used in the construction of the impoundment.

**Photograph 14.** Weathering at the surface of waste and tailings piles creates mineral crusts that are very reactive in intermittent stormwaters. The surface of these mill tailings is rich in pyrite (dark gray) after clays have been washed away, and light-colored sulfate minerals form by capillary action during dry periods.

composition of these materials. Table 1 shows the median and maximum concentrations of elements of possible mineral-environmental interest. In this report the simple terms high and very high will be used to describe concentrations of elements relative to the database of 232 samples. The term “high” will be used to highlight concentrations above the group median; very high will be used to highlight concentrations much higher than the group median (the top decile).

The ranges in compositions of dump and tailings samples from nine deposit types in the Humboldt Basin are shown in figure 5. Clearly, there is a broad range in metal concentration for various samples of materials associated with these nine types of deposits. Although generalizations are risky, there are some general trends. Polymetallic, massive sulfide, and porphyry deposits tend to contain high concentrations of base metals, whereas mercury and epithermal vein deposits tend to be to be lowest in these metals. Uranium was enriched to levels sufficient to create significant radiation in only the uranium vein deposits, although some other environments not studied here are known to be enriched in uranium.

Compositions of mine-waste materials and mill tailings are generally in the same range, whereas altered rocks tend to contain lower concentrations of ore elements such as Ag and Cu (fig. 6). Compositions of individual samples span a large

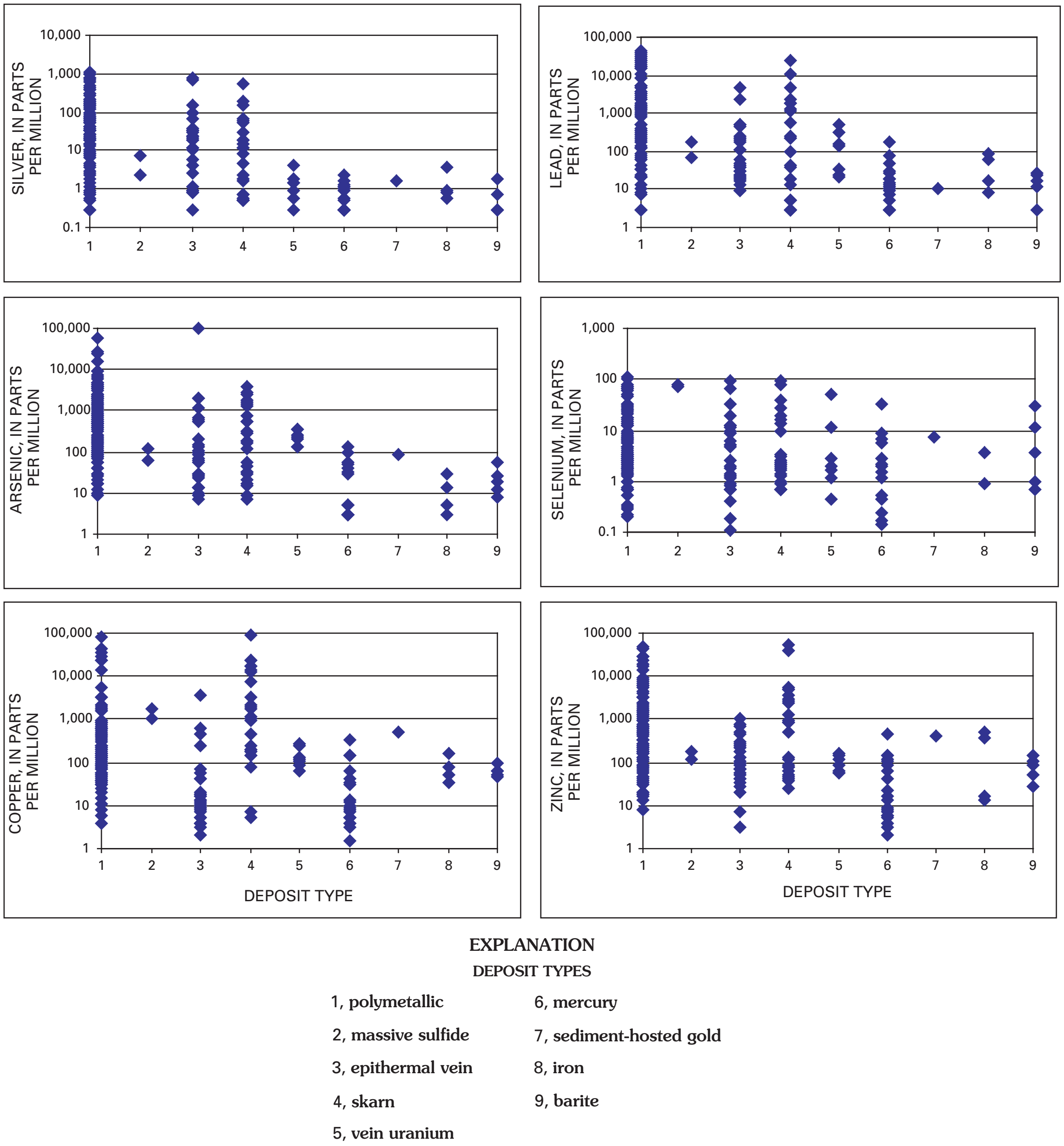


**Figure 5.** Range in composition of mine-waste materials (solids) by deposit type.

range, showing that one cannot assume that these mineralized materials are always high or low in metals.

## Leach Tests of Dump and Tailing Samples

Leach tests were made to determine what metals are soluble, and thus mobile, in various deposit types and mined materials. The behavior of samples during the 24-hour passive leach tests is variable. For many samples, especially those with abundant iron oxides or jarosite (rusty-appearing minerals), the pH dropped to less than 3.5 in just a few minutes. In some samples the pH evolved to lower values during the 24 hours, and in a smaller number of samples (20 percent), the pH rose a few tenths of a unit, reflecting buffering by rock and gangue minerals. The behavior of metals as a function of pH is shown in figure 7, and leach test results are summarized in table 3.

Comparing results for dump, tailings, and altered rock samples, leachate concentrations generally are highest in dump samples and lowest in altered rock samples (fig. 8). One sample of smelter slag was tested, and it released little acid and metals, reacting only slightly; other leach tests on slags from Colorado and Arizona produced similar results (Nash,

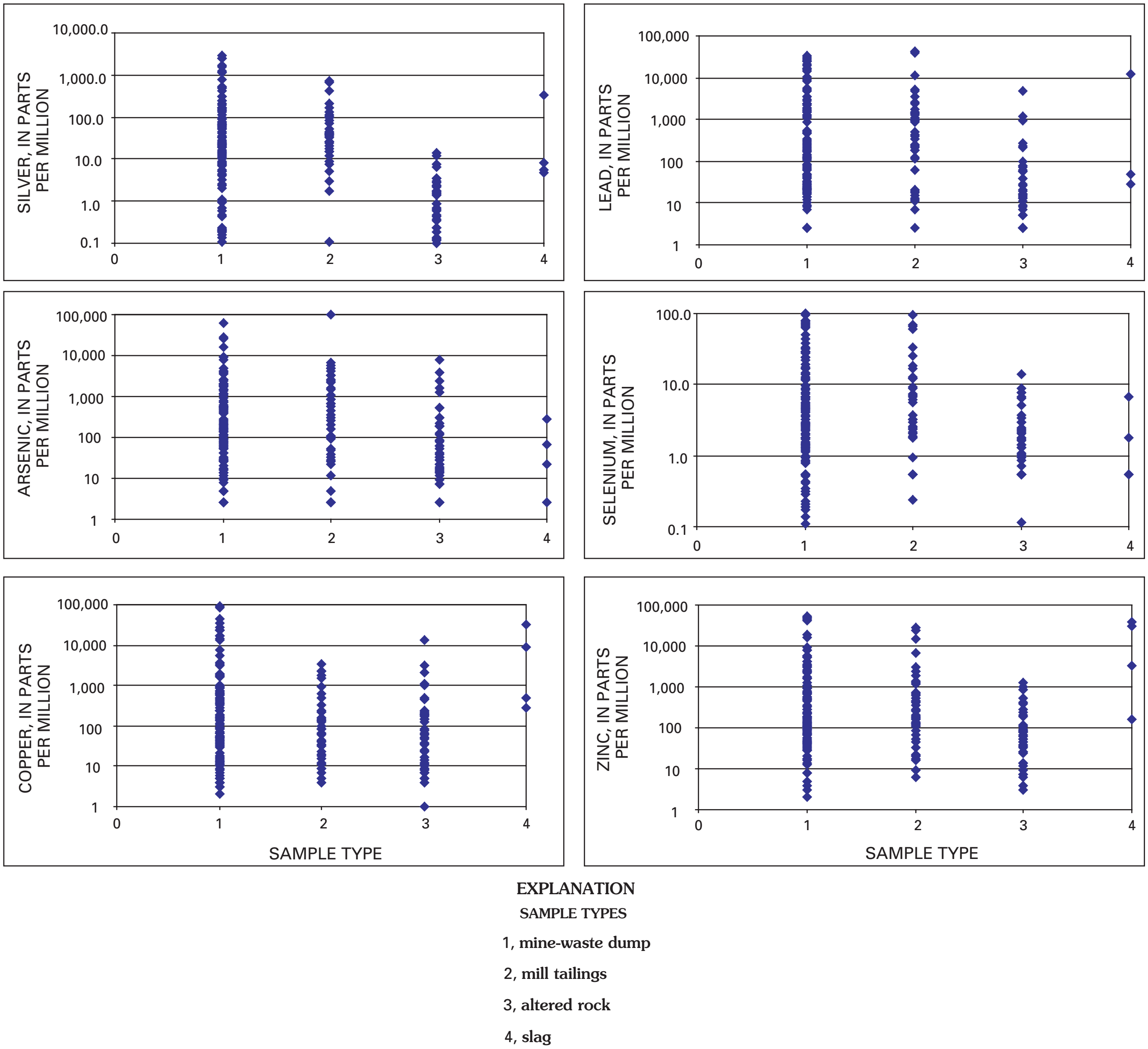


**Figure 6.** Range in chemical composition of mineralized materials by sample type.

2002a). There is wide variation in leachate concentrations within the groups of dump samples, tailings, or altered-rock samples. This wide variation is consistent with the range in dump compositions and differences in tailing composition from mill to mill or even from layer to layer within a tailings impoundment. The mobility of individual metals in leach tests is generally a function of pH, as in surface water (fig. 7; Nash, 2002a).

Trends for leachate compositions, grouped by deposit type, are shown in figure 9. Leachate compositions from samples of nine deposit types span a wide range, and the range within deposit types is large also. Generalizations are not reliable. Base metals and arsenic concentrations tend to be high in polymetallic, massive sulfide and acid sulfate deposit samples, but not exclusively so. I am more impressed by the overlap among the deposit types and the suggestion that waste from many deposit types can release significant levels of contamination.

# Introduction to Mine-Related Waters

Surface water adjacent to metal mines can be relatively pristine or highly contaminated by effluent from mine workings and associated waste products. Much has been learned from the study of acidic water associated with coal mining,

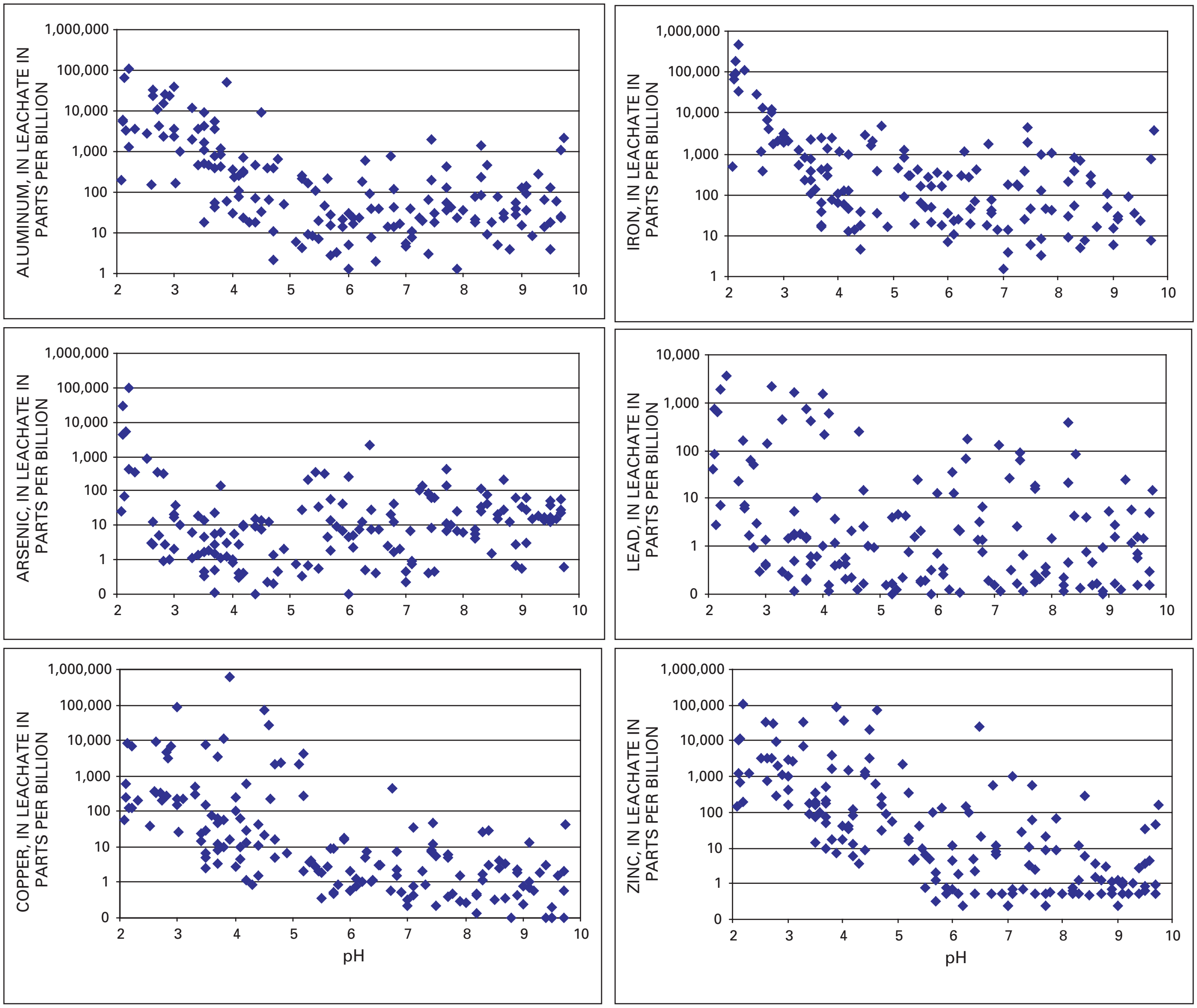


**Figure 7.** Range in leachate compositions as a function of pH.

and in recent years the focus of much research and regulatory action has shifted to contaminants associated with abandoned or active metal mines, mills, and smelters (Plumlee and others, 1999). In this study, surface-water samples were taken from as many sites and situations as possible to obtain facts on water compositions and scale of metal transport from mine sites (fig. 10). The following is a highly simplified summary of some of the major principles, largely taken from reviews by Smith and others (1994), Plumlee (1999), and Plumlee and others (1999).

## Acid Water

Why all the emphasis on acid-mine drainage and acid-rock drainage? In addition to being toxic to wildlife, acids are important for their ability to dissolve minerals and transport metals. Generally it is sulfuric acid at metal mines that initiates many of the concerns. Sulfuric acid is typically generated by weathering (oxidation) of pyrite or other sulfide minerals, often catalyzed by bacteria (Nordstrom and Alpers, 1999; Mills, 1999). Another source of acidity in near-surface water is the precipitation of Fe- and Al-oxyhydroxide minerals during which protons (hydrogen ions) are produced by hydrolysis reactions.

Acidic water has the ability to transport high concentrations of many base metals and also other elements of concern such as aluminum. This generalization is supported by theoretical models, laboratory reactions, and especially by water analyses in mining districts (Smith and others, 1994; Plumlee and others, 1999; Nash, 2002a). In numerous districts, and across many deposit types, there is a predictable relation: the more acid (lower pH), the higher the metal concentrations (fig.

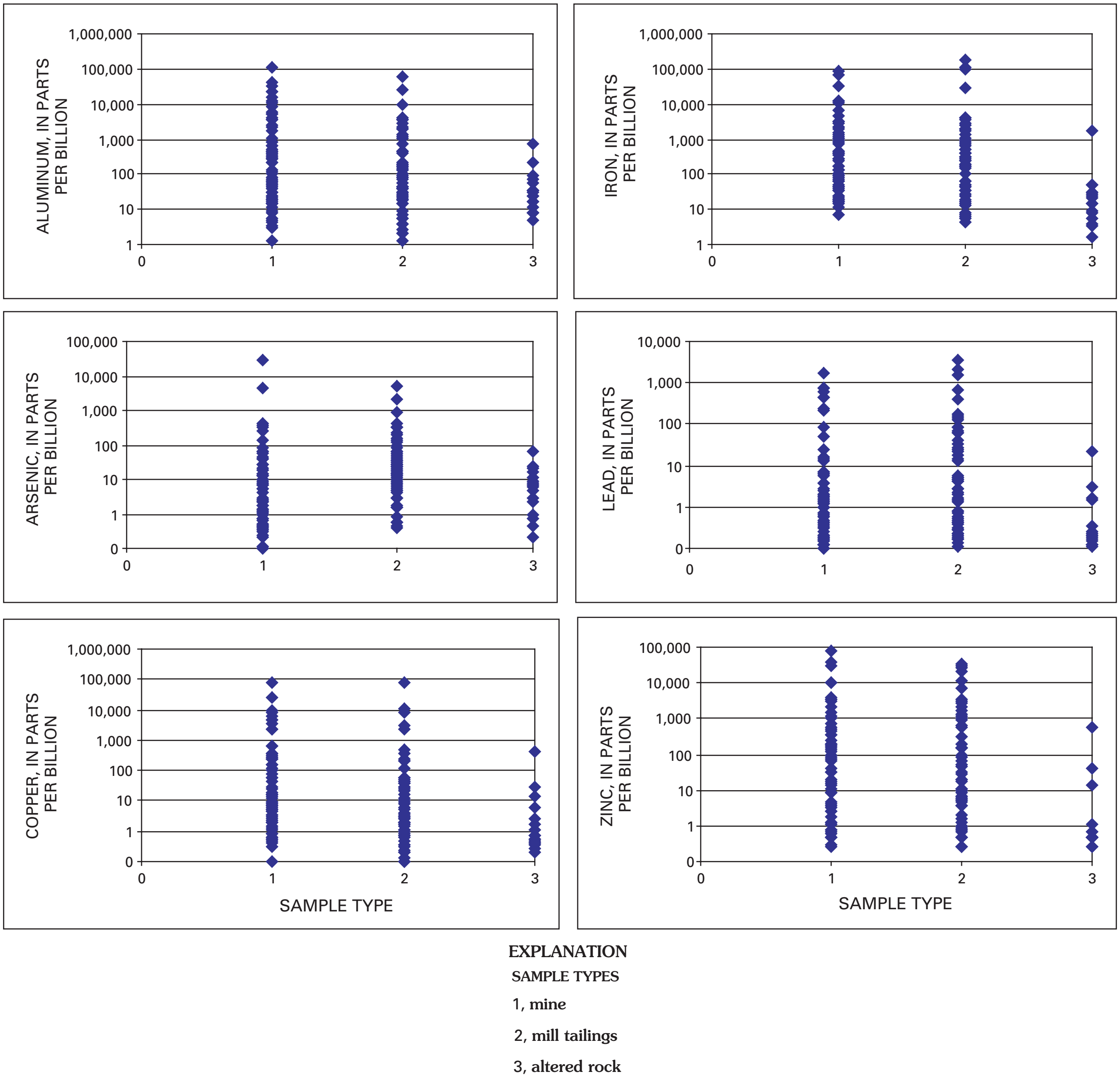


**Figure 8.** Range in leachate composition as a function of sample type.

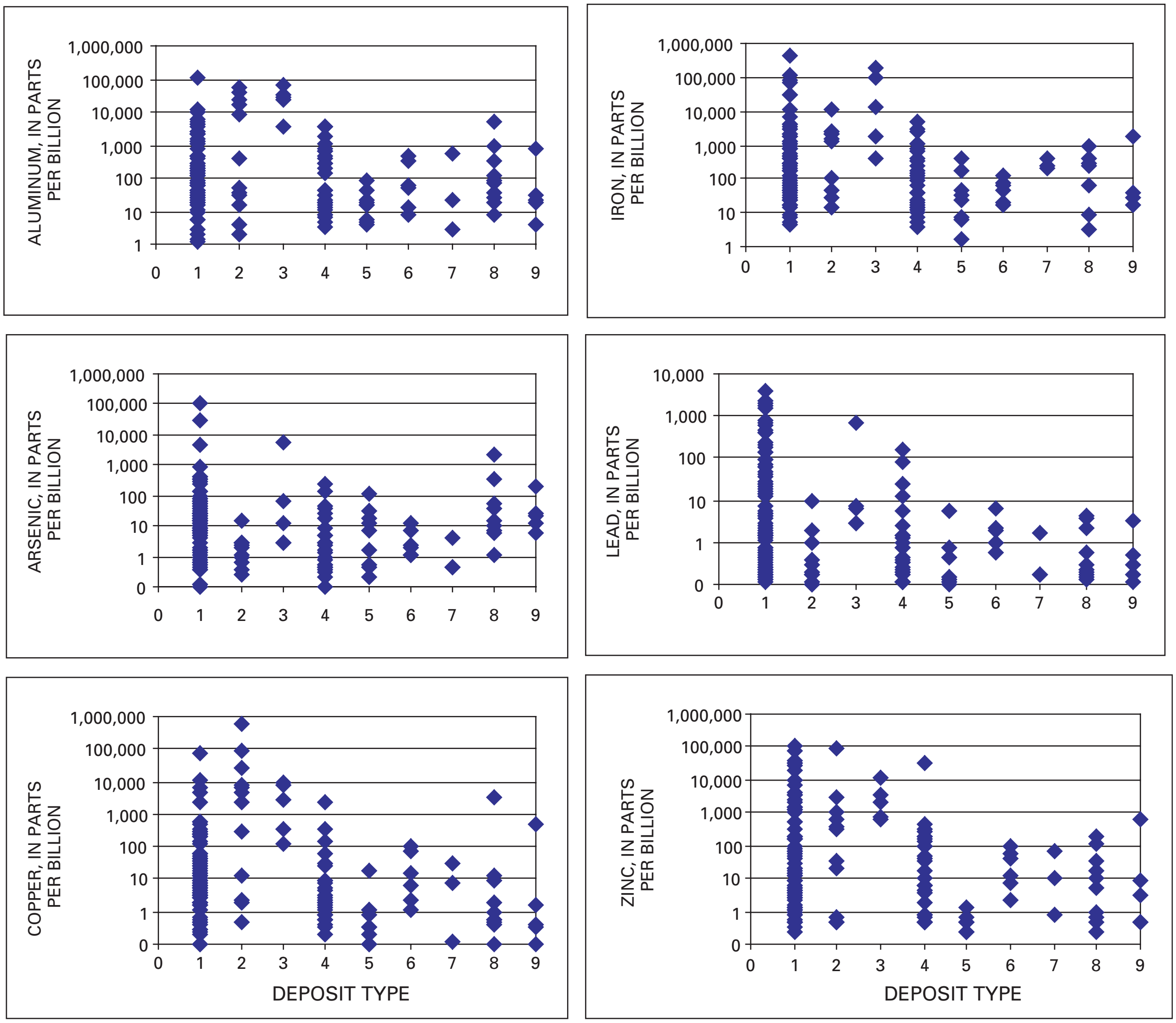
11). Acidic water can be as clear and as colorless (photo 18) as background water because the metals are held in solution.

## Water Composition and Deposit Types

The lithology of host rock and mineralogy of ores lead to some fairly predictable tendencies among deposit types, as discussed by Smith and others (1994) and Plumlee and others (1999). However, there is a wide range in composition within a deposit type, particularly the polymetallic deposits, and there are many exceptions to general “rules” for mine-drainage compositions. For the Humboldt Basin, the trends are summarized in figure 12. Highest concentrations of base metals tend to be from polymetallic and massive sulfide deposits (Big Mike is the example). Contrary to some popular assumptions, concentrations of As and Se are variable and approximately the same range for many deposit types.

## Alkalinity of Surface Water

One of the most striking characteristics of surface water in arid regions of the Western United States is their high content of Ca-Mg-$CO_3$, which also is apparent in measurements of conductivity and alkalinity values. Waters in the Humboldt Basin and many parts of the Basin and Range province generally has conductivity of 300 $\mu$S/cm or more



EXPLANATION

DEPOSIT TYPES

| | |
|---|---|
| 1, polymetallic | 6, vein uranium |
| 2, massive sulfide | 7, skarn |
| 3, acid sulfate | 8, sediment-hosted gold |
| 4, epithermal | 9, miscellaneous others |
| 5, mercury deposits | |

**Figure 9.** Range in leachate compositions as a function of deposit type.

and alkalinity of more than 200 mg/L $CaCO_3$. Alkalinity, the capacity of water to accept hydrogen ions (H+ or protons) and not a descriptor of pH, is generally not a function of contamination but of normal rock and soil reactions with water. In common water with pH of about 5 to 8.3, bicarbonate is the dominant base anion and Ca and Mg are the dominant cations (Manahan, 1994; Langmuir, 1997). Alkalinity of water is measured by titration and expressed as equivalent amounts of $CaCO_3$ in milligrams per liter. Surface-water samples from the study area have alkalinities in the range of 0 to 390 mg/L $CaCO_3$ and a median of 220 mg/L. As in all water systems, alkalinities of samples collected in the Humboldt Basin decrease below pH 7 and are small to nil below pH 5.

The high alkalinities of most water in the study area are potentially significant for natural processes of acid neutralization. These alkaline waters have high capacity to neutralize acidic water when the two mix. If one walks down a stream contaminated by acidic drainage, measuring pH and conductivity every hundred feet, changes in pH and conductivity document mixing with inflowing surface water or subsurface

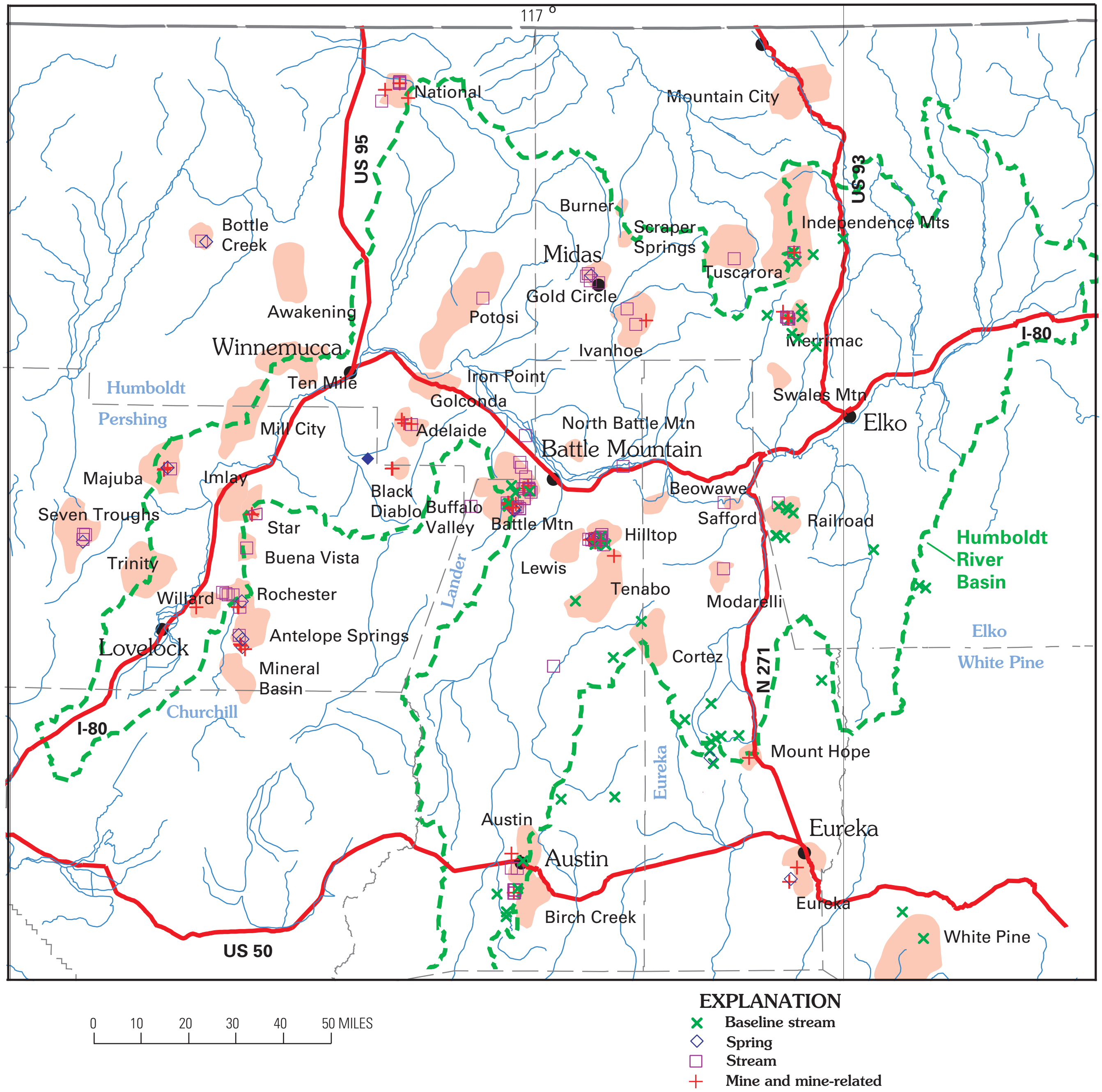


**Figure 10.** Location of water-sampling sites in northern Nevada. Four sample types are distinguished. District outlines are from Tingley (1998); only studied districts are shown.

springs. If the water is initially very acidic, with a pH of about 3, the water generally is clear (all metals are held in solution), but the water becomes cloudy red-brown and precipitates iron oxy-hydroxide minerals ("iron floc") a short distance after mixing as the rising pH causes iron and other base metals to precipitate. This is essentially titration, as done in the chemistry laboratory, of an acidic solution by a basic solution. This process is commonly seen in acidic drainages of Nevada and generally reflects mixing of water rather than reaction of an acidic solution with a rock such as limestone. Two environmentally important base metals that do not precipitate as quickly in the neutralization process are Zn and Cd, as will be discussed later.

## Buffering and Acid Neutralization by Rocks

Natural or engineered mitigation of acidic mine drainage involves raising the pH of water by consumption of hydrogen ions. Limestone, composed chiefly of the mineral calcite, is most effective for consuming acid, but reaction with other

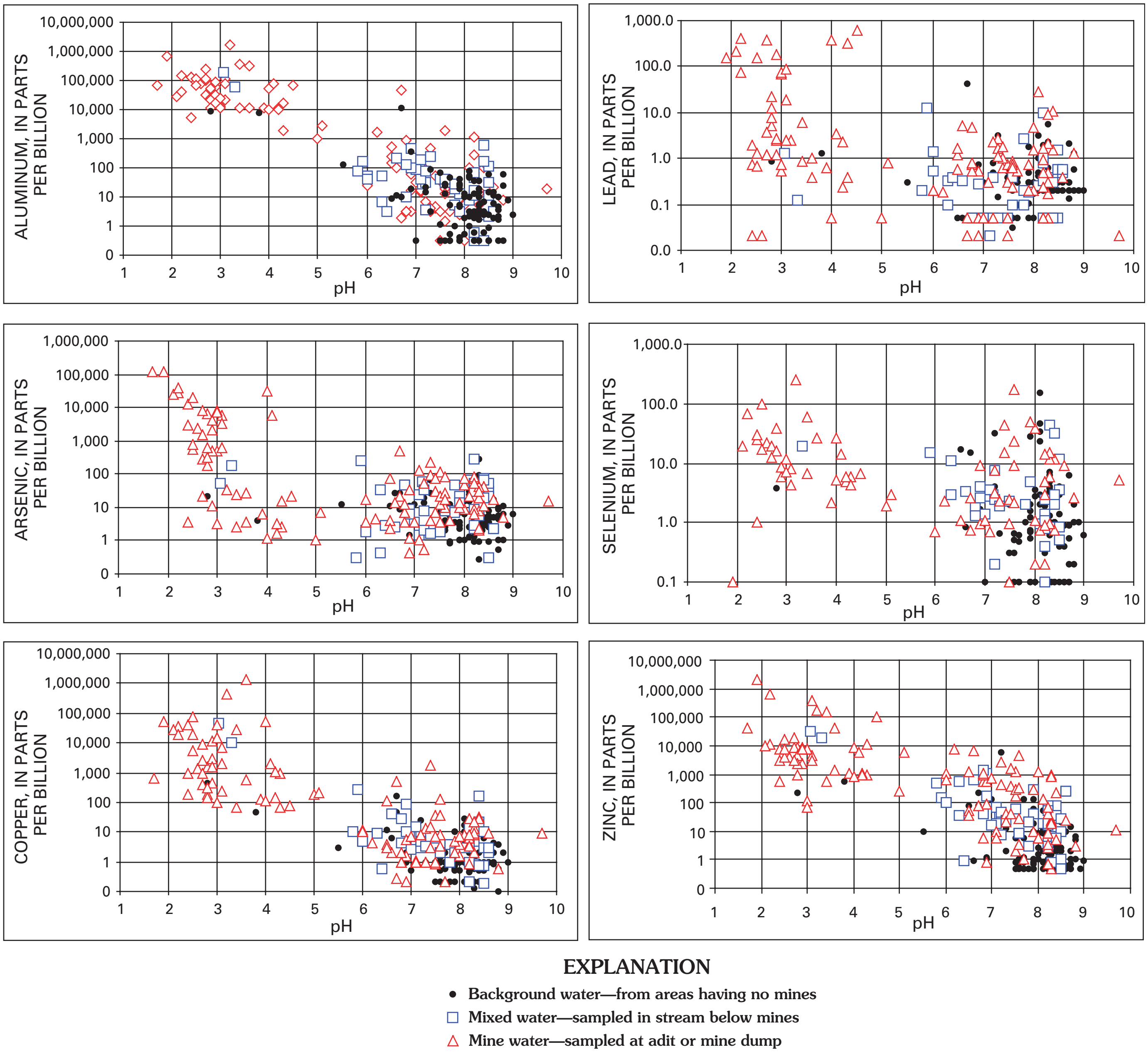


**Figure 11.** Metal concentrations and pH values of mine-related and other surface water.

minerals also consumes acidity, albeit more slowly than for carbonate minerals. Ion-exchange reactions, as with clay minerals, also helps. Acid-neutralization capacity refers to the amount of hydrogen ions that can be consumed per unit weight; chemists would express this as moles per gram. We can consider pure calcite to have very high capacity, whereas that for quartz is nil; for rocks, limestone (composed mostly of calcite) is high, shale (a mixture of clay, quartz and often some calcite) is moderate, granite is low, and sandstone is very low (unless calcite is present and then it can be quite high). Veinlets of calcite can make an otherwise low-capacity rock have high acid-neutralizing capacity.

Estimates of the acid-neutralizing capacity of geologic materials tend to underestimate the widespread occurrence of small amounts of calcite and other carbonate minerals, which are very reactive and overemphasize reactions involving feldspars and clay minerals (for example, Glass and others, 1982). Also, the estimates generally fail to acknowledge the large amount of calcite in alluvium as caliche or the abundance of narrow calcite-bearing veins because these are not easily seen or sampled at the surface. One easy and effective way to estimate rock and soil acid-neutralizing capacity is measuring pH at springs—values in the range 7–8.5 are caused by reactions with carbonate somewhere in the flow path of the water. Water

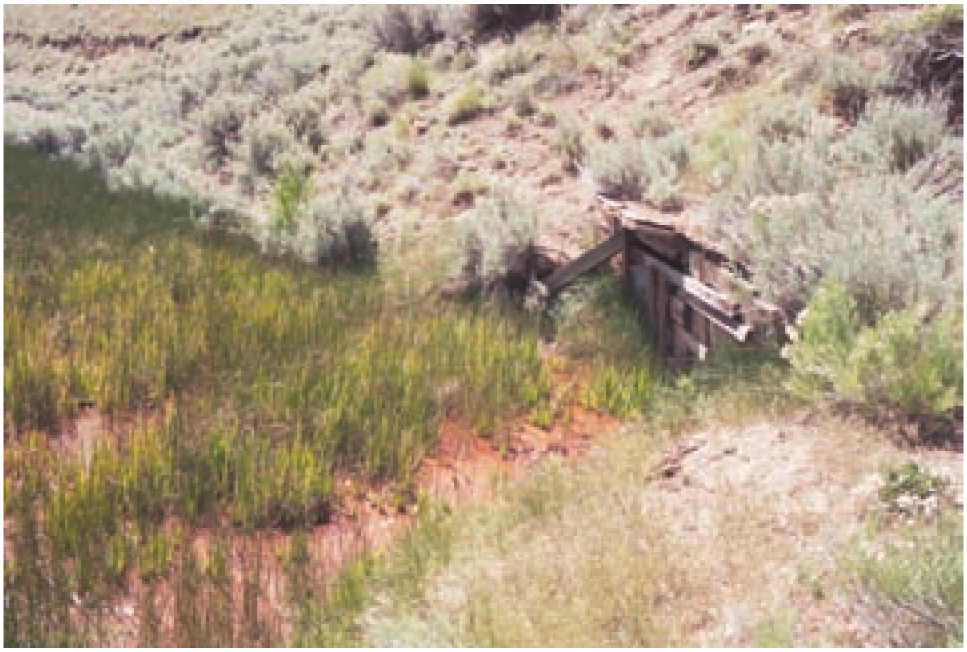
**Photograph 15.** Mine waste dumps are created when rocks are excavated while mining ore. Mine dumps contain altered and mineralized rocks that were not sufficiently rich in ore minerals to merit milling. The materials range in size from fine clays to large boulders and are geochemically enriched in metals relative to unmined rocks.

**Photograph 16.** Slag is a dense, vitreous, black material produced by smelters when ores are melted to separate lead, silver, or other metals. This is a relatively large pile of slag in Tybo Canyon from a smelter that operated in the 1870's.

with alkaline pH can neutralize acidic water, as described previously, or the solids (calcite, biotite, clays) can consume the $H^+$ by several kinds of reactions.

## Reactions that Remove Metals

Mitigation of water quality requires that toxic metals be removed, either by sophisticated engineered systems that are expensive to build and maintain or by some simple reactions in nature. Many reactions occur (Smith and others, 1994; Smith, 1999), including precipitation, sorption, hydrolysis, and reduction. Sorption combined with coagulation of colloids is very effective in nature and generally occurs in response to an increase of pH; we see the result of these processes in the red-brown materials in streambeds and coatings on stream cobbles (iron-oxyhydroxides with entrained trace elements). Among the heavy metals of concern, Pb is the first to be removed by sorption as pH rises from 3 to about 4; Cu tends to be next at pH 4–5, then Zn at pH 5–6, and finally Cd and Ni at pH 6–7 (Smith, 1999). Arsenic is effectively removed by sorption if iron concentrations are high. In nature, these sorption reactions are most effective where Fe-rich colloids coagulate as pH rises

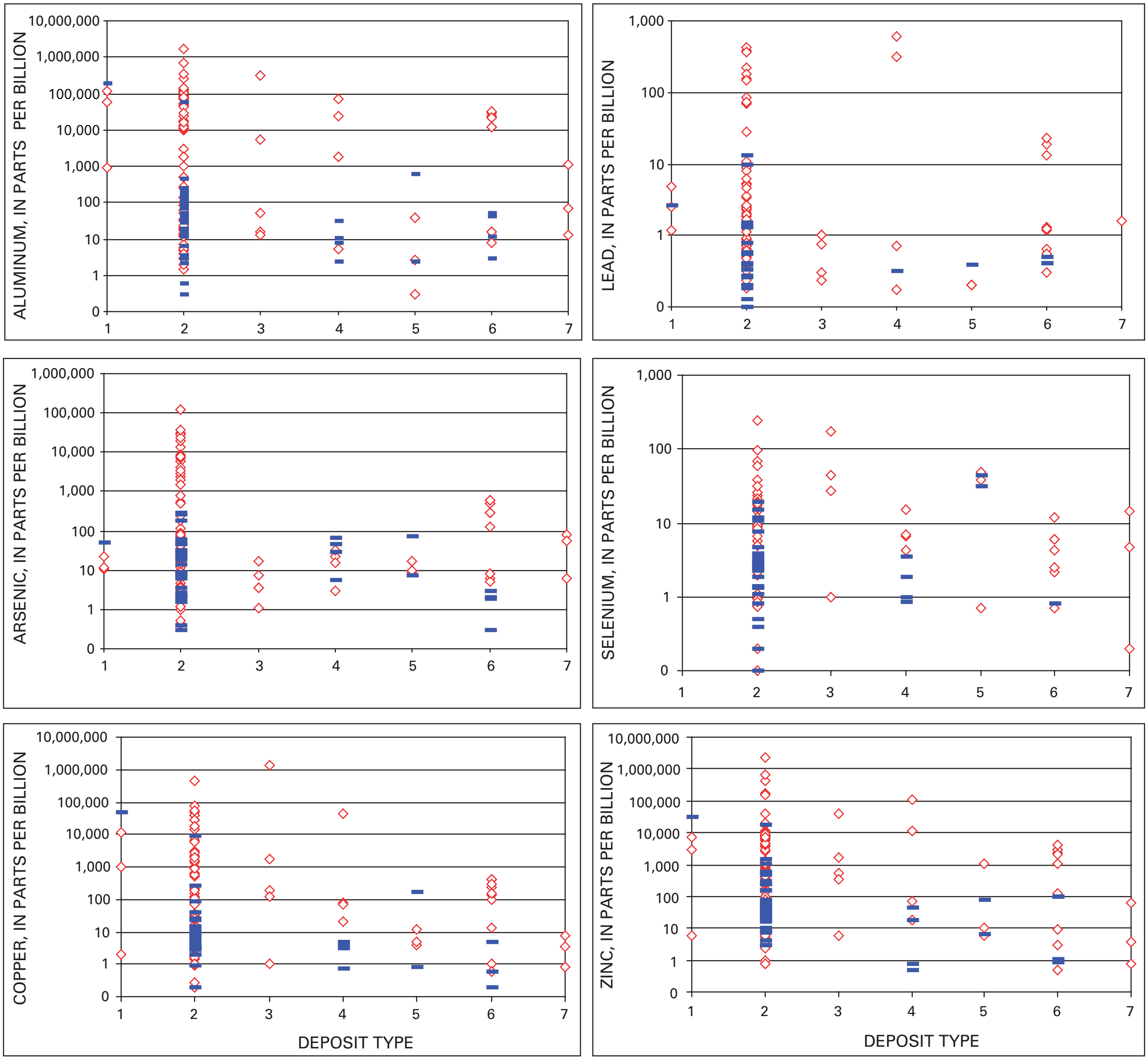


**Photograph 17.** Mine drainage can flow from mine workings for many years after mining was terminated, as in the Leadville mine that was last active in the 1920's. Mine drainage only flows from horizontal mine tunnels, not from mine shafts. The red-colored water is a common feature, caused by the precipitation of iron-oxyhydroxide minerals as the mine waters pick up oxygen outside the mine.

**Photograph 18.** Highly acidic water can be difficult to recognize in the field because it generally is clear and may not produce any visible precipitates at the site. This clear mine drainage in the Hilltop district has a pH of 2.3 and does not appear contaminated until the pH rises on mixing with alkaline waters that cause red iron phases to form.

in zones where acidic waters mix with those of near-neutral pH or contact acid-consuming rocks.

Other transport and deposition mechanisms operate at pH 6–8 for metal-oxyanions, such as arsenate, molybdate, and selenate. These toxic metals are quite mobile in near-neutral to alkaline pH water and pose a distinctly different set of environmental problems because raising pH only enhances their solubility. Sorption and dilution will help reduce the concentrations of these elements, but other natural processes do not appear to be effective in reducing them. If water quality does not meet standards for these oxyanions, the only remedial action may be engineered water systems. Zinc and Cd, which do not form oxyanions, also have fair solubility at neutral pH. In several watersheds, natural mitigation processes neutralize initially acidic water and decrease the concentrations of most metals below concern levels. However, concentrations of Zn, Cd, As, Mo, or Se remain high in some surface water at pH 6–8.



**EXPLANATION**

**WATER TYPES**

▬ Mixed water—sampled in stream below mines or mill tailings

◇ Mine water—sampled at adit or mine dump

**DEPOSIT TYPES**

1, acid-sulfate
2, polymetallic vein
3, massive sulfide
4, skarn
5, sediment-hosted gold
6, epithermal vein
7, mercury

**Figure 12.** Metal concentrations in surface water in relation to deposit types.

# Frameworks for Evaluating Hydrogeochemistry

Specialists and generalists alike need a frame of reference for proper understanding of the hydrogeochemical information collected in this study. Unfortunately, there is no single, simple framework that meets all needs. Environmental scientists and regulators currently use two fundamentally different methods to evaluate water: some express water quality in terms of concentrations, such as parts per billion, and others express it as loads, such as pounds per day. The load of a metal or other constituent is the product of its concentration multiplied by the flow volume in the pipe or stream to yield a value with units such as pounds per day. Thus, the load calculation requires measurement of flow, such as cubic feet per second or gallons per minute, as well as concentration, such as parts per billion. The system of concentrations has been traditionally used by research biologists, hydrologists, and geochemists, whereas the system of loads is coming into increased use by land managers and regulators after the method of Total Maximum Daily Loads (TMDL) was introduced in 1972 in the Clean Water Act, as discussed herein.

For the evaluation of metal concentrations in water, some geochemists advocate the use of compendia on world- or content-scale water-quality analyses (for example, Livingstone, 1963; Forstner and Wittmann, 1979). Another approach is to compare the water in mining areas with the composition of water from nearby basins that have little or no mining—this will be discussed next. A third approach is to use the framework defined by toxicologic studies and regulatory agencies such as the U.S. Environmental Protection Agency (USEPA) and State agencies. The regulatory standards of the Nevada Division of Environmental Protection (NDEP) will be introduced and discussed later in this section.

## Geology-Based Reference Values

Background and baseline compositions of earth materials and water provide a realistic scientific framework for evaluating compositions present in mining areas. In this report “background” will be defined as a composition prior to the influence of humans or mining. Baseline compositions, which include contributions from humans and mining, should include a date of reference. For example, the composition of surface water and alluvium in the Battle Mountain or Eureka areas presumably has changed over the past 130 years (and may have been most degraded during unconstrained mining and smelting of the 1890’s). Miller (2000) reported water compositions from streams and springs in four lithologies at sites believed to have little or no anthropogenic influence. Building on Miller’s work, I collected samples in June 2000, from springs and headwater streams that appear to represent either background conditions in unaltered rocks (minimum influence of humans) or background conditions in visibly altered rocks (possibly small influence of prospecting), the results of which are summarized in table 5 and figure 13.

The composition of water logically reflects the rocks and minerals that react with the water as it flows on the surface or underground, and this was well demonstrated by Miller (2000) with analyses from headwater basins in four geologic settings. My samples are from diverse settings, and the number of samples for various lithologies is small (two to five). Because it is logical to suspect that various geologic settings would influence water compositions, background water compositions have been plotted by geology of the headwater basin that was sampled (fig. 14). There are a few trends, but these may not be significant considering the small number of samples averaged to make the datapoint and the lithologies are only crudely defined. Visibly altered bedrocks appear to be sources for higher concentrations of many elements. Arsenic tends to be enriched in water from volcanic and granitic terranes and Cu and Mo are enriched in some samples from granitic terranes. Two widespread shale units, the Vinini and Chainman Formations, are the carbonaceous variety that commonly are metalliferous, but the associated water compositions are not clearly metal-enriched unless the rocks are altered. Much more sampling will be required to demonstrate compositional relationships to source rocks, particularly the concentration of base metals.

Regardless of source lithology, the metal concentrations in basins having no mining and no visible alteration are very low—far below regulatory water-quality standards. However, water compositions related to visibly altered rocks and scattered small prospects are significantly different from those in unaltered rocks (table 5; fig. 14). Another notable attribute of water from altered rocks is a much higher variation in metal concentrations: not only are mean concentrations higher, some individual samples can be tenfold to a hundredfold higher than those from similar unaltered lithologies. The concentrations of potentially toxic metals in water associated with altered rocks approach regulatory standards, and some individual headwater stream or spring samples do not meet those standards. Sulfate concentrations can be elevated in water that has reacted with unmined altered rock, but Cl and F concentrations are generally not elevated in unmined sources. Because large volumes of rocks in mountain ranges are altered, metal loads from these areas could be significant and should be taken into account in TMDL considerations, described herein. However, in the general framework of metal concentrations used in this report, the concentrations in water from altered rocks having no or minor mining are significantly lower than in streams, seeps, or runoff from mines and mine waste.

## Biology-Based Standards

Toxicity and health effects of water are generally related to concentrations of contaminants (Manahan, 1994; Smith and Huyck, 1999), and these values are the scientific basis for regulatory standards adopted by the USEPA, NDEP, and other

**Table 5.** Summary of water compositions from background stream and spring samples, northern Nevada.

[Analytical values for metals from ICP-MS, anions by ion chromatography, and alkalinity by titration (in mg/L $CaCO_3$); background stream and spring samples collected at sites remote from mining; background-altered stream and spring samples are from areas having visible rock alteration but minor influence of mining. <, less than; µS/cm, microsiemens per centimeter]

| | | Background waters (*n*=38) | | Background-altered waters (*n*=15) | |
|---|---|---|---|---|---|
| **Feature** | **units** | **Median** | **Maximum** | **Median** | **Maximum** |
| pH | | 8.3 | 7.0* | 8.2 | 7.5* |
| Conductivity | µS/cm | 313 | 870 | 347 | 710 |
| Al | (ppb) | 2.4 | 44 | 5.6 | 64 |
| As | (ppb) | 3.6 | 18 | 4.4 | 16 |
| Cd | (ppb) | <0.02 | 2.0 | <0.02 | 0.3 |
| Cu | (ppb) | 0.9 | 2.0 | 1.0 | 2.0 |
| Fe | (ppb) | 39 | 140 | 62 | 83 |
| Mn | (ppb) | 2.8 | 29 | 2.1 | 100 |
| Mo | (ppb) | 1.6 | 16 | 1.6 | 71 |
| Pb | (ppb) | 0.2 | 1.9 | 0.3 | 2.3 |
| Sb | (ppb) | 0.3 | 2.3 | 0.3 | 1.4 |
| Se | (ppb) | 0.9 | 4.0 | 1.0 | 6.2 |
| U | (ppb) | 1.7 | 19 | 1.0 | 7.0 |
| Zn | (ppb) | 1.0 | 130 | 1.5 | 6.0 |
| Cl | (mg/L) | 6.0 | 120 | 8.0 | 64 |
| F | (mg/L) | 0.3 | 0.8 | 0.3 | 0.6 |
| $SO_4$ | (mg/L) | 24 | 190 | 34 | 240 |
| Alkalinity | | 160 | 290 | 160 | 240 |

* Maximum pH is maximum acidity (minimum pH value).

State agencies. These standards generally are based on beneficial use and toxicity to humans or aquatic life. Biologists debate the details of just which species should be protected by the water-quality criterion, such as the differing sensitivities of trout species to heavy metals (Besser, 2000), but such details are not relevant in this study. However, there are questions as to what general quality standards should be applied to surface water in the historical mining areas of Nevada. These waters are regulated by the Nevada Division of Environmental Protection (Nevada Division of Environmental Protection, 2002), but the system is not as easy to follow as in some States, such as Colorado, that list short segments of headwater and mainstem streams, their beneficial uses, and the relevant quality standards. The Nevada system will be discussed in a later section.

To provide a biology-based framework for evaluation of water quality, I will compare water compositions to the Aquatic Life Water-Quality Standard (ALWS), shown in table 6. These ALWS concentrations are used here as a general guideline and to allow comparison among districts, but in detail other regulatory standards may be appropriate. For example, the fine print of Nevada Division of Environmental Protection regulations (http://ndep.nv.gov/nac/445a-118.pdf) stipulates that the most stringent criterion be applied if there are multiple uses—which means that the criteria for As or Pb in drinking water will apply, and the criteria for Cd, Hg, and Se for aquatic life will apply because they are more stringent than for drinking water.

To preview discussions that follow, analytical results for 275 water samples at 241 sites show that many kinds of mining-contaminated water at mine portals, from waste dumps or tailings impoundments, or in puddles and ponds, have degraded water quality. Relative to the criteria in table 6 (bold), the following percentages of sites have compositions that do not meet the water-quality standards: Zn, 44 percent; Fe and Cu, 42 percent; Se, 41 percent; Cd, 37 percent; Mn, 32 percent; As, 30 percent; Al, 22 percent; Mo, 16 percent; Pb, 8 percent; and U, 6 percent. From these numbers we can anticipate that Zn, Cu, and Fe are most likely to be present in concentrations that pose health threats, whereas concentrations of U and Pb are less likely to be concerns. But these statistics are only part of the story; the real questions are: how typical are the high metal concentrations in surface water, and how far do they persist beyond the mining property?

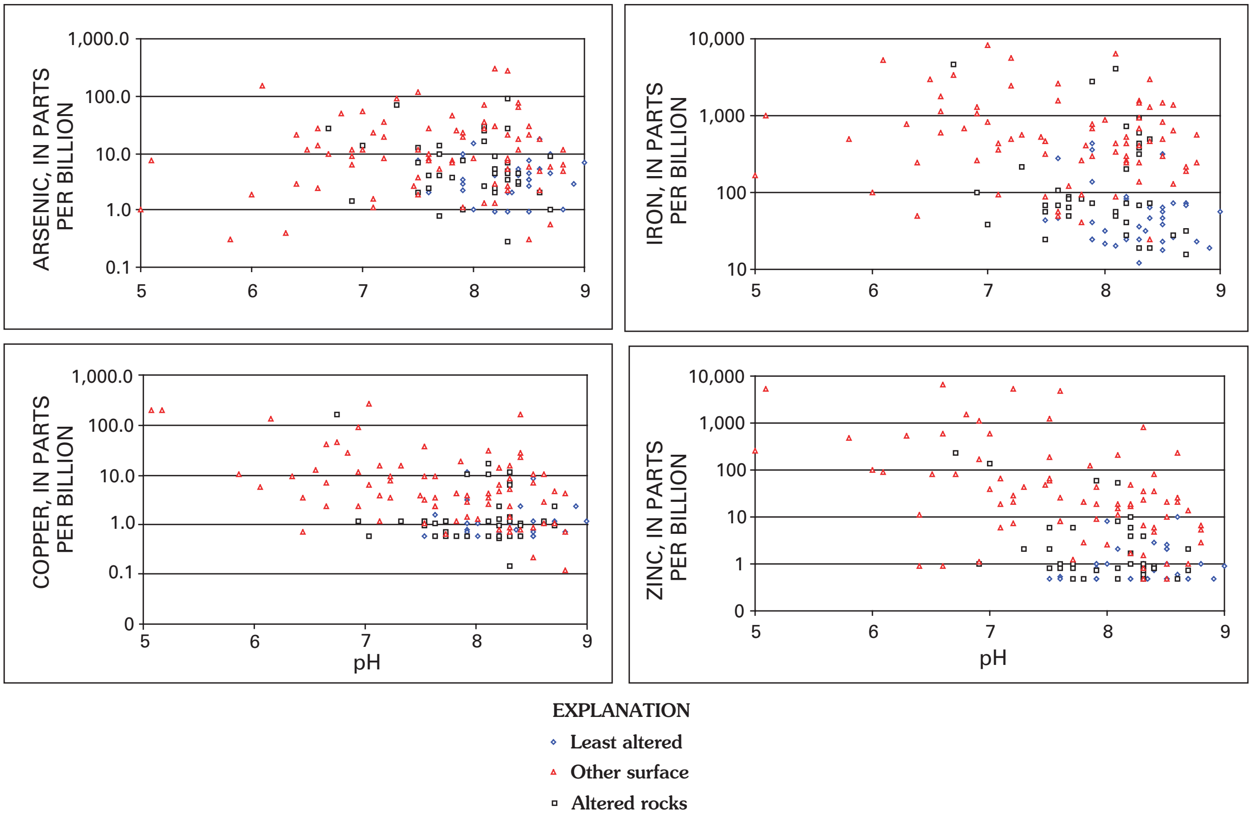


**Figure 13.** Composition of surface water from background and weakly mineralized rocks, northern Nevada. Background water compositions are defined as those from least altered rock; waters from altered rock define another kind of background; the surface waters have variable amounts of input from mines; surface waters with pH values of 2 to 5, not plotted, generally have higher metal concentrations.

## Flow Volumes of Surface Water

The volume and duration of water flow, significant parameters in the hydrogeochemistry of northern Nevada, can be difficult to visualize. Whether measured in gallons per minute (gal/min) or cubic feet per second ($ft^3/s$), the flow volumes observed in northern Nevada span a huge range. Seeps or flows from an abandoned mine may be a few gallons per minute, and a creek that is too wide to jump may flow at about 2 $ft^3/s$ (900 gal/min). The Humboldt River at Battle Mountain has an average flow of about 40 $ft^3/s$ (18,000 gpm), increasing to more than 1,000 $ft^3/s$ at flood stage. Dewatering programs at the large gold mines use pumps capable of withdrawing more than 1,000 gal/min, and collectively the discharge can be in the range of 10,000 to 50,000 gpm (Barrick Goldstrike Mines Inc., 2000). In the late 1990's permitted discharges of mine water into the Humboldt River were approximately 70 percent of the mean flow of the Humboldt at Palisade (Horton, 2001).

**Table 6.** Aquatic life and domestic drinking water-quality standards for Nevada.

[From Nevada Division of Environmental Protection, 2002; values in bold are most likely to be applied; concentrations in parts per billion or micrograms per liter ($\mu$g/L]

| | Aquatic life | Drinking water | | Aquatic life | Drinking water |
|---|---|---|---|---|---|
| Ag | **0.15*** | | Mo | **19** | |
| As | 180 | **5** | Pb | 50* | **50** |
| Cd | **5*** | | Se | **5** | 50 |
| Cu | **10*** | | Sb | | **146** |
| Fe | **1,000** | | Tl | | **13** |
| Hg | **0.05** | 2 | Zn | **100*** | |
| Mn | **1,000** | | | | |

Note: values shown with * should be adjusted for hardness; the values shown are for typical hardness of surface water in the area, 200–300 mg/L. Values in bold are most likely to be applied to multiple-use water.

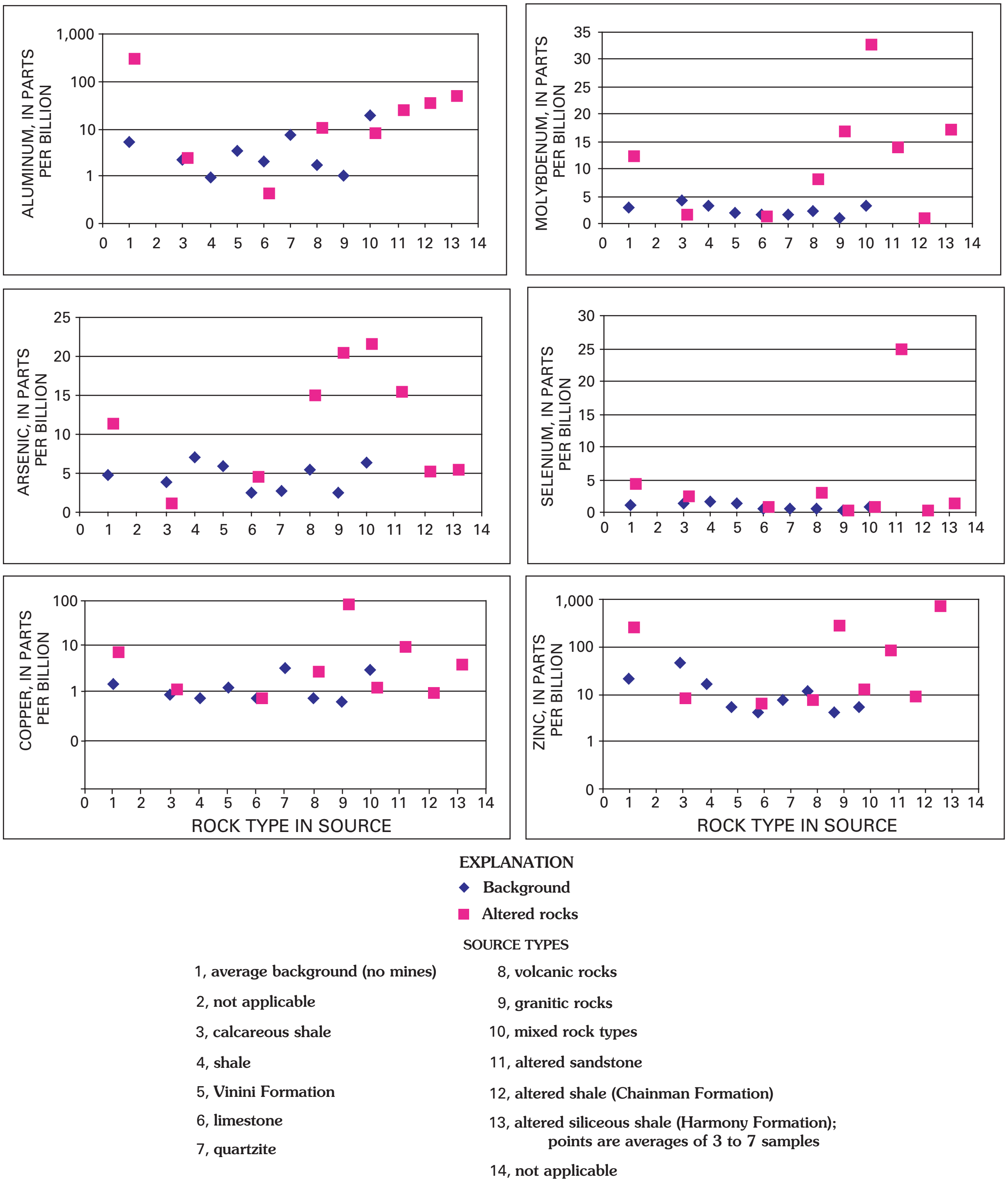


**Figure 14.** Metal concentrations in background samples as a function of rock type.

Many streams in northern Nevada flow a few hours a decade, and a few have perennial flow. Maps can be misleading: the Reese River appears to be a major river about 65 mi long, but for most of that distance and on most days one can step across the barely flowing stream. Another major tributary of the Humboldt River, Rock Creek in northern Lander County, has vertical banks 10 to 20 ft high that attest to deep and raging floodwater a few times per century. The major springs that are shown on topographic maps generally flow at the surface for only a few hundred feet before disappearing into alluvial gravel. Whenever we speak of flowing water, it is important to try to visualize when it was flowing and how typical that flow may be. In my studies it was not possible to make systematic measurements of flow or to collect samples throughout the water year.

A nagging question behind all of the hydrogeochemical studies described here is: how typical is that water for this site or area? And, is it significant if the contaminated water flows only a few days a year? Another set of nagging questions deals with loads: are the loads from a mine drainage with flow of a few gallons per minute important at watershed scale? In the next section, metal loads for the Humboldt River, including pit-dewatering discharges at concentrations that comply with standards, will be shown to be much larger than for the metal-rich, low-volume mine seeps.

## Metal Loads and Total Maximum Daily Loads

The Clean Water Act requires that State agencies develop standards based on loads rather than concentrations, and on the use of TMDL's in watershed planning. TMDL is explained elsewhere (http://www.epa.gov/owow/tmdl and http://www.nv.us/ndep/bwqp/tmdl) from which the following is extracted. A concept introduced in 1972 and refined in 1985, TMDL is a calculation of the amount of a pollutant that a water body can receive and still meet water-quality standards for health and beneficial uses. The TMDL definition starts with the water quality standard for the identified beneficial uses. The TMDL is the sum of the loads of a single metal or pollutant from all point and nonpoint sources and thus includes discharges from industrial facilities, farms, sewage facilities, and natural sources. Inclusion of natural nonpoint sources is important as this requires evaluation of discharges from unmined altered rocks in mining districts. The process of defining TMDL's is complex, but Section 303(d) of the Clean Water Act stipulates that TMDL's must be implemented on impacted watersheds sometime in the next decade.

Although toxicity and health effects of water are generally related to concentrations of contaminants (Manahan, 1994; Smith and Huyck, 1999), there has been increasing use of metal loads for watershed management (Black, 1996). Metal loads, defined as the metal concentration times flow volume and expressed in terms such as pounds or grams per day, provide an alternative way, and metal loads can be used to evaluate or rank mining-related water contamination. One complication is the need for a measurement of streamflow, which is a complicated task and one that the author can do only as a visual estimate for small flows in the 1- to 300-gal/min range. Examples of metal loads are in table 7, in which loads (in grams per day, g/day) are computed for four sources and the consequent downstream flows after mixing and attenuation. The loads are compared with those computed for the Humboldt River. All of these figures are approximate, with an uncertainty of about ±100 percent (for uncertainties in both analytical values and in Q, flow volume). The Humboldt River analyses (three) are for samples I collected from the main stem near Battle Mountain. The loading values are easiest to grasp when considered relative to other values in the same units (grams per day):

1. Metal load values decrease significantly downstream from the sources; the in-stream values are low compared to those at the source adits or seeps;
2. Metal load values for all metals at mine sources are low in comparison to those of the Humboldt River, chiefly because of the multiplier effect of flow volume.

A good example of the load value "paradox" is in the values for As: the concentration of As is relatively low (8 to 9 ppb) in the Humboldt River, well below the drinking-water standard, but the load value of 10 g/day is much higher than for the mine drainages having 1 to 4,300 ppb As. Likewise, for Cu and Zn the concentrations in the Humboldt River are very low (3 and 1 ppb, respectively), but the loadings are a hundredfold higher than the highly concentrated but low-flow mine drainages containing 0.3 to 6,100 ppb Cu and 2 to 7,300 ppb Zn (three atypical samples are excluded). The sampled mine waters do not flow directly into the Humboldt River. The loadings described here are simply compared to the Humboldt River, the area's largest flow of water, for comparison.

The concept of loads reminds us to think of the total amount of metal released from a source. Although the details are complex, it is helpful to contemplate the differences between such scenarios as (1) a 1-gal/min seep of acidic, metal-rich (5,000 ppb As) water from a mine dump; (2) a large streamflow (thousands of gallons per minute) carrying relatively low metal concentrations (10 ppb As); and (3) a mountain of altered volcanic rocks (unmined) containing disseminated sulfide minerals that weather and release acid and metals to runoff and ground water. In this study, it was not possible to quantify the flow parameter for discharges, although visual estimates were made; especially, it was not possible to quantify the numerous small springs and seeps that hydrologists term "diffuse sources" in a mountain range. At places in the descriptions of mining districts, comments will be made on metal loads in an attempt to translate the geochemical information into the new system of loads and TMDL's.

# Hydrogeochemical Investigations of Historical Mining Districts

Investigations made by the author from 1995 to 2000 were in 50 mining districts (21 outside of Humboldt River Basin), at selected historical sites that allowed access. The approach was to examine and sample the mines that had relatively large production because I assumed that the larger operations would have more effect than smaller prospects and mines—they disturb more ground and create larger waste dumps, and most have associated mills and tailings. Mining districts in the western part of the Humboldt Basin were described in a previous report (Nash, 2001) and are only briefly described here. The following district descriptions emphasize the districts in the central part of the Humboldt Basin. Reference is made to some districts outside of the

**Table 7.** Examples of metal loads from mining areas compared to Humboldt River.

[Explanation: Cond., conductivity, in microsiemens; Watyp, water type: MD, mine drainage; SW, stream; SWL, stream leaving mining area; TPW, tailings pore water; Q, flow in gallons per minute (gal/min); LRH, load relative to Humboldt River; loads in grams per day (g/day); >, greater than]

| Sample ID | pH | Cond. | Watyp | Q gal/min | Al g/day | Al LRH | As g/day | As LRH | Cu g/day | Cu LRH | Fe g/day | Fe LRH | Zn g/day | Zn LRH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BATTLE MOUNTAIN DISTRICT** | | | | | | | | | | | | | | |
| NNW131 | 3.0 | >2,000 | MD | 2.5 | 0.18 | 0.00 | 0.11 | 0.01 | 0.19 | 0.03 | 2.86 | 0.01 | 0.10 | 0.23 |
| NHW834 | 8.5 | 510 | SWL | 25 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.11 | 0.00 | 0.00 | 0.01 |
| **HILLTOP DISTRICT** | | | | | | | | | | | | | | |
| NHW498 | 2.7 | 1,740 | MD | 2.5 | 3.38 | 0.09 | 0.11 | 0.01 | 0.12 | 0.02 | 3.01 | 0.01 | 0.11 | 0.26 |
| NHW505 | 7.1 | 470 | SWL | 25 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.01 |
| NN0W320 | 7.8 | 414 | SWL | 250 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.03 | 0.06 |
| **MERRIMACK DISTRICT** | | | | | | | | | | | | | | |
| NHW650 | 1.8 | 2,500 | TPW | 0.1 | 0.35 | 0.01 | 0.10 | 0.01 | 0.03 | 0.00 | 2.63 | 0.01 | 0.74 | 1.72 |
| NNW995 | 7.9 | 444 | SWL | 5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 |
| **NATIONAL DISTRICT** | | | | | | | | | | | | | | |
| NHW629 | 3.1 | 1,430 | MD | 10 | 1.13 | 0.03 | 0.03 | 0.00 | 0.01 | 0.00 | 6.27 | 0.01 | 0.16 | 0.37 |
| NNW120 | 2.7 | 1,415 | MD | 10 | 1.64 | 0.05 | 0.02 | 0.00 | 0.02 | 0.00 | 1.47 | 0.00 | 0.16 | 0.38 |
| NNW124 | 6.0 | 202 | SWL | 500 | 0.14 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.30 | 0.00 | 0.27 | 0.63 |
| **HUMBOLDT RIVER** | | | | | | | | | | | | | | |
| Average of 3 | 7.8 | 370 | SW | 225,000 | 35.9 | 1.00 | 10.4 | 1.00 | 5.88 | 1.00 | 438.6 | 1.00 | 0.43 | 1.00 |

Humboldt River Basin for the information that they provide as analogs to mining areas within the basin.

## Adelaide District (Gold Run)

*Location.*—East side of Sonoma Range, 10 mi south of Golconda in, Humboldt County (fig. 15). Features are shown in figure 16.

*Major commodities.*—Au, Ag, Cu, Pb, Zn

*Mining history.*—District was organized in 1865; a burst of activity in 1897–1910 included building a narrow gauge railroad from Golconda, a smelter at Golconda and expansion of mines (Lincoln, 1923). The Adelaide and Adelaide Crown mines were the major producers prior to 1940 and were served by a major mill; the underground mines and mill did not reopen after World War II. An unsuccessful attempt was made to bulk mine the lode Ag-Au ores in the period 1989–91 by small, open-pit operation to recover Ag and Au by cyanide heap-leach methods.

*Status of mining and exploration.*—No mines were active in the late 1990's, but there was modest exploration and property surveying.

*Production.*—Production figures are lumped for several districts in the area; according to Willden (1964), the majority of the $1.4 million production from the area was from the Adelaide and Adelaide Crown mines. This is consistent with the size of the "new" (1930's?) electrified mill and volume of tailings. A substantial amount of rock was excavated in the 1980's open-pit operation that attempted to mass mine vein zones that earlier were selectively mined underground; the amount of gold recovered probably was quite small. Data compiled by Vanderburg (1938b) for 1907–36 for the Adelaide district show production was high in Cu, Pb, and Zn, and although Ag was much more abundant than Au, the values from Au were high. The total value for 1907–36 was $561,232 from lode deposits and $6,170 from placer deposits. Production at the Adelaide Crown open pit and heap leach was 3,068 ounces (oz) Au and 37,537 oz Ag in 1990, and about one-half of that in 1991; the operation has been idle since then (Bonham and Hess, 1996).

*Geology.*—Information is inconsistent because there is no published detailed (1:24,000 scale) map of the western half of the district; the eastern half was mapped by Marsh and Erickson (1978) who show that the Adelaide mine is in thermally altered Cambrian Prebble Formation. A fairly large body of Late Cretaceous (104 Ma) granodiorite is exposed a mile east of the Adelaide mine and is inferred to extend below the metasedimentary rocks because of the observed metamorphism and also the magnetic signature of the area. The western part of the district contains Valmy Formation in the upper plate of a thrust that may correlate with the Roberts Mountains thrust (Cookro and Theodore, 1989). Ore in the district is restricted to the Prebble Formation, which comprises carbonaceous phyllite, calcareous shale and limestone, and minor quartzite. Several types of dikes cut the Prebble in the vicinity of deposits; the dikes range in composition from diorite to rhyolite, and some are highly altered. North-striking, high-angle faults are common in the district and are the major control on the western deposits as in the Adelaide Crown group.

*Ore deposits.*—There are at least three ore types: (1) Copper skarn with byproduct Ag-Au-W; (2) epithermal veins and stockworks in altered sedimentary rocks, possibly with similarities to the Carlin sediment-hosted type (Cookro and Theodore, 1989); and (3) placer gold in several of the east-flowing streams.

The skarn deposits were the major producer of the district at the Adelaide and nearby mines where calc-silicate minerals such as garnet, vesuvianite, and diopside replace calcareous strata in the Prebble, along with sulfide minerals including pyrrhotite, pyrite, galena, chalcopyrite, molybdenite, and scattered scheelite (Ransome, 1909; Cookro and Theodore, 1989). Most of the mining of the skarn ores was prior to 1908 when F.L. Ransome visited and noted that the Adelaide shaft was 300 ft deep and workings in ore were at least 400 ft long.

The deposits in the western part of the district are associated with normal faults and silicification, rich in silver and gold, and considered to be epithermal in character (Cookro and Theodore, 1989). The alteration to jasperoid and the trace-element assemblage of As, Sb, Hg, Tl, Ag, and Au suggests a similarity to Carlin-type sediment-hosted deposits (Cookro and Theodore, 1989), but more definitive work needs to be done to set these deposits into current concepts for Nevada gold deposits. The silver-gold deposits were mined from many underground workings, in and near the north-striking Adelaide fault, over a distance of about 4 mi. Geochemical results of Cookro (1993) for more than 40 elements show wide variation locally in the belt of silver-gold mines, suggesting multiple types of geochemical enrichment, including the unconventional variety rich in Be-Li. The district may be geochemically zoned, albeit complexly. The presence of skarn-suite elements (Cu-Mo-Bi, and others) in the belt of "epithermal" silver-gold deposits suggests that skarn-type fluids may have migrated well west of the Adelaide mine and that local variations in fracturing and in sedimentary lithologies complicate the zoning pattern.

Chemical analysis of five typical samples collected for this study show the ores to be polymetallic in character. Dump samples of the skarn deposits have high concentrations of Ag, Bi, Mo, Pb, Se, Te, and W and very high concentrations of Cd, Cu, and Zn. Samples from the veinlike deposits have high concentrations of Ag, As, Cd, Mo, Sb, and Zn, which is not unusual for some epithermal deposits that have a polymetallic aspects. A sample of slag from athe smelter at Adelaide has high concentrations of Bi, Cu, Mo, Se, Tl, W, and Zn; this composition confirms that skarn ores were processed by the smelter.

### Mineral-Environmental Conditions

Environmental geochemistry in this district is more complex than in most districts and not easily evaluated. On the negative side, this district has widespread mining and surface trenching and very little reclamation. Geochemical studies (Cookro, 1993) show that the ores and waste piles contain high levels of base metals and arsenic. On the positive side, there is very little surface water, many of the ores are oxidized, and carbonate-bearing rocks and gangue are abundant. Silicified zones are commonly rich in iron oxides, creating gossanlike rocks that look hazardous. These silicified zones tend to be low in carbonate after the hydrothermal alteration has destroyed calcite, but calcite-bearing rocks are not more than tens of feet away. If acidic water is created during storm events or in mine drainage, the acids will not move very far before they are naturally mitigated to neutral pH.

*Mineralized rocks and ores.*—Analytical results for four dump samples and two tailings samples are similar to the much more extensive data of Cookro (1993) and the known mineralogy: values for Pb, Zn, and Ag are high, as are As and Sb. Skarn ores and waste rocks are rich in base metals, arsenic, and sulfide minerals in the deeper unoxidized zones. These rocks have the potential to generate metal-rich acid-rock drainage, but there is no evidence for that in the prevailing dry climate. Dumps produce no visible drainage trails of iron-oxide coatings or vegetation kill. Carbonate minerals in the metasedimentary rocks probably neutralize acids as soon as they develop. Leach tests on one sample showed a pH of 7.4 and low concentrations of base metals but a high level of Se.

The lode Ag-Au deposits in the Prebble Formation contain an “epithermal suite” of elements (As, Hg, Sb, Tl) but generally low levels of base metals (Cookro and Theodore, 1989); pre-mining oxidation of most ores and waste rocks destroyed sulfide minerals in most mined rocks. The ore-associated trace metals are fairly stable in oxide forms. Leach tests on two samples developed pH’s of 5.1 and 5.7; the pH 5.1 leachate had high to very high levels of Cd, Cu, Se, and Zn.

*Mills and tailings.*—The location and status of early mills could not be determined, but the newer mill (1930’s–1950’s? of the Adelaide Crown mine produced a fair volume of tailings. These tailings are in a lowland, but the impoundment is stable and does not appear to have been breached. The tailings samples contain relatively low levels of base metals, but about 20 ppm Ag is present.

A small amount of slag (tens of tons) is present where it was poured from an old smelter near the Adelaide mine shaft. Nothing remains of the smelter structure. The vitreous black slag is typical of slag from the late 19th century with varied textures that resemble vesicular lava flows; inclusions of limestone flux are common. Chemical analysis of the slag shows very high amounts of Cu, Pb, Zn, and As. Leach tests on similar slags show them to be relatively stable in near-neutral pH water. The slag poses no significant concerns in the current situation, but use of this material for construction purposes could cause ingestion of particles containing very high concentrations of base metals.

*Surface water.*—Four samples (three streams, one pit lake) collected in 1996 and 1997 have pH values in the range 8.2–8.5 and low to moderate conductivity. Water chemistry of a pit lake (Adelaide Crown) is presented and discussed by Price and others (1995) who measured a pH of 7.0. My sample of water, ponded in a cut through a skarn deposit, contained high concentrations of As, Cu, Mo, and Se. A sample from a small pit lake in the Adelaide Crown property (polymetallic vein type) contained high As, but other metal concentrations were below the study average. A sample from a puddle on crushed material near the heap-leach facility contained high concentrations of Al and As.

Goldrun Creek, which flows through the area of skarn and polymetallic deposits and mines, has substantial flow and is an important resource for the area (wildlife, livestock, irrigation). The pH of 8.5 is normal, the conductivity of 650 $\mu$S/cm is higher than normal for the area, and concentrations of As, Mo, and Se are higher than the study average but below the ALWS and drinking-water standards. Other metal concentrations, including Zn, are low to very low. The water in this district appears to be effectively buffered by the sedimentary rocks, which may have prevented mobilization of the acid suite of base metals such as Cu and Zn.

Summary.—The gold-bearing placer deposits in the district are evidence that mineralized rocks were exposed at the surface: ore-associated metals in addition to gold must have been dispersed down the paleostreams before the arrival of people and mining. The prevailing alkaline pH values near 8.2 suggest that the sedimentary rocks of the district, as well as alluvium, are effectively buffering pH and minimizing the mobility of most metals. Metalloids (As, Mo, Se) are enriched in surface water, but concentrations are below water-quality standards. There is virtually no chance for these waters to contaminate the Humboldt River because there rarely is flow that far at the surface in Goldrun Creek, a tributary to Ragan Creek. Dilution and adsorption reactions would mitigate metals in the ground-water regime. This is typical of streams leaving mining districts 5 to 15 mi from the Humboldt River.

## Antelope Springs District

This mercury mining district, located 15 mi east of Lovelock (fig. 2), was active intermittently from about 1914 to 1970 and most productive in the 1940’s, with a total of more than 12,000 flasks. Mineral-environmental descriptions and data can be found in Gray (2003) and Nash (2001).

## Austin District (Reese River, here includes Birch Creek District)

*Location.*—West side of Toiyabe Range, Lander County, 80 mi south of Battle Mountain (fig. 15). Features of part of the area are shown in figure 17.

*Major commodities.*—Ag, U, minor Au, Cu, Pb, Zn, and turquoise

*Mining history.*—Silver was discovered in 1862 along the route of the Pony Express, leading to a great land rush.

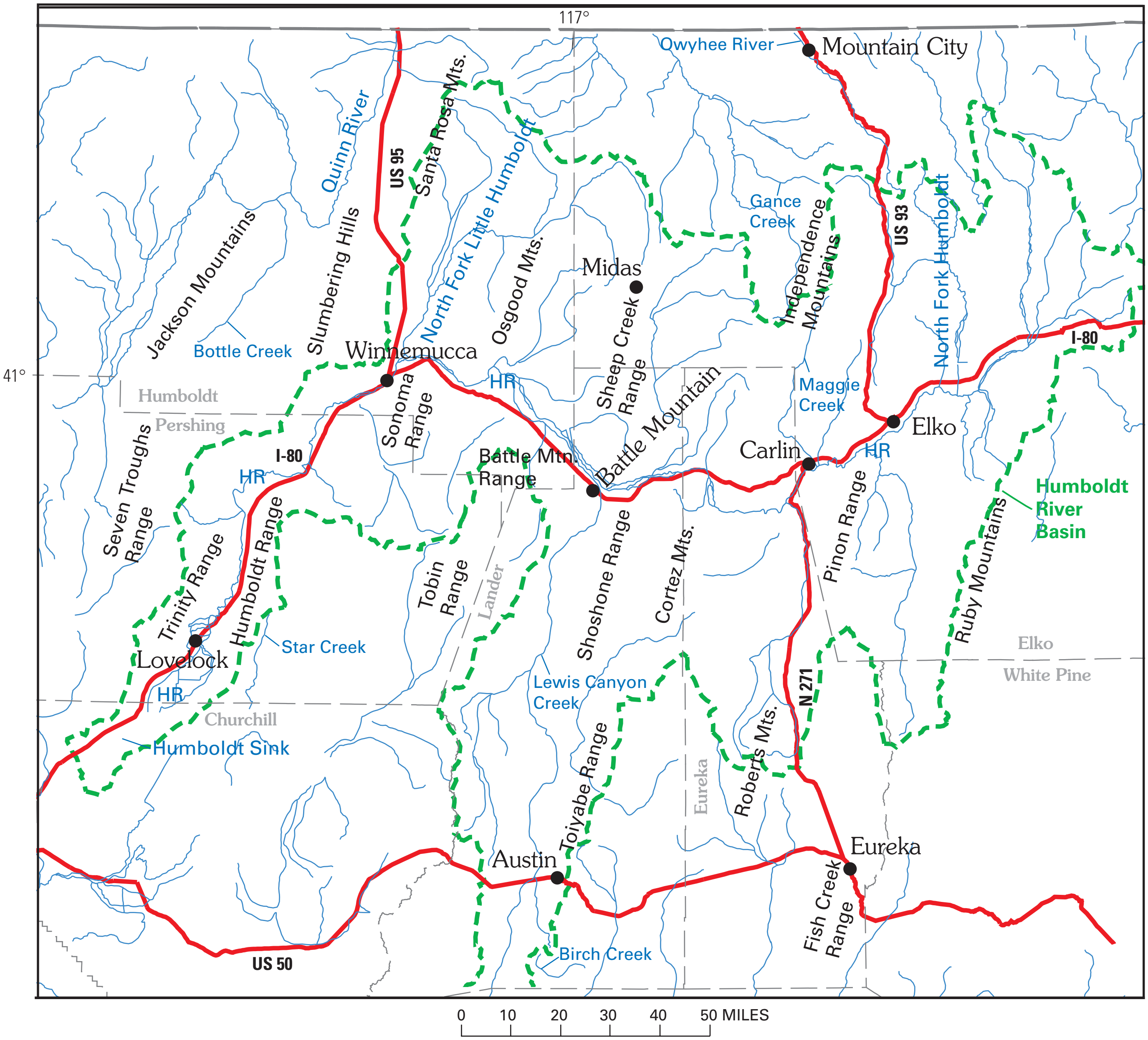


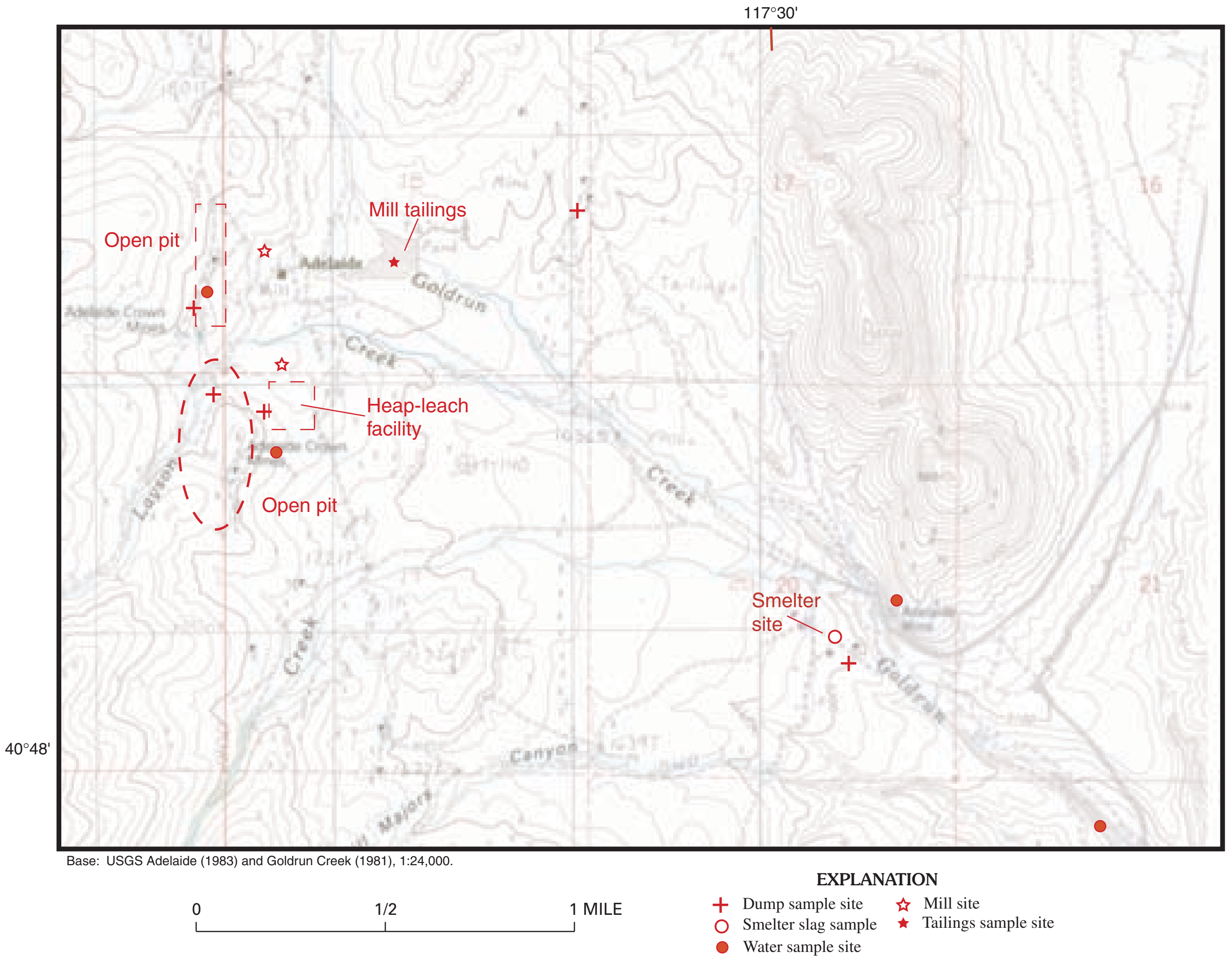
**Figure 15.** Northern Nevada showing geographic features referenced in report; HR, Humboldt River.

The richest ore was mined in the 1860's, and mining declined through 1886. There was modest silver production after 1900. The uranium rush of the 1950's hit this area, and the largest uranium deposit in Nevada was located in 1953; the Apex (Rundberg) mine was active in the 1950's and explored again in the late 1970's, but no mill was ever built. Small, high-quality turquoise deposits have been mined intermittently since 1930.

The Quito gold deposit was discovered in the early 1980's at the site of a known stibnite deposit, 10 mi southeast of Austin. This sediment-hosted deposit was mined by an open pit, with substantial logistical difficulties in the rugged mountains, from 1986 to 1989.

*Status of mining and exploration.*—The silver prospects have been dormant for many years in a period of depressed silver prices. The Quito gold mine and heap-leach facility have been closed and reclaimed. Stockpiled uranium ore at the Apex mine has remained untouched in 15 years of low prices. Exploration in the district is minor.

*Production.*—Records for the early days of silver mining are incomplete but estimates are about $20 million, with possibly $500,000 to $1,000,000 after 1900. At an average price



Base: USGS Adelaide (1983) and Goldrun Creek (1981), 1:24,000.

**Figure 16.** Features of the Adelaide mining district, showing sample localities.

**Photograph 19.** The old Adelaide Crown mine dump is relatively large, but it appears to produce very little contamination because it generally is dry. No water drains from the nearby mine workings because they were accessed by a shaft. Also, the skarn ores contain calcite and other minerals that would neutralize any acid produced in the dump. A smelter (around 1890) was at this site, and its slag is nearly buried by mine waste.

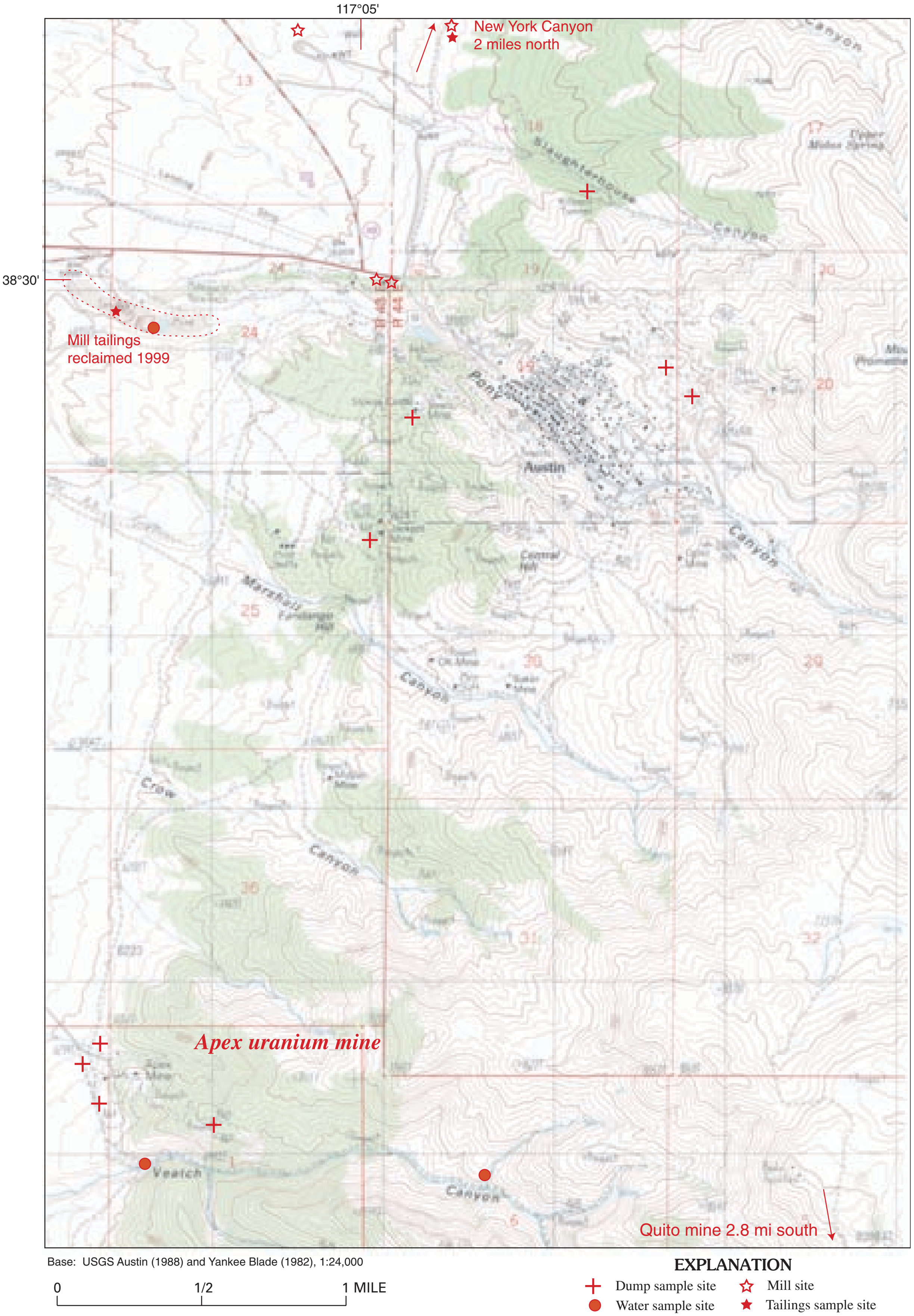


**Figure 17.** Features of the Austin mining district, showing sample localities.

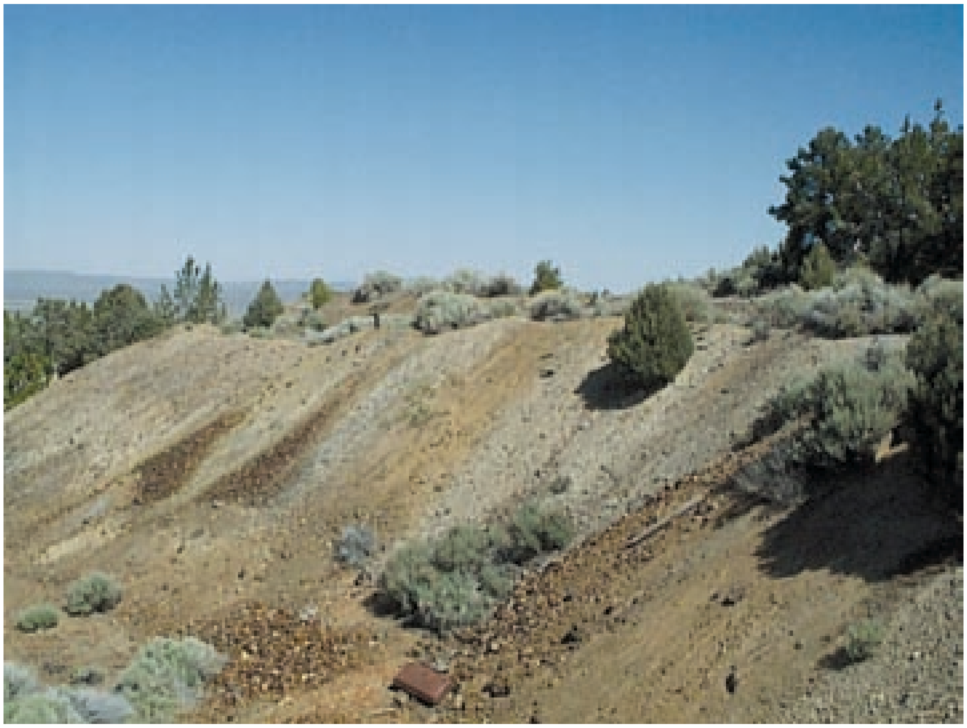
**Photograph 20.** Waste from mercury retorts (calcine) are present in large piles in the Antelope Springs district. The calcines from the Pershing mine were placed on a heap and sprayed with cyanide in an effort to recover precious metals in the 1980's.

**Photograph 21.** The Antelope Springs district generally is dry, but after storm events runoff can collect in trenches made for exploration, as shown here. This ephemeral puddle carried high mercury concentrations in 1998.

of $1.20 an ounce for silver from 1863 to 1886, actual silver production would have been about 17 million ounces. The value of uranium was more than $100,000 and of turquoise, probably less than $50,000.

*Geology.*—Geology of the silver deposits was described in detail by Ross (1953) and the district setting revised by Stewart and McKee (1977). Oldest rocks in the district are early Paleozoic metasedimentary rocks, which were intruded by the large Austin pluton of Jurassic age and intermediate composition. Thin patches of Tertiary volcanic rocks overlie the older rocks. The many silver veins cut the pluton and nearby metasedimentary wall rocks, and the uranium veins likewise are in quartzite and phyllite at the southern margin of the pluton. The Quito gold deposit is in Paleozoic sedimentary rocks that are highly deformed by thrust and normal faults.

*Ore deposits.*—Three types of ore deposits have been important in this district: (1) silver-rich quartz veins associated with the Jurassic pluton; (2) uranium (pitchblende and autunite) veins in metasedimentary rocks; and (3) gold disseminated in siliceous and calcareous rocks. The gold deposits have been called "Carlin-type" (sediment-hosted gold) but the other deposits are of uncertain classification. The silver veins are not like most epithermal veins in other parts of Nevada; rather, the silver minerals are in very coarse-grained quartz that has a texture suggestive of a hotter and deeper "mesothermal" setting, consistent with the probable deep setting of the Jurassic



**Photograph 22.** This mine dump at the Apex mine, 2 miles south of Austin, looks like thousands of dumps in Nevada, but this one is very radioactive. Stockpiles of uraninite-pyrite ore from the late 1970's are especially radioactive because ore-grade material was not shipped to a mill.

**Photograph 23.** The Quito open-pit gold mine in the Toiyabe Range south of Austin is in carbonaceous shales, similar to gold deposits of the Carlin trend. The mine and heap-leach pad were reclaimed in the mid-1990's after a few years of operation under difficult conditions in rugged mountains.

pluton. Tourmaline in the silver veins also is suggestive of the deeper plutonic setting, such as present in polymetallic quartz veins in plutons of Montana and Arizona. The veins at Austin were deeply oxidized and the silver enriched above the water table. There is no model for these veins in Cox and Singer (1986).

Chemical analyses of seven samples from mine dumps and tailings related to the Ag veins show them to be characterized (relative to other deposits and districts in this study) by high concentrations of As, Cd, Cu, Mo, Pb, and Zn, and very high concentrations of Ag and Sb.

The uranium veins and disseminations are in metasedimentary rocks and dikes adjacent to the Austin pluton and some ore is in the pluton itself (Garside, 1973; J.T. Nash, unpub. data, 1977). Most of the early mining was in near-surface zones containing autunite and iron oxide minerals, but the prospecting in the 1970's was chiefly in deeper reduced zones containing pitchblende with pyrite. The uranium deposits are of uncertain age and origin because most of the geologic observations were for autunite, which is probably redistributed from older primary pitchblende (Plut, 1979). Sulfide- and pitchblende-rich ores, abundant on stockpiles, were not exposed in workings or dumps in 1977, when I examined them, and are not described in older publications. The pitchblende has not been reliably identified. The primary sulfidic ores may have been similar to uranium deposits of the Midnite mine, near Spokane, Washington (Ludwig and others, 1981).

New chemical analyses of seven dump samples from the Apex mine show them to be enriched in many metals in addition to uranium. Relative to the median concentrations for all dump samples in this study, the Apex dump samples have high concentrations of As, Bi, Cd, Cu, Mo, Pb, Sb, Se, and Tl; concentrations of Mo, Sb, Se, and Tl are notably high. Leach tests on six samples of uranium-mine waste yielded pH values in the range of 4.0 to 6.8. The more acidic leachates carried high concentrations of Al, As, Cd, Cu, Se, and Zn and very high concentrations of U. The potential for acidic water to mobilize U from these waste piles may be significant and, for this study, is unique to these materials.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—The silver, gold, and uranium deposits of the district have very different rock and mineral compositions. One major difference is the composition of the Austin pluton and adjacent siliceous metasedimentary rocks: both of these rock types are predicted to have low acid-neutralizing capacity (Glass and others, 1982). The Paleozoic rocks in the Quito gold mine area, however, are rich in carbonate minerals and are predicted to have very high acid-neutralizing capacity. The silver veins are richest in base metals that can be toxic if transported, the gold ores are rich in a small suite of elements (As, Sb, Se, Zn) that can be a concern, and the uranium deposits are rich in uranium and radionuclides, which pose a distinct set of environmental concerns. Deep oxidation of the silver ores prior to mining (and the tendency to mine those ores only in the oxidized zone) means that the mine workings and waste dumps contain oxide minerals rather than sulfides. Here, potentially toxic metals such as As and Pb tend to be stable in oxidized minerals (or are adsorbed on iron oxide minerals), and there is a decreased tendency to form acid-rock drainage.

The uranium ores pose concerns that are unique in the study area. The mined rocks are very rich in uranium. Judging from radioactivity measured by a scintillometer (an indirect measurement of uranium and radioactive decay products, or radionuclides as a general term), the radioactivity of mined rocks (waste or stockpiles) ranges from not much higher than some volcanic rocks of the region to extremely high. Some of the rock piles with highest radioactivity appear to be stockpiles of material mined in the late 1970's—these are less weathered and contain more pyrite than the rocks on piles thought to be from mining in the 1950's. Many of the piles have higher radioactivity than ores in other districts that were hauled to mill for processing. Based on experience with uranium ores at other mines but having no training in health physics, I estimate that about one-half of the waste piles do not meet radioactivity standards. The caveat in this case is exposure: are people being exposed to the radioactivity of these waste piles? Is the exposure short-term or long-term? Further work is needed to assess the exposure risk to humans. Caution is suggested to residents. In particular, these rocks should not be hauled away for use in construction where people will be living on them or breathing their dust.

The uranium ores and waste dumps are surprisingly rich in As, Bi, Cd, Cu, Mo, Pb, Sb, Se, and Tl, all of which are potentially toxic. Leach tests of six samples of mine-waste dumps and stockpiles produced results that are unique among the samples in this study. The leachate pH values were in the range of 3.6 and 6.8, not unexpected considering the pyrite and iron oxides in these rocks. However, the composition of the leachates was much richer in metals than anticipated. The leachates were high in the following metals: As (6 samples), Cu (4), Fe (1), Mo (1), Pb (6), Sb (5), Se (4); and U was very high in all six leachates (the highest values observed in this study). The concentrations of uranium (15 to 135 ppb) were higher than concentrations obtained from samples of uranium dumps from two uranium districts in Colorado using the same leach and analytical methods (Nash, 2002a).

*Mills and tailings.*—This was one of the largest of the early mining camps with 11 mills erected prior to 1868; Vanderburg (1939) noted that many of the mills were speculative and unproductive. Numerous "firsts" were made here, including the Reese River process for roasting silver ores with salt to improve the recovery of silver and gold (this process creates the distinctive red tailings seen at many mills in the region). The numerous mills described in the literature are difficult to reconcile with features seen today because they commonly burned or were dismantled, and tailings commonly were reprocessed as technology improved. Because the veins were mined underground and ores were hand sorted underground and again at the mill, the volume of tailings produced is much smaller than expected for a district that produced $20 to $50 million in silver. Another reason for the discrepancy in observed tailings is the common practice of retreating or removing early (pre-1900) tailings that contained substantial amounts of silver that the early processes failed to recover. Today, five mills are evident but several pre-1900 mills were not recognized. A significant volume of tailings is present only in Pony Canyon on the west edge of Austin, west of the Clifton tunnel that extends under the mines on Lander Hill. Two mills are at the Clifton tunnel (photo 25), an older one built of wood and a newer one of metal, probably built in 1935. A large concrete mill foundation can be seen in New York Canyon, 3 mi north of town, near the True Blue mine; no tailings could be located at this site. Two relatively modern mills are located at the western mouth of Slaughterhouse Gulch, a mile

**Photograph 24.** A seep in the floor of the Quito east pit creates this red water, indicating that iron is being transported in acidic water. The pH value of 6.0 and composition are not as bad as this looks, and this spring flows only in the early summer.

**Photograph 25.** Two mills, one of wood and one of tin construction, processed silver ores on the west side of Austin. Tailings were placed in Pony Canyon, middle of photo, and reprocessed at various times.

north of town, but they appear to have had only small production.

Tailings in Pony Canyon west of Austin blend in with alluvial sands shed from the granitic rocks; thus, their volume and extent are difficult to estimate. In recent years an attempt was made to recover silver in a heap-leach operation on the mill tailings. Most of the heap-leach operation was reclaimed by the BLM in 1999. A pond in the middle of the tailings area that was left after reclamation collects water with a pH of 8.0 and high conductivity; concentrations of Cu, Sb, and U are elevated, and the concentration of As is notably high at 77 ppb.

The Pony Canyon tailings are possibly at risk to erosion in an extreme storm. The canyon setting and geometry seem favorable for focusing stormwater, and a substantial part of the tailings remain in the flood plain after reclamation. Many of the questions for this site relate to regulatory criteria that deal with effects on human or wildlife health. Erosion of tailings in a storm event probably would have little effect on property as there are no structures downstream. These tailings are relatively unreactive, judging from their composition, and stormwater carrying tailings probably would have only a transient effect on wildlife or ground-water quality upon infiltration.

*Surface and ground water.*—The higher elevations of the Toiyabe Range receive far more precipitation, especially as snow (more than 16 inches), than the valleys (about 8 to 16 inches; Houghton and others, 1975). The main productive area of the district near the town of Austin is intermediate in terms of precipitation, but there is little surface water, and only a few mine portals drain water. During the main period of mining, deeper operations that were reached by shafts had significant water problems that required costly pumping. A drainage tunnel was driven from the west after most of the mines ceased operating (Ross, 1953). No samples of water were collected, but there were no signs of acid-mine drainage (such as Fe-Mn-oxide coatings). No water drains from uranium mine workings, and surface water in that area does not contact waste rocks; however, storms and snow do affect these dumps, and some of that moisture infiltrates dumps and enters ground water.

Trees and flowing surface water testify to the high amount of precipitation in the Quito mine area at an elevation of 8,500 ft. The open pits, which have been reclaimed, contain no ponds and produce only a small amount of seepage. One seep in the floor of the east pit had a pH of 6.0 (photo 24), and seepage through the waste dumps has pH values of 7.9 and 8.0. The acidic seep carried high concentrations of Cd, Cu, Fe, and Zn relative to the average values for this study. The seeps through the mine-waste dumps carried very high Se concentrations (32 and 48 ppb). The streams leaving the Quito mining area are well buffered at pH 8.2–8.4 and have metal concentrations well below the study average and below the ALWS.

A small amount of water flows episodically in Pony Canyon, west of the village and west of the mining and milling area. In June of 2000, a small pond of water collected in the area of mill tailings along Pony Canyon, in the area reclaimed in 1999 by BLM. The pond water had a pH of 8.0 and carried high As and U concentrations but low metal concentrations. This water may reflect multiple sources and processes, including effects of past heap-leaching and evaporative concentration. Water in the canyon generally infiltrates the porous alluvium east of the mill tailings but during some storm events must flow a mile or more to the west. The water well formerly near this site was dismantled by the BLM and no longer is a factor in water-quality management.

*Summary.*—Uranium stockpiles and waste dumps pose an environmental concern that is unique in the study area but which cannot be quantified with available information. Uranium, As, Se, and other metals are mobile in water that percolates through these materials because of acids generated by pyrite and iron-sulfate minerals. The fate of this water during storms is not known, but this suite of elements is soluble in alkaline as well as acidic water; thus, carbonate in rocks and alluvium is not expected to mitigate these elements as it does base metals such as Cu, Fe, and Pb. Environmental standards have not been set for uranium in mine-waste dumps. Exposure to uranium-bearing rocks or ingestion of uranium-bearing dust is a health risk. Reclamation of the dumps should be considered, both to reduce the mobility of uranium in dust and water and to reduce radiation by addition of a covering layer of nonradioactive rocks or soils.

Waste and tailings from the silver mines probably do not pose a health concern in the present dry locations. Runoff during storm events has the potential to carry metals such as As, Cu, Pb, and Zn, and these metals may move longer distances in this district than elsewhere because the granitic rocks have low buffering capacity. However, runoff probably would undergo natural mitigation when those waters encountered caliche-bearing alluvium. Mine workings and waste dumps from the gold mines high in the Toiyabe Range have the potential to generate metal-rich acid-rock drainage locally, but that drainage water is neutralized and mitigated by carbonate-bearing sedimentary rocks and alluvium within hundreds of feet. Transport of As and Zn in alkaline water after neutralization is a potential problem, but analyses of four samples suggest that concentrations downstream are below concern levels.

## Awakening District

*Summary.*—This mining area about 35 mi northwest of Winnemucca (fig. 2) has a long history of gold mining, most recently at the Sleeper mine. The Sleeper mine was one of the first open-pit operations in northern Nevada to mine below the water table, requiring that substantial amounts of water be pumped to keep the pits dry. The epithermal gold-silver ore was mostly oxidized, allowing heap-leach processing of lower grade zones. From 1986 to 1996 more than 1.6 million oz of gold was recovered from a combination of high-grade bonanza veins and low-grade breccia zones (Nash and others, 1995). See descriptions in Nash (2001).

## Battle Mountain District

*Location.*—Battle Mountain range, southwest of Battle Mountain in, Lander County. The features of this large district are shown in figure 18; more detailed features are shown in figure 19 and figure 20.

*Major commodities.*—Au, Ag, Cu, Pb, Zn, Sb; turquoise

*Mining history.*— The discovery of silver in Galena Canyon in 1863 led to one of the first mining camps in the region; mining soon began and two smelters were operating by 1870. Production through 1885 depleted most of the near-surface oxide silver ores. Mining increased in 1909 with the discovery of placer gold deposits in Copper Canyon. Placer gold and underground Cu-Pb-Ag mines were intermittently active through the 1950's. Drilling at the previously mined Copper Basin and Copper Canyon properties in the 1960's defined reserves to start the new era of open-pit mining in 1967. Skarn copper deposits were identified in the late 1960's, and in the 1970's attention shifted to gold-silver skarns, nine of which have been defined and mined in the southeastern corner of the district near Copper Canyon. In the 1980's exploration in the northwestern part of the district also focused on gold, resulting in many discoveries in the Marigold mine complex and the multiple ore bodies of the Trenton Canyon mine.

*Status of mining and exploration.*—Mining of gold continued in the Copper Canyon area (Battle Mountain Gold) through 1998; in 2001 there was predevelopment activity in that area for a new gold mine. In 1997, mining commenced on two open pits for the Trenton Canyon mine complex of Newmont Gold (ex-Santa Fe Pacific). Mining of gold and exploration continued at the Marigold mine complex in the northwest corner of the district. Modest exploration activity by small companies occurred in the Elder Canyon and Snow Gulch areas. There was no activity in the Buckingham area where a porphyry-type molybdenum deposit contains resources of as much as a billion pounds of Mo and 100 million ounces Ag (Doebrich and others, 1995).

*Production.*—Production through 1969 was about $50 million, chiefly in copper and gold, with lower values for silver, lead, zinc, antimony, arsenic, and turquoise (Stager, 1977). Although most of the metal production was from hard-rock mines, placer gold mining was significant at Copper Canyon and other canyons, yielding more than100,000 oz Au. The modern open-pit copper and gold-silver mines produced about 250 million pounds of Cu (mill and heap-leach facilities), about 10,000,000 oz Au and 30 million oz Ag (Doebrich and Theodore, 1996). Proven and probable reserves are greater than 1 million oz Au at several deposits in the Battle Mountain District, including Marigold and Phoenix/Battle Mountain Gold (Doebrich and Theodore, 1996; Tingley, 2001). The Phoenix project proposes to process gold ore from five separate open pits in the southeast corner of the district, of the "distal-disseminated" and skarn types in sedimentary host rocks (Cary and others, 2000).

*Geology.*—The geology of the district is well known from extensive work by Roberts and Arnold (1965), by Theodore and Blake (1975), and continued work by Doebrich and Theodore (1996). These thorough studies have unraveled the very complex geology of the district and the relations of many kinds and ages of ore deposits to that geology. Summarized in highly generalized terms, the district comprises four packages of Cambrian to Permian (about 550 to 250 Ma) sedimentary and volcanic rocks emplaced by thrust faults that caused severe folding and shearing of the rocks. The rocks are mostly siliceous (chert, shale, silt) but thick limestone units also are present. A Late Cretaceous stock intruded this sequence and created the huge Buckingham molybdenum deposit. The Trenton Canyon gold deposits probably are related to a similar stock. Other small stocks of intermediate composition were emplaced at about 38–34 Ma and created the porphyry copper and gold-silver deposits (Doebrich and Theodore, 1996). Younger Tertiary volcanic tuffs and flows covered the district. North- and northeast-trending faults of late Tertiary age (post-ore) created the current physiography, as in other parts of the Humboldt River Basin.

*Ore deposits.*—Many kinds of ore deposits have been recognized in this district (Theodore and Blake, 1975; Doebrich and Theodore, 1996). Economic geologists describe them as multiple porphyry-type intrusive complexes that produced zoned systems of ore deposits. The core of the systems, as at Copper Canyon, are porphyry copper deposits. These grade outward into copper- and gold-bearing skarn deposits, polymetallic deposits, stibnite deposits, and distal-disseminated gold deposits. The Buckingham system is different in that it is older (about 86 Ma), the multistage stock is more felsic in composition, the central ore is richer in Mo, and the outer part is rich in Cu as shown in the Copper Basin deposits. Fifteen or more gold deposits in the northwest part of the district are a newly recognized variety (distal-disseminated gold) that appears to be related to porphyry-style intrusions, is low in base metals, and is enriched in trace elements (Au, [but low Ag] As, Ba, Hg) similar to Carlin-type sediment-hosted gold deposits (Doebrich and others, 1995; Doebrich and Theodore, 1996).

In the simplified framework of this study most of the historical mines in the Battle Mountain district can be classified as polymetallic: they are rich in many base metals and originally were rich in sulfide minerals. The skarn Au-Ag deposits of the Copper Canyon area are prototypes of the skarn class as used here. The distal-disseminated gold deposits, as at Marigold and Lone Tree, were not studied. For geo-environmental work, the latter might best be lumped with Carlin-type deposits because the sedimentary host rocks are presumed to play a major geochemical role and the trace elements are more akin to Carlin-type than to polymetallic type. Many of the deposits mined years ago were deeply oxidized, which minimizes their potential for acid-mine drainage. Sulfide-rich zones have been mined in recent years

**Figure 18.** Features of the Battle Mountain mining district, showing major mining areas.

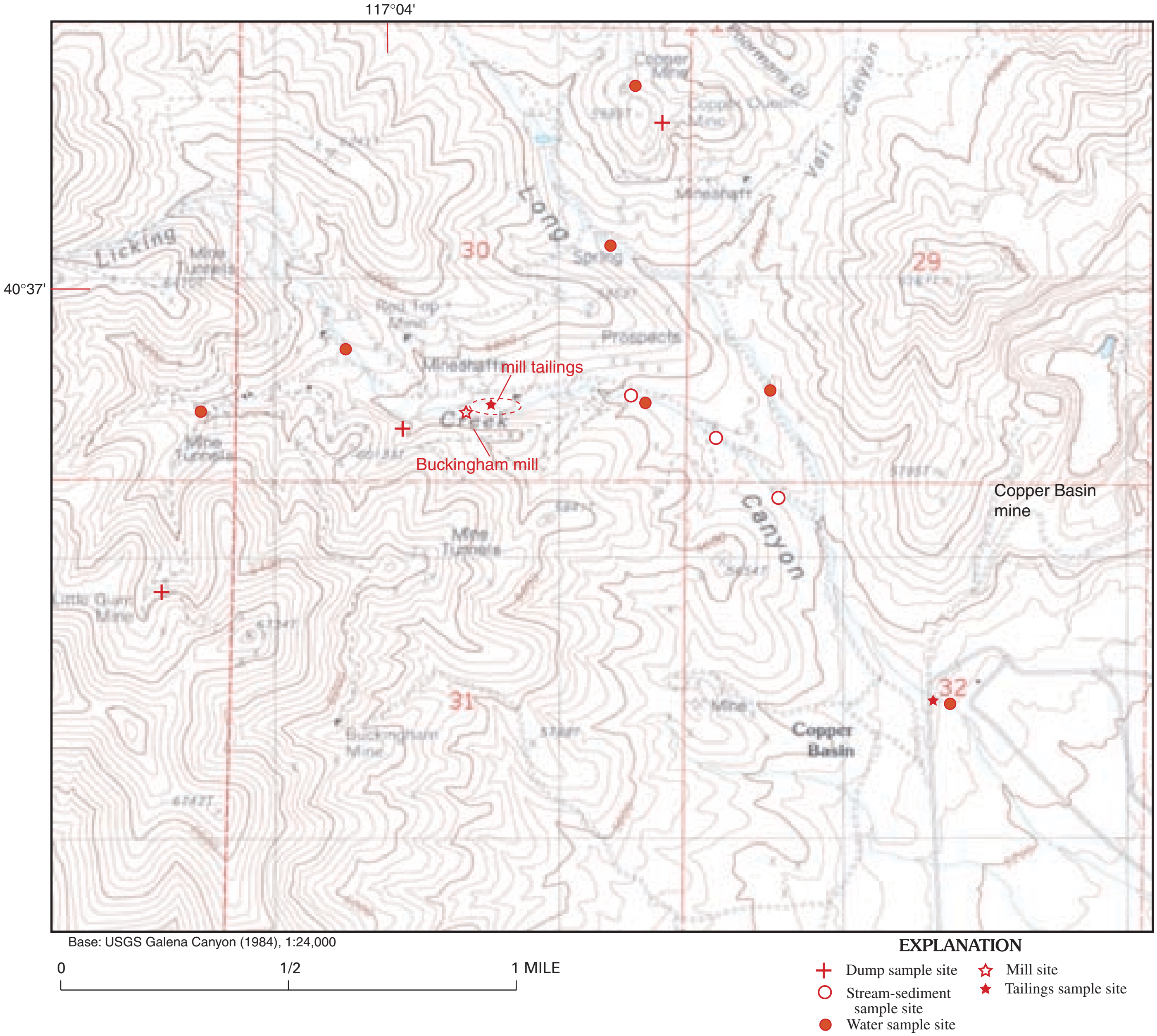


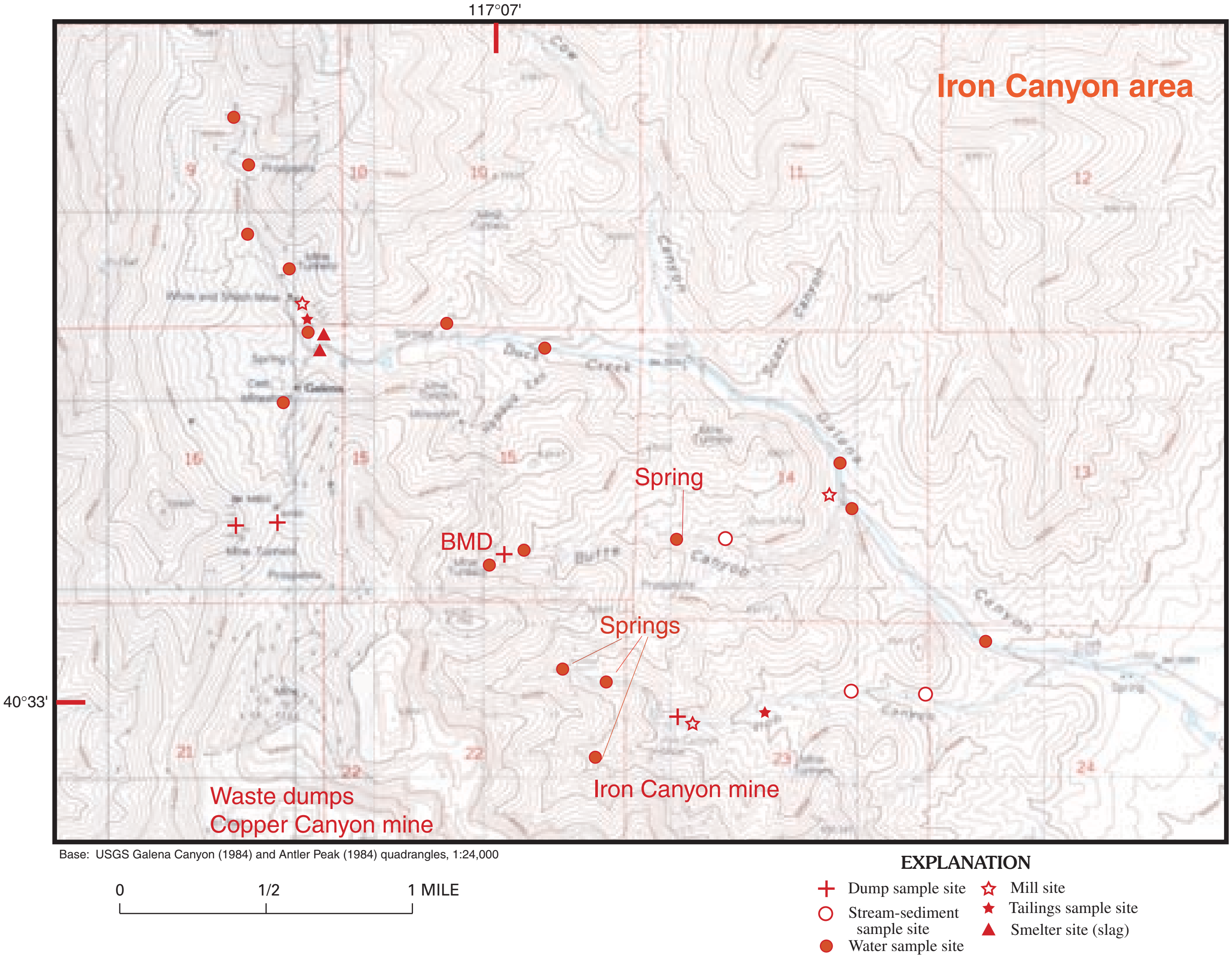
**Figure 19.** Features of the Buckingham mining area of the Battle Mountain district, showing sample localities.

from skarn and distal-disseminated gold deposits, and for those open pits and waste dumps the potential for acid-mine drainage and acid rock drainage must be evaluated relative to the generally high acid-neutralizing capacity of the host rocks: the net result appears to be neutral-pH water with low concentrations of most base metals but possibly elevated concentrations of As and Zn.

## Mineral-Environmental Conditions

Geochemical expression of mined and unmined mineralization is highly variable in this large and diverse mining district. Although the kinds of deposits present have reputations for causing severe environmental degradation (Plumlee and others, 1999), the district is generally healthy because most ores and rocks are deeply oxidized (thus produce little or no acidic drainage) and there is enough calcite in sedimentary rocks and alluvium to neutralize and naturally mitigate the acid drainage that is typically present elsewhere.

*Mineralized rocks and ores.*—Hydrothermal alteration is widespread in the district and extends far beyond ore bodies (Theodore and Blake, 1975). Pyritic alteration of several types surrounds most known or prospective mineralized zones, and the altered rocks carry enhanced levels of many metals but especially As, Sb, Bi, Hg, Pb, and Zn. Systematic geochemical studies undertaken 10–25 years ago by Theodore and coworkers to describe the deposits, prospects, and



Base: USGS Galena Canyon (1984) and Antler Peak (1984) quadrangles, 1:24,000

**Figure 20.** Features of the Iron Canyon mining area of the Battle Mountain district, showing sample localities.

geochemical halos for exploration now provide an excellent database of background geochemical values for elemental distribution in unmined rocks. Geochemical analyses of rocks in the Copper Canyon area (Theodore and Blake, 1975; 2,927 samples) reveals that many unmined rocks contain greater than 2,000 ppm As, greater than 50 ppm Bi, greater than 200 ppm Cu, greater than 100 ppm Pb, and a lesser number of samples contain high values of Mo or Zn. In the Buckingham Mo-Cu system (Theodore and others, 1992; 128 samples), many unmined rock samples contain greater than 50 ppm As, greater than 20 ppm Pb, greater than 175 ppm Cu, and some contain 10–40 ppm Mo or 25–250 ppm Zn. Jasperoid alteration zones that are prospective for disseminated gold deposits (Theodore and Jones, 1992; 78 samples) contain high concentrations of toxic metals; unmined samples of jasperoid commonly contain greater than 50 ppm As (to 15,000 ppm), greater than 30 ppm Pb (to 100,000 ppm), greater than 170 ppm Zn (to 56,000 ppm), and greater than 25 ppm Cu (to 24,000 ppm ). High concentrations of Bi, in excess of 10 ppm, are fairly common in all three areas.

New sampling and analyses in this study are consistent with the results of Theodore and coworkers, summarized above, for the eastern side of the district. Eight dump samples from old polymetallic mines on the eastern side of the district are high (above the median for dump samples) in Ag, As, Bi, Cd, Cu (very high), Mo, Sb, Se, Te, Tl, and Zn. Leach tests on eight dump samples and one tailings sample produced pH values of 2.1 to 5.9 , and high concentrations of As, Cd, Cu, Mo, Pb, and Zn—and some were high in Se. The most acidic leachate solutions carried very high concentrations of As, Fe, and Pb. A sample of altered rock yielded a pH of 7.7 and a leachate with high concentrations of As, Cu, and Mo.

The Elder Creek-Paiute Canyon area, northeastern part of the district, contains scattered small mines and prospects on polymetallic deposits, and an uneconomic porphyry deposit has been drilled (Doebrich and Theodore, 1996; Ivosevic and

**Photograph 26.** The mill tailings in Pony Canyon were reclaimed by the BLM in 1999 to minimize runoff and ground-water contamination. Some of the tailings could not be moved and are subject to erosion in a major storm.

Theodore, 1996). Samples of oxidized ore from dumps are rich in Cu, Ag, Bi, and very high in As and Se (to 70 ppm). The iron oxides in the vein-filling materials may be scavenging As, Se, and similar metals. These metals are potentially toxic but appear to be relatively immobile (not bioavailable) when adsorbed and held in these iron oxide phases (Smith and Huyck, 1999). A leach test on a dump sample rich in iron oxides created a pH of 4.2 (probably from jarosite, not pyrite), and high concentrations of Cd, Cu, Mo, Pb, and Zn. Although there are high concentrations of As and Se in this sample according to an analysis of the solid material, the leach tests shows that only low concentrations of these elements went into solution at pH 4.2.

*Mills, tailings, and smelter slag.*—Two smelters that operated in the 1870's in Galena Canyon, at the east edge of the Galena townsite, do not seem to have been very large, judging from the small piles of slag that amount to about 200 tons or less. The slag does not appear to be reactive in this environment and it appears to be quite stable where it is. The smelters may have produced plumes of acrid smoke more than a century ago, but the geochemical consequences in soils were not tested. The slag is rich in many base metals and generally unreactive in surface water, but these solids should not be ingested by humans or animals.

The volume of identified historical mill tailings seems lower than expected for the substantial production here. Mills and associated tailings were identified at Buckingham (fig. 19), Iron Canyon, and Galena (fig. 20), but others may have existed in Copper Basin or Copper Canyon, which are the sites of large open pits and waste dumps. A small volume of tailings was observed at the edge of waste-rock piles from the Copper Basin mine, and more tailings may have been covered by post-1960 mining waste. Only small volumes of tailings were observed at Iron Canyon and Galena and neither site appears to pose a risk of failure in a storm event. The red tailings near Galena are the scant remains of a larger volume that was removed for reprocessing by the 1930's (Vanderburg, 1939). Leach tests on samples from the Buckingham and Iron Canyon mill tailings yielded pH's of 2.1 and 5.6. The acidic leachate contained high concentrations of As, Cd, Cu, Mo, Pb, Se, and Zn, whereas the pH 5.6 leachate contained high concentrations of As, Mo, and Pb.

One area of tailings may be a cause for concern: the tailings pile at the Buckingham mill (fig. 19) which appears to date to the 1940's–1950's. The mill and some of its equipment are partly intact. The unconfined mill tailings were placed in the channel of Licking Creek (photo 28), which is ephemeral. Erosion of the tailings piles is moderate, and thin layers of transported tailings are visible in the creek bed for more than a mile downstream. Three stream-sediment samples from Licking Creek show elevated metal concentrations reflecting contamination from the tailings (and other sources). In June 1998, a week of rain created a small flow in this creek; 400 yards below the mill tailings the creek had a pH of 5.1, and concentrations of Al, Cd, Cu, and Zn were very high. This surface-water analysis is similar to that from a leach test; both analyses show that efflorescent crusts on the tailings are highly soluble in water. Both analyses show that episodic storms produce acidic, metal-rich "first flush" water. Mill tailings are the most obvious source of these contaminants, but mine dumps and altered rocks also are likely contributors. The combination of the tailings piled across the ephemeral streambed and the basin to the west suggests that the Buckingham tailings pose a high risk of reacting or eroding in a major storm event.

**Photograph 27.** The open pits at the Sleeper mine yielded more than 1.6 million ounces of gold and large piles of waste rock. The pink to reddish hues are from ferric iron that formed from pyrite; this pre-mining oxidation decreased the potential to create acid in the waste piles.

The catchment pond at the White and Shiloh mine above Galena (fig. 20) releases water on rare occasions, as in June of 1998 when the overflow pipe carried water with a pH of 4.5, conductivity of 1,800 $\mu$S/cm, and very degraded water quality. Concentrations of Al, Cd, and Zn were extremely high, and concentrations of Cu, Fe, Mn, and Pb were very high. There are some red tailings on the edge of this pond (most were removed for reprocessing) but the major source of contaminants probably is the mine-waste piles to the west of the pond.

Several storm events during the study period (1995–2000) released metal-rich water in Butte Canyon (fig. 20). The water was released from several places, including a collapsed adit and springs. Dried rusty material on the streambed contains more than 9 percent Fe and high concentrations of As and

**Photograph 28.** Mill tailings from the Buckingham mill were placed in Licking Creek and are subject to episodes of erosion. Despite the bad location, only thin layers of fluvial tailings are found for a mile below the site.

**Photograph 29.** Waste rocks from the Copper Basin open-pit mine and mill tailings from an old mill (possibly buried by the waste piles) would appear to contaminate Long Canyon Creek. However, the pH of 7.2 and analyses of samples collected over a 4-year span show that only small amounts of metals enter the creek, possibly because the materials are oxidized.

other metals. The water had pH values of 2 to 3, conductivities greater than 2,000 $\mu$S/cm, and high sulfate concentrations; the acidic water was extremely rich in many metals. In most years these drainages (spring and mine) do not reach Galena Canyon Creek, but in June of 1998 the flow was very large and did mix with the larger creek. In 1998, similar acidic, Fe- and metal-rich water flowed in the midsection of Iron Canyon, and that flow was collected and treated by a portable water-treatment facility.

*Surface water.*—Several streams in this large district have sources in springs at high elevations in the range, but in general there is little surface water in most of the area below about a 6,500-ft elevation, except for brief flows in the spring. I could find only a few mine adits with flowing water, despite diligent search on about 20 days over a 5-year span, including studies during two unusually wet late springs. Among the numerous historical mines in this district, a relatively small percentage are adits, and only a few of those release water to the surface. I collected 41 water samples from 37 sites in the Battle Mountain district. The pH values ranged from 2.4 to 8.5, and conductivities ranged from 430 to greater than 2,000 $\mu$S/cm. The majority of samples collected in or near mining properties had degraded water quality, as shown by the high and very high concentrations of Al, As, Cd, Cu, Fe, Mn, Se,

**Photograph 30.** Waste from old mines on polymetallic sulfide veins in Butte and Iron Canyons is rich in sulfide minerals. Mine drainage, which leaves the tunnel (out of sight behind the waste pile) with a pH of 2.2, reacts with the waste and becomes even richer in metals.

**Photograph 31.** Acidic, metal-rich mine waters flowed for unusually long distances in May of 1998 and created these iron deposits on the streambed. These deposits are are highly reactive in later storm events, releasing acid and metals.

and Zn. Noteworthy are very high concentrations of Mo and Pb in seven samples. Most of the elevated metal concentrations were detected together at the same sites. Compositions at 23 of the 37 sites exceeded ALWS for one or more metals. However, natural attenuation processes are effective in greatly reducing metal concentrations within a mile of the source, as will be discussed in the section on “Attenuation Mechanisms.”

Surface water in the district appears to be mostly carbonate-buffered with near-neutral to alkaline pH values. The pit lake at the Fortitude open pit (Copper Canyon mine complex, fig. 18) is in contact with sulfidic rocks, but there is more than enough calcite in the wall rocks to maintain an alkaline pH (P. Wotruba, Battle Mountain Gold, oral commun., 1995). A few mine drainages from adits high in the range generate acidic water from oxidizing sulfide minerals inside the mine workings, in wall rocks and in sulfidic dump rocks. A good example is the collapsed mine portal in Butte Canyon (BMD, fig. 20) that has a flow of about 10 gpm and a pH of 2.1 to 3.0 (on five sampling events). These mine waters react with sulfidic dump rocks within 100 yards of the portal (photo 30) to become even more acidic (pH 2.0 to 2.4) and metal-rich. This acidic water generally infiltrates alluvium another 200 yards north of the dumps, but in some very wet seasons the surface flow extends farther down the canyon and mixes with other surface water (discussed later). In June of 1998 the acidic water in Butte Canyon, from several sources, flowed into Galena Canyon Creek and was eventually neutralized by natural reactions in Galena Canyon, as discussed later. The mixing reactions created iron-oxyhydroxide deposits on the streambed that resemble schwertmannite (photo 31); these iron coatings and deposits are soluble in subsequent stormwater. The unusual persistent flow of mine water for more than a mile in 1998 probably was caused by saturation of soils in that unusually wet spring season, which minimized infiltration into alluvium as occurs in most storm events.

*Summary.*—The long history of mining in this district has produced many kinds of disturbance and piles of waste. The pre-1960 production, large for the region, created a relatively small and localized disturbance compared to the open-pit mining of recent years. Some of the mine adits, dumps, and tailings piles release highly contaminated water during unusually wet seasons. Discharges from springs and mine tunnels on the flanks of the range may reflect shallow ground-water transport of acid and metals from unmined veins and from mined deposits higher on the range in complex flow paths that generally are not evident in other districts. Reclamation methods that were successful in the Hilltop district, described herein, may not be effective here because of the greater structural complexity. One manifestation of the chemical and structural complexity is the spring-water compositions that are unusually rich in sulfate and metals. Surface-water compositions in this district show the beneficial effects of pre-mining oxidation of sulfide minerals and high acid-neutralizing capacity of sedimentary rocks and alluvium.

## Beowawe District

*Location.*—Eureka County, about 20 mi east of Battle Mountain (fig. 2).

*Major commodities.*—Hg, Ba

*Mining history.*—Mercury was discovered in 1924, and the Red Devil mine was worked through the 1930's, yielding a modest 150 flasks. A barite deposit (Sansinena) 4 mi southwest of the town was located in 1939 and mined in the late 1970's and 1980's. The Mule Canyon gold deposit was discovered in the early 1990's and brought into production in 1997; it will be discussed briefly here.

*Status of mining and exploration.*—Other than the Mule Canyon mine, no other mines were operating in the late 1990's. Exploration in the eastern (original) part of the district was not evident in 1997.

*Production.*—Production from the Red Devil mine was about 149 flasks of mercury through 1943 (Bailey and Phoenix, 1944), and there does not appear to have been mining since then. The Sansinena barite mine was a relatively small producer (Papke, 1984), but the pit is more than 1,000 ft long, about 300 ft wide, and more than 100 ft deep.

*Geology.*—Bedrock in the central part of the district is chert, shale, and quartzite of the Ordovician Valmy Formation (Roberts and others, 1967). Miocene volcanic rocks dominate the western part of the district and cap ridges south of the town.

*Ore deposits.*—Three types of deposits are known in this district: (1) hot-springs cinnabar, at the Red Devil mine; (2) epithermal or hot-springs gold at Mule Canyon; and (3) bedded barite at the Sansinena mine. Also present is the modern hot-springs system that has been tapped for geothermal energy at Beowawe Hot Springs.

The cinnabar deposit at Red Devil mine is associated with intense silicification of Valmy quartzite and quartz pebble conglomerate. The deposit is in a fault zone that fractures the tough quartzites; the age of the ore has not been determined but is probably Miocene or younger. Chemical analyses show there are relatively low concentrations of metals other than mercury in this ore.

The bedded barite deposit at Sansinena mine is deformed strata of the Vinini Formation (Papke, 1984); the two barite bedded zones have a combined thickness of about 26 ft. The barite zones are interbedded with chert and black shale and are unconformably overlain by Tertiary sedimentary and volcanic rocks.

The Mule Canyon gold deposit, 10 mi west of Beowawe, occurs in a complex structural zone in Miocene volcanic rocks, both related to the Northern Nevada Rift (John and Wallace, 2000). The deposit was nearly covered by younger basalt flows. Much of the ore is highly pyritic, which formerly posed problems, but the high pyrite ore is being hauled to autoclaves west at the Lone Tree and Twin Creek mine complexes.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Ore and waste rocks at the Red Devil and Sansinena mines contain low concentrations of most metals. Concentrations of the "epithermal" suite of elements, including As, Mo, Se, and Zn, are below the median for this study. Leaching tests suggest that only a few metals are soluble. The leachate from a barite waste sample (crushed reject material) carried a notably high concentration of As.

*Mills and tailings.*—Ore was processed through a retort at the Red Devil; a sample of the crushed cinnabar ore at the retort was leached and found to create a pH of 8.5. Although very little went into solution, concentrations of As and Mo were high in the leachate. Leaching of a sample of crushed rock from the Sansinena barite mine created a pH of 7.9; the leachate had low concentrations of most metals, but As and Mo concentrations were high.

*Surface water.*—No water was observed to be flowing from mined areas.

*Summary.*—Ores and waste rocks at the Red Devil and Sansinena mines have relatively low metal concentrations, and most metals are not mobile. As in all mercury mines, the mercury ores and waste materials should be treated with care to avoid uptake of Hg by humans. The Mule Canyon mine was not investigated.

## Black Diablo District

*Location.*—Tobin Range, 35 mi south of Winnemucca in Pershing County (figs. 2, 15). Features of the Big Mike mine area are in figure 21.

*Major commodities.*—Cu, Mn

*Mining history.*—Manganese was known since about 1900 but mining did not start until 1929. Mining, chiefly at the Black Diablo mine, continued intermittently until 1954. A small prospect for copper was located on the Big Mike deposit in the 1930's, drilled in 1968 and mined out in 8 months of 1970 (Rye and others, 1984). In-situ leaching of more than 5,000,000 tons of blasted rock in the pit was attempted in 1973 with unsatisfactory results. Subsequently, the blasted low-grade ores from Big Mike were hauled from the pit, segregated into various piles for barren waste, low-grade ore, and the better material processed by a heap-leach facility through 1978 (photos 32, 36). Additional experiments were made in later years on the low-grade materials, including crushing to improve permeability.

*Status of mining and exploration.*—There was no mining or exploration activity in the late 1990's.

*Production.*—The small open-cut manganese mines produced about 60,000 long tons of Mn from about 200,000 long tons of crude ore (grades were between 28 and 36 percent Mn). Big Mike was a small but rich ore body; 100,000 tons of shipping ore averaged about 10.5 percent Cu (Rye and others, 1984). The heap-leach facility treated about 300,000 tons (unspecified grade). Byproducts such as silver are not reported.

*Geology.*—Rocks in this district are chert, greenstone, and argillite of the Devonian-Permian Havallah Sequence. This unit contains submarine cherts, basalt pillow lavas, and volcaniclastic sandstones. The Mn and Cu deposits formed syngenetically with the enclosing rocks in association with submarine (island arc) volcanism. Later these rocks were

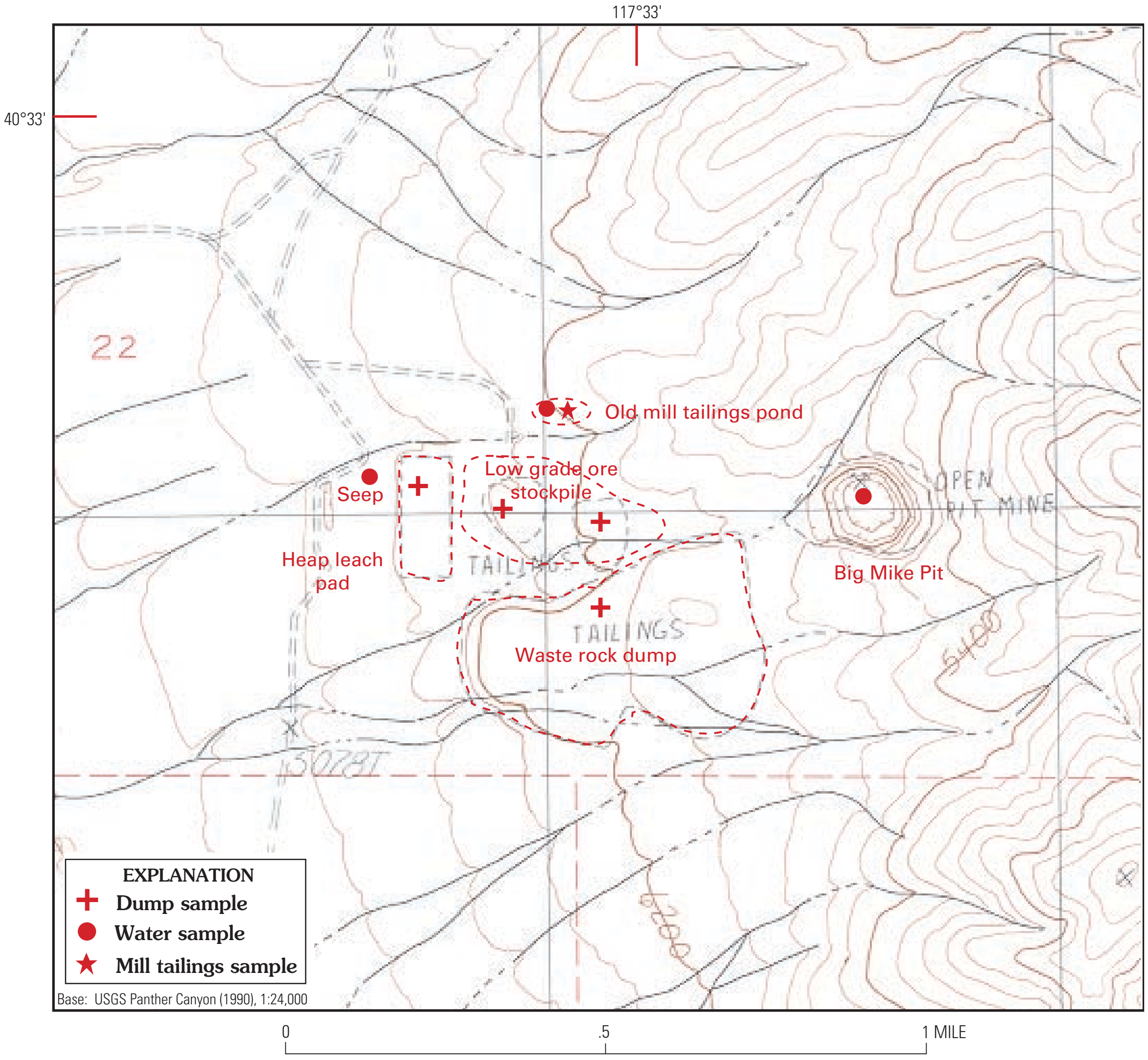
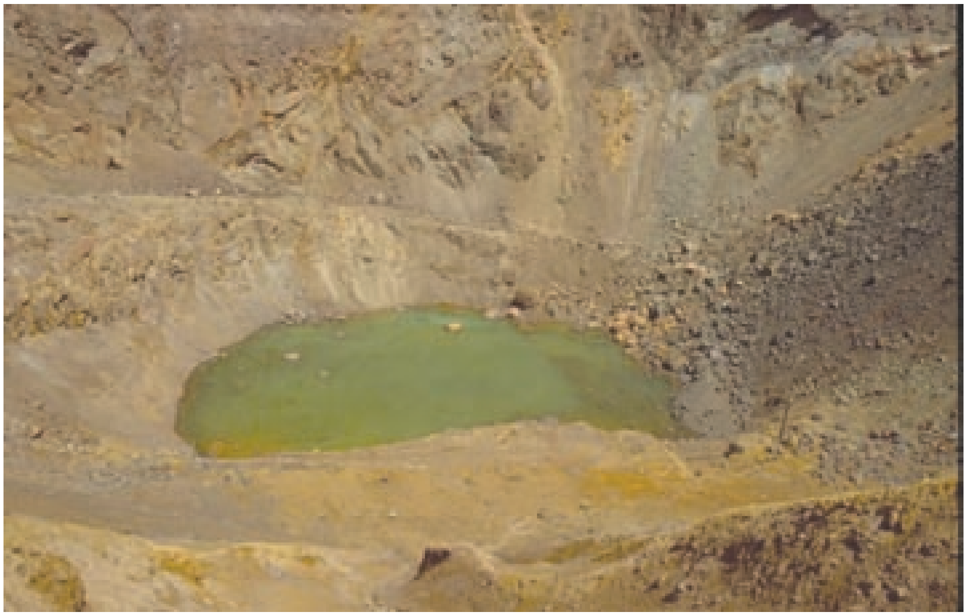


**Figure 21.** Features of the Big Mike mine area, showing sample localities.

**Photograph 32.** The Big Mike massive sulfide deposit was bulk mined after the high-grade core was removed selectively. A heap-leach operation was attempted in the 1970's, leaving the large pile of sulfidic waste (HL). Acidic, copper-rich seeps (S) emerge to the right of the leach pad. Dark barren waste rocks (BW) pose no concern, but the low-grade stockpiles (LGS) are similar in composition to the heap. A tailings pond (TP) remains from a 1930's operation.



**Photograph 33.** The Big Mike pit lake varies in volume according to the recent weather and some years is dry. The pH of 7.6 reflects the beneficial effects of the oxidized, chlorite-altered mafic host rocks.

folded and thrust-faulted and metamorphosed slightly to greenschist facies. Several ages and styles of faults cut the ore deposits.

*Ore deposits.*—Both Mn and Cu deposits are volcanogenic and formed from similar processes on the sea floor, but the two types do not grade into each other in the mined deposits. The Mn deposits consist of massive to bedded manganese oxide minerals, intergrown and overlain by chalcedony and jasperoid (red chert). There are no sulfide lenses at the Mn deposits.

The Big Mike is a volcanogenic massive sulfide deposit of the Cyprus type. Most of the ore came from one lens of massive, sulfide-containing, fine-grained bedded pyrite with chalcopyrite and other copper sulfide minerals. Sphalerite was sparse, and there was no galena; silver content was low (less than 25 ppm). Greenstone wall rocks are metamorphosed and altered to chlorite-calcite and originally contained small amounts of pyrite. Most greenstones in the upper part of the pit are oxidized.

## Mineral-Environmental Conditions

The Mn deposits contain oxide minerals that are stable in the prevailing climate. Although Mn can be toxic, the Mn in these ores and waste piles does not appear to be mobile and no problems are evident. The massive sulfide deposit at Big Mike creates several kinds of water-borne contaminants, but none appear to be of the magnitude of the similar massive sulfide deposit at the Rio Tinto mine, in the Mountain City district.

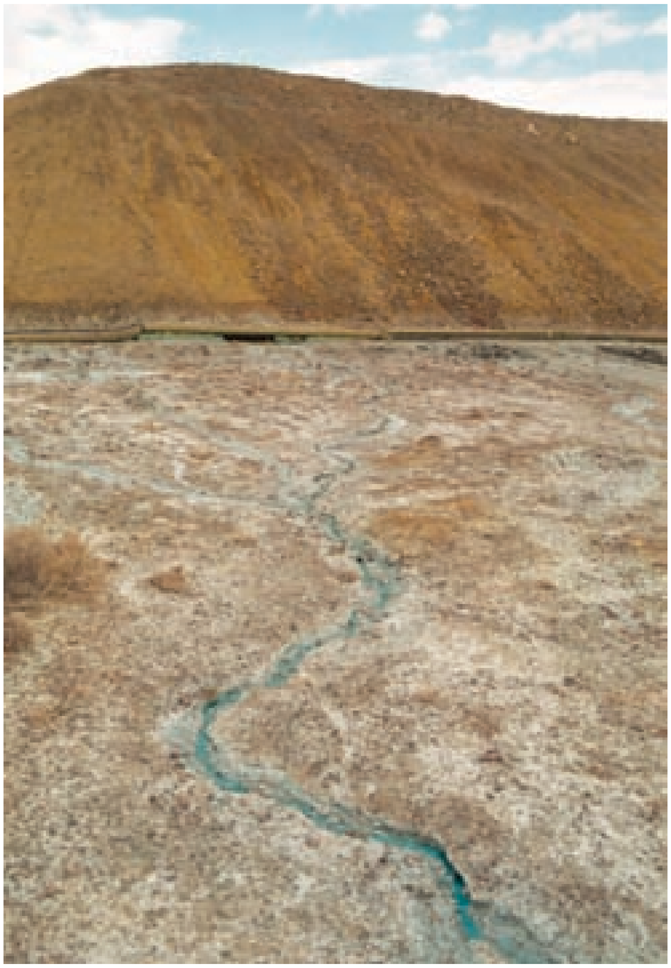
*Mineralized rocks and ores.*—The massive sulfide lens at the Big Mike was extremely rich in copper sulfide minerals and pyrite, but those rocks were selectively mined and shipped

**Photograph 34.** The two large areas of ocher rock are stockpiles (S) of low-grade copper ore, similar in composition to the rock on the heap. These sulfidic rocks generate acid and release copper and other metals when wet. Also shown are the remains of a small mill and a pile of mill tailings (MT) from a 1930's operation.

**Photograph 35.** The heap at Big Mike, containing about a million tons of crushed sulfidic rock, releases a small but significant seep of acidic (pH 3.1) water that is extremely rich in copper. The former solvent precipitation tanks are at the left base of the heap.

to Europe for smelting and thus pose no problems at the mine site. Lower grade ores were crushed and placed on a heap-leach pad, and about 3 million tons of overburden and barren greenstone was excavated and placed on waste dumps. The waste rocks are oxidized, and most had low sulfide content before mining. The waste rocks do not appear to generate acid-rock drainage, and leach tests of two samples from waste dumps yielded pH values of 8.4 and very low metal concentrations.

A very large tonnage of copper-bearing rocks was placed on the leach pad, and rocks of similar appearance, but probably containing less copper, were piled on two benches (photo 34). The pad and stockpiles seem to be a greater tonnage than the 300,000 tons from the 1970–78 operation described by Rye and others (1984). Perhaps additional material was mined after 1978. Chemical analysis of the material on the pad shows about 0.2 wt percent Cu compared to 0.1 percent Cu for a sample from the stockpile. Both materials are rich in other base metals, as expected, but the very high content of Se (69 and 79 ppm) is somewhat unexpected and may be significant for the environment. Leach tests on five samples of low-grade rock and of crushed rock on the leach pad produced solutions with pH values in the range 2.8 to 5.2 and high to very high metal concentrations. The notably high



Photograph 36. The seeping leach water evaporates, creating a crust of white and green sulfate minerals. These mineral crusts can dissolve in surface waters, creating an acidic, copper-rich runoff.

metals in the five leachates include: As (2 samples), Cd (5), Cu (5), Fe (5), Mo (2), Pb (4), Sb (1), Se (5), and Zn (5). A similar inference may be taken from the composition of a puddle on a low-grade dump: puddle water had a pH of 2.7, some of the highest metal concentrations present in this study, and notably high concentrations of Se (1,340 ppb). These extreme metal concentrations are in part related to evaporative concentration. The abundance and mobility of Se in these materials deserves special attention. Water infiltrating the large heap is mostly confined above a cement pad, but the pad is cracked, and a highly concentrated fluid—blue-green, viscous, pH 3.1, and very rich in copper—is leaking onto the alluvial fan. Much of this fluid infiltrates the alluvium over a distance of about 500 ft, but some evaporates to form a green crust (photo 36) that is soluble in the next rainstorm. An analysis of the seeping leachate shows extremely high concentrations of Cu but also extremely high Al, Cd, Fe, Mn, Se, and Zn—some of the very highest of the high concentrations observed in this study.

An earlier stage of mining by small shafts, prior to 1940, had a small conventional mill. Mill tailings, mostly in a tailings pond, are surrounded by, and possibly partly covered by, the later waste rocks from the Big Mike open-pit mining. The volume of tailings is relatively small, possibly 20,000–40,000 tons by visual estimate. Normally dry, the pond collects runoff in wet periods (photo 37). The ephemeral pond waters are very acidic (pH 3.6) and Al, Cd, Co, Cu, Fe, Mn, Ni, and Zn concentrations are extremely high (orders of magnitude greater than ALWS). Some of the metal enrichment probably reflects cycles of evaporation. A leach test on a sample of the tailings produced a leachate with a pH of 4.7 and very high Cu and high Zn concentrations. The tailings pond appears to be physically stable on a gentle slope, with no streams or arroyos nearby, but the ephemeral pond water is toxic to wildlife and may contaminate ground water.

Photograph 37. A small milling operation created this pile of tailings that collects water from rare storms. The water has a pH of 3.6 and very high metal concentrations.

**Photograph 38.** Mercury mines and prospects of the Bottle Creek district are scattered over low hills, as shown here. The valleys contain small ephemeral streams that rarely flow in the very arid climate.

**Photograph 39.** The Arizona mine, the largest in the Buena Vista district, created moderate-sized piles of waste rock and mill tailings (conical pile, foreground) that are relatively benign because they contain calcite in calcareous rocks and gangue.

*Surface water.*—There is no surface water in this district as it is one of the driest parts of the study area. A small lake collects water at the bottom of the Big Mine pit, about 150 ft in diameter and generally less than 20 ft deep (photo 33). The small lake appears to be seasonal, drying out in many years. The composition of the lake has significant implications. The pit water has a pH of 7.6, high dissolved solids (conductivity greater than 2,000 $\mu$S/cm), and very high sulfate content. The composition is not as extreme as one might expect of a massive sulfide deposit (Taylor and others, 1995), but Cu, Fe, and Zn are somewhat higher than the average for the study area, and Se and Mn concentrations are very high. The composition of the pit lake demonstrates the neutralizing effect of the altered wall rocks and much better water quality than would otherwise be created by the massive sulfide rocks alone. Similar alkaline water was present at massive sulfide deposits in central Arizona where altered greenstones buffered pH values (Nash and others, 1996).

*Summary.*—The manganese deposits and their waste dumps pose no environmental hazards. The Big Mike massive sulfide deposit produced millions of tons of waste and low-grade copper ore that is stacked in huge dumps and a leach facility. Some of these rocks produce sulfuric acid when exposed to precipitation, and the effluent contains high to very high concentrations of many base metals. Water in the pit is alkaline and has poor quality but would be far worse if

**Photograph 40.** The Buffalo Valley gold mine was a relatively small open-pit mine at the site of some earlier shaft mines. The totally oxidized rocks create no acid and release little or no metal in this arid setting.

the wall rocks were sulfidic (they are oxidized) and had low buffering capacity (the altered rocks contain calcite). Waters infiltrating the dumps and leach pile and runoff water from these rocks become acidic and rich in base metals, but the fate of the water is not known. The calcite-bearing wall rocks and alluvium have high buffering capacity and appear to be capable of neutralizing the acid-rock drainage within relatively short distances (hundreds of feet?), but metals such as As, Cd, Se, and Zn probably will be transported into ground water. The concentrations of these metals and the distance of transport in ground water cannot be measured without monitor wells.

The Big Mike heap-leach pile and adjacent low-grade stockpiles are the largest tonnage of reactive, acid- and metal-producing materials that I observed as inactive mine waste on public lands in northern Nevada. In 1999, there were discussions between BLM and a private firm to process and reclaim the low-grade copper stockpiles and leach pile (Steve Brooks, BLM, written commun., 1999). Reprocessing of mine waste, with recovery of metals, would be a creative approach to reclamation at Big Mike or other large mine-waste piles in the area.

## Bottle Creek District

*Summary.*—This mercury mining area, located about 45 mi northwest of Winnemucca, was most productive in the 1940’s. Total production was about 4,500 flasks, among the highest in Nevada. See descriptions by Gray (2003) and Nash (2001).

## Buena Vista District

*Summary.*—This mining area located 25 mi northeast of Lovelock on the east side of the Humboldt Range (figs. 2, 15) was a modest producer of silver but has not been active in the last 40 years (Nash, 2001). The largest mine, the Arizona, worked a polymetallic deposit in calcareous sedimentary rocks (photo 39).

## Buffalo Valley District

*Location.*—Western side of Battle Mountain, about 15 mi west of Battle Mountain in Lander County (fig. 2; fig. 18).

*Major commodities.*—Mn, Au, Cu, Ag

*Mining history.*—There was prospecting and minor mining starting about 1870, but the first real mining was in the 1920’s at the Buffalo Valley mine, which had small production through 1951. Manganese was mined during the war years of the 1940’s. An open-pit mine (photo 40) and heap-leach facility for gold operated at the site of the Buffalo Valley mine in 1989–90. In the late 1990’s major new mines were developed at Lone Tree, Trenton Canyon, and Marigold (fig. 18), which are not considered here. The new gold mines, in similar geology, are astride the borders of the Buffalo Valley, Battle Mountain, and Buffalo Mountain districts as defined by Tingley (1998).

*Status of mining and exploration.*—Major open-pit gold mines were developed in the 1990’s and continued to expand at the end of the decade as more reserves were identified. Five or more areas of disseminated gold were producing gold or were drill-defined as of 2000 (Tingley, 2001). Reserves or resources are more than a million ounces of gold in these large deposits (or clusters of several deposits).

*Production.*—Total production was small compared to adjacent districts, for a total value of about $300,000 through 1970. The heap-leach facility at the Buffalo Valley mine produced about 65,000 oz Au, which is tiny by Nevada standards. The new mines, such as Lone Tree, produce more than 200,000 oz Au per year. A new autoclave at the Lone Tree mine allows Newmont Gold to process high-sulfide gold ores, which include ores hauled in from other Newmont mines.

*Geology.*—Geology of this district is continuous with that of the Battle Mountain district to the east and southeast. Fine-grained siltite, chert, and calcareous siltstone of the Havallah Sequence are complexly faulted and intruded by Cretaceous and Tertiary stocks (80 Ma and 35 Ma, respectively; Doebrich and Theodore, 1996). Relatively recent (6–2 Ma) faults of several types offset tectonic blocks and promote deep oxidation that enhances the economic viability of the gold ores.

*Ore deposits.*—The historical Mn deposits in the district are of the type that form on the seafloor along with the enclosing sedimentary rocks. Sub-economic porphyry Cu-Mo prospects are associated with altered stocks, similar to the Buckingham system to the east in the Battle Mountain district. The porphyry stocks were more important in forming distal-disseminated gold deposits and prospects at more than five localities in this district. The Buffalo Valley mine operated in the 1920's, and a modest amount of oxide copper was mined prior to rediscovery as a disseminated gold deposit (Kizis and others, 1999). The Lone Tree and Trenton Canyon mines exploit a series of gold deposits in altered siliciclastic rocks of the Havallah Sequence; the gold reserves and resources are many millions of ounces in each mining complex (Doebrich and Theodore, 1996; Theodore, 1998).

## Mineral-Environmental Conditions

Historical mines in this district created relatively small amounts of disturbance and small dumps, and the oxidized materials create no acid-rock drainage. Oxidized Mn and Cu minerals on the waste piles appear to be stable in this dry environment. New open-pit gold mines differ enormously in magnitude and depth, which takes mining below the water table and requires pumping to dewater the mine. These modern mining operations are permitted and operate under State and Federal regulations and monitoring.

*Mineralized rocks and ores.*—Samples of mineralized rocks and fractures from the open pit at Buffalo Valley mine were sampled in 1997, with the permission of Fairview Gold, Inc. Twelve samples of oxidized rocks in the pit showed generally low to very low base metal concentrations; only the concentrations of Cu and Mn were high. Clay gouge from a fault (ore) contained 26 ppm Au and higher than median concentrations of As, Cu, and Sb. Three stream-sediment samples from dry streambeds west of the pit and heap-leach facility contained relatively low concentrations of most metals relative to other stream-sediment samples in this study, but the concentrations of Cu and Pb were relatively high. No leach tests were made of these materials, but based on their oxidized, iron-oxide-rich nature, I would infer that waste and pit rocks should release little acid or metals to episodic surface water.

*Mills and tailings.*—There are no historical mills in this district. The heap-leach facility from the Buffalo Valley gold operation was partly reclaimed by 1995.

*Surface water.*—This area is extremely dry, and no surface water was seen in 1997. Water for mining or drilling must be hauled or piped from the mountains to the east or pumped from deep wells.

*Summary.*—The small historical mines in this district pose no threats to the environment because the ores were oxidized and metals in waste are not mobile in the dry climate. The historical mines are not relevant analogs to the newly developed gold mines because the magnitude of mining is magnitudes larger, the mineralogy of the ores is sulfidic at depth, and water must be pumped from the deeper pits. The magnitude of dewatering at Lone Tree is evident in the two 3-ft-diameter pipes that one sees going under I–80 toward the Humboldt River (photo 7). A surprisingly large amount of water must be pumped from the pits in this environment, which is dry at the surface. The mines operate in conformance with evolving regulations.

## Burner District (Burner Hills)

*Location.*—Western Elko County, 16 mi northeast of Midas (fig. 2).

*Major commodities.*—Ag, Pb, Zn, Cu

*Mining history.*—Mining was episodic after the 1880's, and there has been no production for many years.

*Status of mining and exploration.*—There is no active mining, but there was modest exploratory trenching and drilling in the past 10 years.

*Production.*—A small amount of silver-lead ore was produced in the 1880's, with a value of about $30,000.

*Geology.*—Basement rocks are Ordovician Vinini Formation, exposed in a window or structural high, unconformably overlain by Tertiary andesite flows and volcaniclastic rocks. Small intrusions are associated with the Tertiary volcanics. Structure is seemingly simple, with only a few high-angle faults. Vein deposits are along north- to northeast-trending faults.

*Ore deposits.*—The polymetallic deposits, rich in galena and sphalerite, were mined for their silver content. The largest mine, the Mint, has abundant coarse-grained quartz, galena, sphalerite, pyrite, and arsenopyrite in dump rocks. Fluorite has been reported. The texture of the vein-filling materials is surprisingly coarse grained, suggestive of moderately high temperatures in epithermal deposits studied elsewhere.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Mineralization in this district is rich in base metals and carries abundant pyrite in local structures. These rocks have the potential to create acid-rock drainage and release substantial concentrations of As, Cu, Pb, Zn, and other toxic metals. However, the dumps are relatively small (most well under 1,000 tons) and are not causing visible effects on vegetation. Any acid-rock drainage would be mitigated by carbonate in rocks and alluvium within a short distance of the source.

*Surface water.*—This area is drier than many parts of the study area, and surface water is very rare. The Mint mine portal produces a small flow of water that wildlife and cattle drink; the pH is 7.9 and conductivity is 570 $\mu$S/cm. There is no chemical analysis of this water, but by analogy to other drainage samples of this pH, the only metals of possible concern would be Zn and As. The mine drainage infiltrates alluvium within 200 ft of the portal.

*Mills and tailings.*—None.

*Summary.*—There was no visible evidence for significant effects from mining. Any effects from mining and mined rocks should be highly localized and not persist beyond claims.

## Cortez District (Mill Canyon)

*Location.*—Forty mi southeast of Battle Mountain (30 mi south of Beowawe) in Lander and Eureka Counties (figs. 2, 15). Features of the Cortez silver mine area are shown in figure 22.

*Major commodities.*—Au, Ag, Pb, Zn, Cu; turquoise

*Mining history.*—The original silver deposit was found in 1863, mined until about 1903, and reopened with a new mill in 1919 that operated until 1930. The major mine was the Garrison, also known as the Cortez silver mine. Deposits in the Mill Creek area, north of the area of figure 22, were also discovered in 1863, and many mines were developed but none has been as productive as the Garrison mine. The Cortez gold deposit was indicated by geochemical prospecting in 1960–64, drilled in 1964–67, and mined by open pit from 1968 to 1973. The Horse Canyon disseminated gold deposit, east of the area of figure 22, was discovered in 1976 and mined by open pit from 1983 to 1988. Mining of turquoise has been intermittent since about 1915, and the Fox mine west of Cortez is possibly the largest producer in Nevada.

*Status of mining and exploration.*—There was no mining in 1996 to 2000, but the Cortez gold mill was used for gold ore from the new Pipeline mine to the west in Crescent Valley. There was no obvious exploration in recent years, but exploration was intense for many years after discovery of the Cortez gold deposit.

*Production.*—Production from the Garrison silver mine (underground) was about $14 million in Au, Ag, Cu, Pb, and Zn; details of early production are not known but from 1902 to 1958 production in the district was 4,488,821 oz Ag, 24,149 oz Au, 2,704,483 pounds Pb, and lesser amounts of Cu and Zn (Roberts and others, 1967). The Cortez gold mine yielded 3.5 million tons averaging 0.26 oz/t Au (910,000 oz Au). Pre-mining reserves at Horse Canyon were 3.1 million tons averaging 0.10 oz/t Au (310,000 oz Au); the Horse Canyon ore was hauled to the Cortez gold mill.

*Geology.*—The district was mapped by Gilluly and Masursky (1965), described by Roberts and others (1967), and the new Cortez gold deposit studied in detail by Wells and others (1969). Thrust-faulted sedimentary rocks of Cambrian to Devonian age are intruded by a Jurassic pluton and overlain by a thick Oligocene tuff. The Garrison silver deposit is in Eastern Assemblage rocks (Hamburg Dolomite, Eureka Quartzite, Hanson Creek Formation, Roberts Mountains Limestone, and Pilot Shale) exposed in a window through the Roberts Mountains thrust. The Cortez gold deposit is in silicified Silurian Roberts Mountains Limestone and is overlain by a thick section of impure limestone (Devonian Wenban Limestone). An altered felsic porphyry dike intrudes these rocks on the southern margin of the gold deposit (Wells and others, 1969).

*Ore deposits.*—The older mines in the district are not well described in modern terminology, but good observations are reported by Emmons (1910). The district had three types of ore deposits: (1) polymetallic fissure veins and replacements or mantos in limestone, valuable chiefly for Ag (Garrison; Mill Canyon); (2) disseminated, sediment-hosted gold (Cortez gold); and (3) turquoise.

The silver deposit at Cortez was mined by extensive underground workings of the Garrison mine that were in excess of 3,300 ft long and 700 ft high, as shown on maps and sections in Gilluly and Masursky (1965). Most of the ore was in Hamburg Dolomite, but some was in Eureka Quartzite and overlying Hanson Creek Formation. I was given a brief underground tour by Ralph Roberts in 1968, but details of geologic observations are unclear. However, I do recall some very large stopes and numerous narrow “burrows” that Roberts said were made by Chinese miners using single jack (hand) drilling tools. The erratic structural character of the ore shoots is consistent with their being a combination of fissure veins, replacements, and manto-style replacements along bedding. Prospecting was active in the early days but discovered very little additional ore beyond the Garrison mine. Some diamond drilling was done in the early 1960’s to test for new reserves downdip from the mined stopes, such as a 1,500-ft hole mentioned by Roberts and others (1967), but evidently there were no significant ore intersections. The selectivity for ore in a rather small volume of rock appears to be a fact in this district, as it has been in many other polymetallic districts in Nevada (Eureka, Tybo, and others).

The ore minerals of the Garrison mine are reliably reported by Emmons (1910, p. 104) as:

> “quartz, calcite, galena, stibnite, pyrite, zinc blende (sphalerite), gray copper (tetrahedrite) and other minerals of antimony and arsenic. The oxidized ore is composed of silver chloride, copper carbonates, and iron and

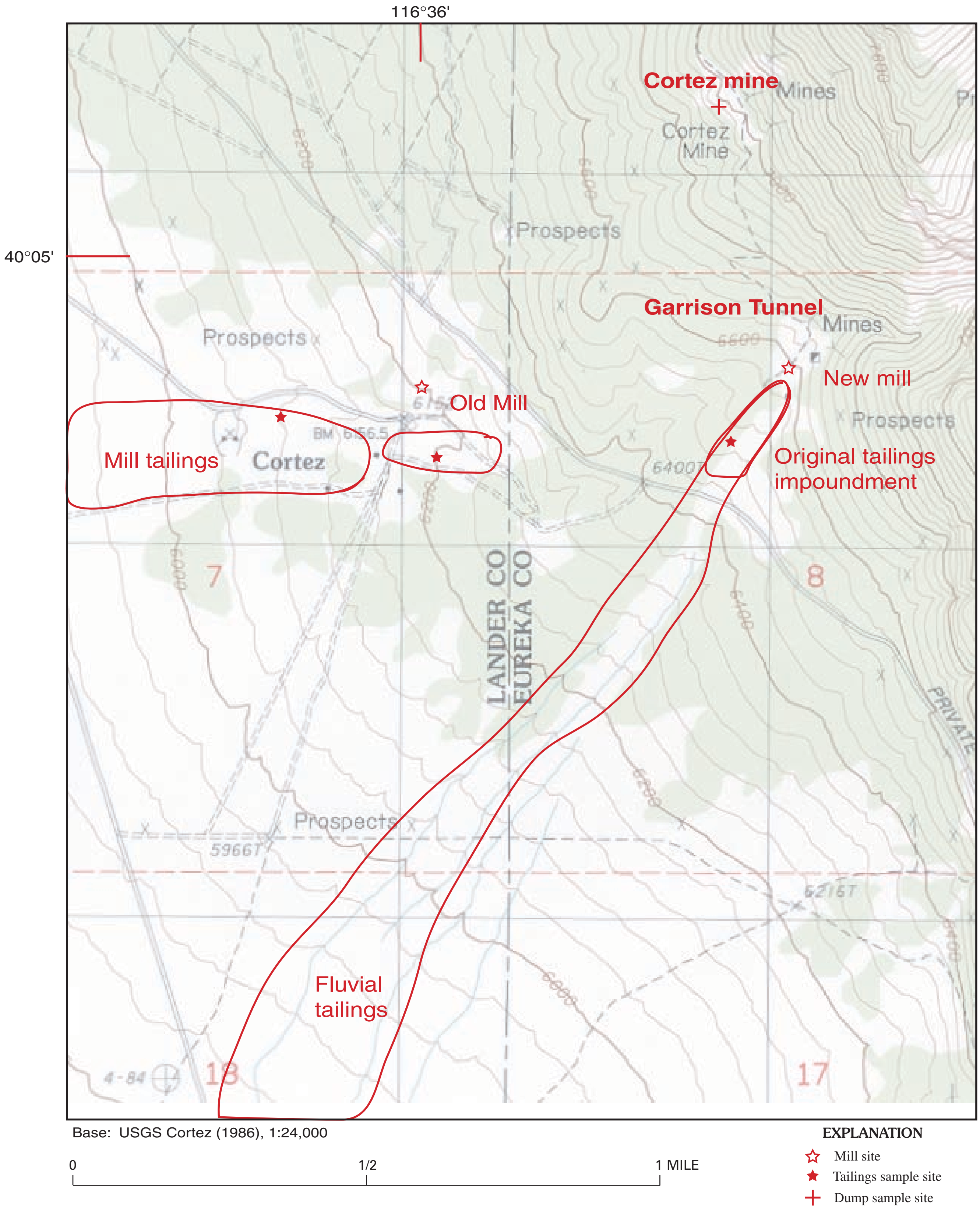


**Figure 22.** Features of part of the Cortez mining district, showing sample localities.

**Photograph 41.** The original Cortez silver mill from the 1890's, constructed on a stone foundation, released coarse-grained stamp tailings on the north edge of the hamlet. Those tailings were reprocessed in the 1930's and resemble sand dunes today.

**Photograph 42.** The new mill at the Garrison mine tunnel built in 1923 had a concrete foundation and used flotation to recover silver and lead. It operated until 1930 at a rate of 125 tons per day or more.

manganese oxides. The galena is very rich in silver, especially where it is coated with dark films of a sooty black sulfide that is presumably argentite. The milled ore runs from 30 to 80 ounces of silver and $3 in gold to the ton. Where pyrite is abundant the mill runs range up to $15 in gold to the ton. The completely oxidized ores were very much richer."

The polymetallic deposits of Mill Creek were well described by Emmons (1910) as being within altered granodiorite or within 300 ft of the intrusion as veins and irregular replacements in limestone. He noted quartz-pyrite-sericite alteration along veins in granodiorite. Ore minerals in veins cutting granodiorite included quartz, calcite, galena, sphalerite, pyrite, argentite, stephanite, tetrahedrite, and stibnite; the same ore minerals were observed in replacement deposits (with the addition of chalcopyrite and lack of sulf-antimonides). Outcrops and oxidized veins to a depth of 100 ft contained “spongy ferruginous quartz carrying silver chloride, lead carbonate, and other minerals.” One of the larger mines in Mill Creek Canyon, the Bullion Hill on the Aurora vein, produced $50,000 between 1883 and 1908, not much for 600- and 375-ft-long adits along the vein.

Deposits of gold at Cortez and Horse Canyon are described as generally similar to the larger sediment-hosted gold deposits in the Lynn and Jerritt Canyon districts to the northeast. At both deposits, gold ore and alteration are structurally controlled by the intersection of thrust faults (Roberts Mountains) and younger high-angle faults. Host rocks are lower plate Wenban Limestone and upper plate Vinini Formation siltstone and chert. Gold deposits are associated with zones of decalcification, silicification, and enrichment in As, Sb, Hg, and Tl. Stibnite, fluorite, barite, and cinnabar have been identified but are rare. Gold in primary (unoxidized) ore occurs on rims of As-rich pyrite and probably as submicron-sized grains, whereas gold in oxidized ore is in coarser crystals in pyrite sites and in silica veinlets.

*Geochemistry.—* Abundant geochemical data exist for the Cortez district from the studies of Erickson and others (1966), which contributed to the discovery of the Cortez gold deposit, and Wells and Elliott (1971), for a large part of the district including Mill Creek Canyon, and the Buckhorn and Horse Canyon deposit areas north and east of the area of figure 22. The more than 1,000 rock samples collected in those studies show a wide range in metal contents, commonly with very high values (greater than 1,000 ppm) but the samples were not collected to provide data on the typical composition of rocks or pre-mining background. Rather, the samples were taken from atypical outcrops in order to emphasize geochemical anomalies for exploration (Wells and Elliott, 1971). Anomaly thresholds are very high compared to modern methods that consider Au greater than 0.1 ppm and As greater than 200 ppm to be very high. The Mill Canyon area, including the granitic intrusion, was characterized by high values of Ag, Au, Cu, Mo, Zn, As, Sb, Hg, and Te. Rocks in Horse Canyon, near the site of the future mine of that name, were high in Ag, Cu, Mo, As, Sb, and Hg, and rocks in the area of the Buckhorn mine were high in Ag, Au, Cu, Mo, As, and Hg. Samples in the vicinity of the old Cortez silver mine were less enriched in metals than many parts of the district but were high in Ag, Cu, Zn, and Sb. Many of the mineralized rock samples were 200 to greater than 5,000 ppm As, 100 to greater than 1,500 ppm Sb, and 0.5 to greater than greater than 5 ppm Hg. Concentrations of base metals (Cu, Mo, and Zn) were high but not extreme (in the range of 20 to 1,000 ppm).

## Mineral-Environmental Conditions

New observations have been made only in the vicinity of the Cortez silver mine. The open pit at the Cortez gold mine has been reclaimed and is now full of water. The Mill Creek properties were not accessible.

*Mineralized rocks and ores.—*Mine dumps at the Garrison mine are fairly large, but they are dry most of the year and no acid-rock drainage is evident, presumably because sulfide minerals are sparse in the mine waste and calcite is abundant in waste rocks and gangue. Mine dumps in Mill Canyon were not investigated.

*Mills and tailings.—*The largest mill and tailings impoundment in this district is that of the Cortez Gold mine, which continues to process gold ore from mines to the west in the Tenabo District (Gold Acres, Pipeline, and others). This tailings impoundment was not studied. The mills of interest here are the two that treated silver ores from the Garrison and related mines near the Cortez townsite. The original mill, with stone foundation, was built in 1886 and used a unique hyposulfate leaching process. Tailings from the original mill were placed on the gentle slope to the west. These tailings, amounting to about 125,000 tons, were reprocessed by the cyanide method in 1908–15 (Vanderburg, 1938a). Today these tailings have the appearance of sand dunes. They seem to be stable, except for some movement by wind.

The new mill, with concrete foundation, was built near the lower tunnel in 1923. Initially a cyanide mill, it was soon converted to flotation. The new mill operated until about 1930 and possibly intermittently in later years. The new mill ground ore to a fine size and released the tailings into a gulch that trends southwest through pines to the sagebrush-covered fan; a haul road constructed in the 1980’s cuts across the middle of the tailings. Because of severe erosion, the design of the impoundment is difficult to discern today but probably included two dams across the gulch within about 700 yards of the mill.

The Garrison mill tailings provide good lessons on what happens to tailings in Nevada. These tailings are highly eroded, with gullies 6 to 12 ft deep (photos 43, 45), and the tailings now extend for 2 mi down the wash. There is evidence for two impoundments below the mill in which the operators piled the wet tailings to a depth of 9 to 15 ft. The operators used flumes with spigots to direct the slimes and sands to appropriate places; the dams were made from tailings sands with some boards. The dams have been breached on one or more occasions (Nash, 2002b). The 1980’s haul road has acted as a dam about 10 ft high, and it too has been eroded by stormwaters, as shown by repairs made in recent years. The downslope tailings surround mature pine trees and have killed some; the large trees must have been growing before the tailings were deposited. The materials to the west are stratified, as in the ponds closer to the mill, indicating deposition from water. Sedimentary features and the geometry of the tailings suggest that they were redistributed during one or more dam failures during flash floods (Nash, 2002b).

*Surface water.—*Flowing streams and springs are rare in this district; thus, only a few samples could be collected. The large and deep tunnels at the Garrison mine are dry. The pit at the Cortez gold mine collects water, described by Price and

**Photograph 43.** The Garrison mill sluiced its tailings into two ponds that were built across the canyon, each with a dam about 20 feet high. Erosion, shown here, is deep and extensive but cannot explain the huge volume of tailings in the canyon and fan to the west. The tailings shown here were probably deposited after the previous dam failed and was repaired.

**Photograph 44.** These mill tailings, below the two impoundments, are part of a swath of tailings that extend for 8,000 feet southwest of the impoundments. They appear to have been transported by floodwaters, probably in several flood events. Bedding in the tailings dips about 8 degrees, parallel to the slope of the upper alluvial fan. No gravel beds could be identified. Relatively recent stormwaters have eroded deep gullies into the tailings.

others (1995), who refer to analyses by the USEPA. Reported pH values ranged from 7.55 to 8.13, and As concentrations ranged from 0.04 to 0.38 mg/L (40 to 380 ppb as used in this report). The mines in Mill Creek Canyon are high on the Cortez Range and presumably are wet but were not accessible. Mill Creek at the mouth of the canyon shows no signs of iron precipitates typical of acid-mine drainage and has a pH value of 8.4. Metal concentrations are low except for As, which is above the study average at 66 ppb. Two springs southwest of Cortez townsite, distant from mining, have very low metal concentrations, but one sample contained surprisingly high Se (3 ppb).

**Photograph 45.** The fluvial mill tailings extend beyond the Grass Valley road as a blanket more than 400 feet wide and 6 to 20 inches thick. There was no channel for the stormwaters where the slope of the alluvial fan flattens to about a 1-degree slope.

*Summary.*—Historical production from this district prior to 1960 was high from just a few mining areas. The effect of that mining today appears to be small, largely due to the beneficial effects of abundant limestone. The mines of Mill Creek, not studied, release few metals as measured a mile downstream. The large silver mines produce no drainage, and the large tailings piles appear to be benign. The large swath of fluvial tailings more than a mile from the mill are the results of one or more dam failures in storm events, probably while the mine and mill were active.

## Golconda District

*Location.*—Humboldt County, 13 mi east of Winnemucca (fig. 2).

*Major commodities.*—W, Au, Ag

*Mining history.*—Tungsten and other deposits were known as early as about 1870 but there was little production until 1941 to 1945 when tungsten was needed for World War II. Kramer Hill was prospected in 1907 and produced a modest amount of ore prior to 1930. It was re-evaluated and mined by a relatively small open-pit mine in the early 1990's and reclaimed by 1997.

*Status of mining and exploration.*—There was no active mining in this district in 1996–97, and exploration was not evident.

*Production.*—Underground mining of gold at Kramer Hill yielded about $96,000 in gold in the early 1900's. The open-pit operation was designed to mine 300,000 tons containing 0.046 oz/t Au. Gold was recovered by heap leaching at the Pinson mine complex to the north. The Golconda tungsten mine produced about 125,000 tons of ore worth $2,300,000.

*Geology.*—Oldest rocks in the district are Cambrian quartzite and phyllite; thrust faults emplaced Pennsylvanian-Permian chert, shale, greenstone, and limestone. These rocks were intruded by a Cretaceous granodiorite, and all are overlain by Miocene basalt flows and latite tuffs. The gold deposits are in fractured siliceous shales in a high-angle fault zone. The tungsten deposits are in Pleistocene sediments and related to hot spring activity.

*Ore deposits.*—The tungsten deposit is an unusual type, probably of hot spring origin. The tungsten occurs chiefly as blanketlike layers that are rich in Fe-Mn oxides. The tungsten is microcrystalline in oxide material, possibly enriched by adsorption on iron and manganese gels (Kerr, 1940). Tufa deposits overlie the tungsten-rich blankets. The W-Fe-Mn precipitates appear to be related to hot springs, possibly on the margin of Pleistocene Lake Lahontan. Veinlike occurrences of similar W-Fe-Mn-oxides that occur in bedrock phyllites are possibly hot-spring feeder structures.

The structurally controlled gold deposits at Kramer Hill differ in some details from the major sediment-hosted gold deposits of Nevada. The gold is in veins and brecciated veins, and is disseminated in silicified wall rocks (Kretschmer, 1991). Deep and total oxidation makes the ores amenable to heap leaching. The strong influence of rock fracturing on gold distribution is similar to that in the Marigold mine, but insufficient definitive work has been done at Kramer Hill to establish its genesis as a distal-type gold deposit.

### Mineral-Environmental Conditions

*Mineralized rocks and ores.*—New chemical analyses of two dump samples from Kramer Hill show high concentrations of Ag, Cd, Cu, Hg, Mo, Pb, Sb, Se, Tl, and Zn relative to other dumps in this study. However, compared to other ore types, the gold ores at Kramer Hill contain low levels of Cu-Pb-Zn and modest amounts of As, Hg, and Sb (Kretschmer, 1991). The siliceous rocks have low acid-neutralizing capacity, but the ores and rocks are not generating acidic water. Sites of former pyrite crystals are filled by secondary iron oxides, and sulfide minerals are sparse or absent. The oxidized-ore zones and waste rocks appear to be chemically stable in the dry climate; there was no evidence of acid-rock drainage and there was no water draining from mines or dumps. Laboratory leach tests on two samples of gold ore show that very little material is dissolved at pH's of 7.7 and 8.2, but the leachates did have high concentrations of As and Sb. The leach tests are a reminder that during rare storms alkaline water might transport As and Sb from the mines or waste dumps.

The tungsten mine and dumps were not examined or sampled in 1997 because the area was being reclaimed by heavy equipment. I visited the mine on a field trip in 1983 and base the following generalized descriptions on that brief visit. The deposits do not contain sulfide minerals, and the fine-grained W-Fe-Mn oxide materials appeared to be stable. Content of trace elements such as As was not determined but is not expected to be a concern because many trace metals would be adsorbed on Fe-Mn-oxides and should be quite stable. Associated tufa deposits have high acid-neutralizing capacity should there be any acid generation by sulfate minerals such as jarosite.

*Mills and tailings.*—A stamp mill at Kramer Hill processed ore in the early stages of mining, producing a small pile of tailings on the west side of the hill. The tailings, amounting to a few thousand tons, are on a side slope but are generally dry and appear to be relatively stable.

A smelter in the village of Golconda, described as being near the railroad, treated ores from the Adelaide district to the south. It apparently operated in the 1880's. A brief search of the village did not reveal a structure or slag pile.

*Surface water.*—No surface water was observed at Kramer Hill. Episodic flash floods run through arroyos west of the old underground workings and new pit, but transport of mined rocks appears to be minor and for only short distances.

The tungsten mine is in low hills about 1 mile from the Humboldt River. The mined pits and dumps were dry when I saw them in 1983, but reclamation work in 1997 should minimize the possibility of storm runoff reaching the river.

*Summary.*—The gold ores and waste rocks at Kramer Hill appear to be stable in the prevailing dry climate. Total oxidation has destroyed sulfide minerals; thus, there is low potential for acid-rock drainage. Under rare wet conditions, some transport of As and Sb may be possible, but this is not expected to involve significant amounts or distances of transport. Any potentially toxic conditions would probably be local and not exceed the scale of the mining claims.

The tungsten mines and waste dumps should have minimal adverse effects as long as surface water is controlled by the recent reclamation. Tufa associated with the tungsten deposits would neutralize any local sources of acid; drainage would be alkaline and could possibly transport some As. Because of the reclamation, the chances for contaminants reaching the Humboldt River are small.

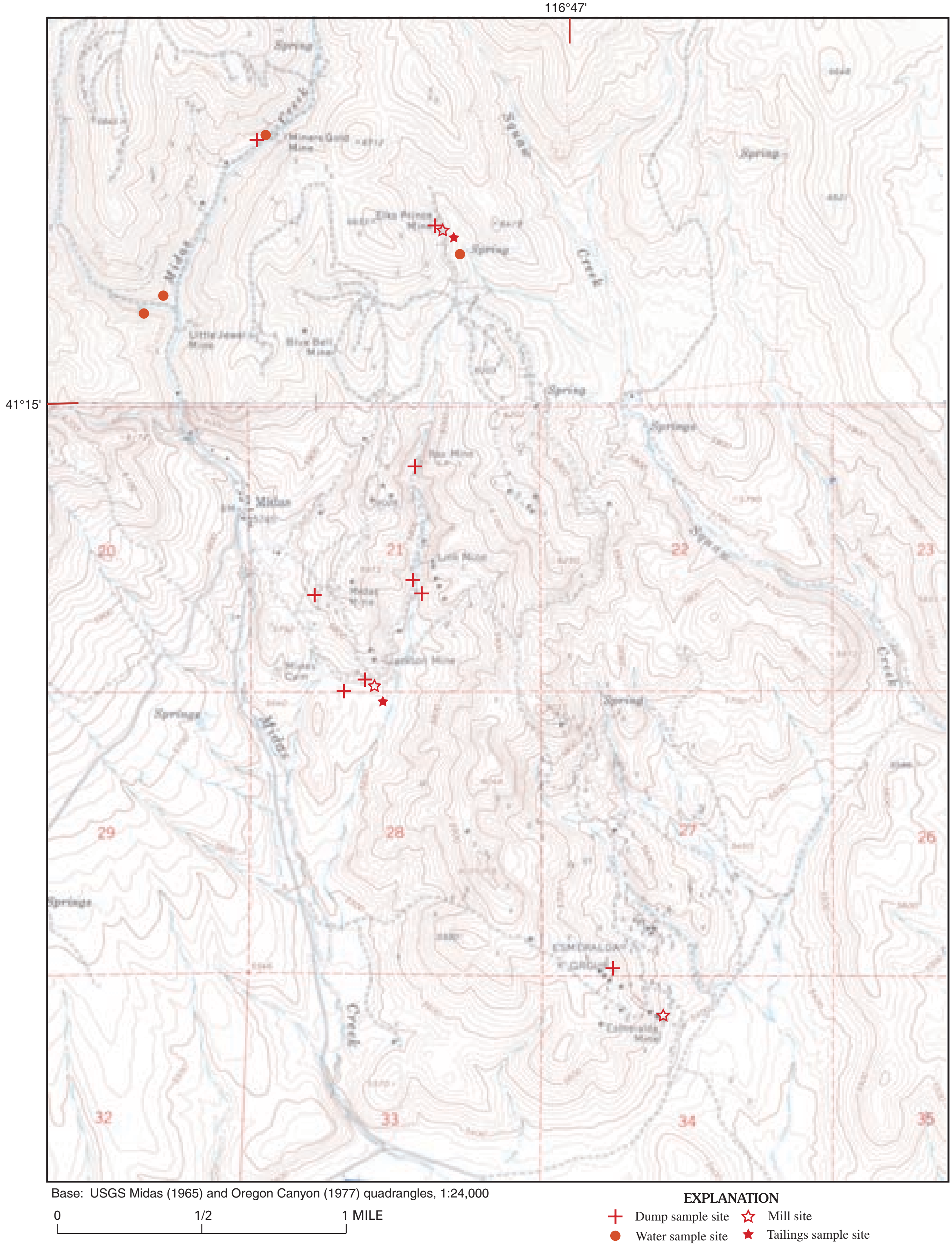
## Gold Circle District (Midas)

*Location.*—Northwestern Elko County, 45 mi north of Battle Mountain (fig. 2 ). Features of the district are shown in figure 23.

*Major commodities.*—Au, Ag; minor Cu, Pb, Zn

*Mining history.*—Gold was discovered in 1907, relatively late for Nevada. Activity and production were high until 1916, and production has been intermittent since then. New concepts for deeper vein targets in the 1990's are reviving exploration

**Photograph 46.** Stormwaters have breached the berm along the haul road more than once over 15 years since the road was built. The berm is 6–8 feet high where the haul road crosses the arroyo filled with tailings. This shows that episodic storm events continue to affect the distribution of fluvial mill tailings.



Base: USGS Midas (1965) and Oregon Canyon (1977) quadrangles, 1:24,000

**Figure 23.** Features of the Gold Circle mining district, showing sample localities.

and definition of new mineralized zones below former producers. The Ken Snyder "discovery" went into production in 1998 with reserves of 3 million tons at 0.82 oz/t gold.

*Status of mining and exploration.*—There was no significant production for many years, but the recently developed Ken Snyder mine was a significant producer after 1999. Exploration in recent years has been intense (several million dollars per year) on well-defined targets. Several companies are active in this district.

*Production.*—Production of lode gold was 129,400 oz, lode silver 1,660,000 oz, and placer gold 59 oz, prior to 1980. The Ken Snyder mine is producing about 200,000 oz Au and 2,000,000 oz Ag per year.

*Geology.*—No pre-Tertiary rocks are exposed in the Gold Circle district, although Paleozoic rocks are reasoned to be present at depth (Wallace, 2003). A thick and complex sequence of Miocene volcanic rocks is present, erupted from local sources. Careful mapping of volcanic stratigraphy and structure and dating of rocks and alteration demonstrate complex activity and ore formation in short period of time in the Miocene (17 to 15 Ma; Wallace, 2003).

*Ore deposits.*—The Gold Circle ores are of the epithermal type, similar to Comstock, Tonopah, and other famous Nevada precious-metal vein districts in Tertiary volcanic host rocks. Primary ore minerals include gold (electrum), sphalerite, galena, chalcopyrite, and silver-sulfantimonides such as tetrahedrite; in the oxidized zone are native silver and silver-halide minerals. Alteration along veins is locally intense and comprises sericite, adularia, pyrite, chlorite, and calcite. Average grade of ore produced through 1969 was about 0.32 oz/t Au and 4.1 oz/t Ag.

New chemical analyses of 13 samples of dump rocks and mill tailings show them to have relatively low concentrations of most base metals but some samples have high concentrations of Ag, Cu, Hg, Mo, Pb, Sb, Se, Te, Tl, or Zn. Some tailings samples are notably rich in Se.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Rocks in the Gold Circle district are commonly altered to pyrite and clay minerals, accompanied by elevated concentrations of ore and trace elements that are considered toxic. Because historical mining was underground and miners carefully selected ore zones, dumps are not large for the amount of ore produced. The dump waste rocks are rich in As, Cu, Cd, Pb, Sb, and Zn. There is a tendency for pyrite and jarosite in the dump rocks to generate acid (acid-rock drainage). Leaching tests on six samples show that some Midas dump samples generate acid (pH 3.5 to 6.5) and some leachates were weakly alkaline (pH 7.5). The leachates carried high concentrations of As, Pb, Se, and Zn. Mineralized rocks in mines may also generate acid and metal-rich water similar to those of the leach experiments. However, there is evidence in surface-water compositions for buffering by carbonate in volcanic rocks and alluvium because six streams in the area have measured pH values in the range of 7.9 to 8.4.

*Mills and tailings.*—The gold-silver boom at Gold Circle in 1907 resulted in the construction of as many as 11 mills (Ken Snyder, oral commun. to Alan Wallace, U.S. Geological Survey, 1997). Six or more mills were destroyed by fire prior to 1916, and the district suffered a major setback when the Gold Prince mill burned in 1921 (LaPointe and others, 1991). Three of the mills can be located today, but none created a large volume of tailings. The unconfined tailings piles are distant from streams and houses. Leach tests on three samples of tailings yielded solutions with pH values in the range of 4.2 to 6.8. The only metal of notably high concentration in the leachate was Se. The selenium is not unexpected in this district, which is known to have silver-selenide minerals; but the high concentrations suggest that Se may become concentrated near the surface by wicking of solutions to the surface and evaporation to form a selenate efflorescent crust. The selenium might be a hazard for wildlife or livestock if they were to drink from puddles or eat Se-enriched plants over long periods of time (chronic exposure).

*Surface and ground water.*—The Gold Circle district receives more precipitation than most mining districts in the study area (8 to 16 inches), and this is reflected in the many springs in the district and two creeks that flow much of the year. Cottonwood trees were planted in the village and have thrived. I observed no drainage at mine tunnels in 1997. Water from springs and small creeks (six sites) appears to be of good quality: pH ranges from 7.9 to 8.5, and conductivity is low (170 to 490 $\mu$S/cm). Chemical analyses show that metal concentrations generally are below the study average and regulatory standards. The one site with detectable contamination is a seep located a short distance east of the Prince mill tailings: the sample from that site had a very high Se concentration, Mo was higher than average, and the pH value of 8.1 was not unusual.

*Summary.*—In theory, the sulfidic ores and dumps of Midas that are rich in base metals could generate acidic, metal-rich water. Observed surface water is buffered by calcite and does not contain high concentrations of toxic metals. Natural buffering by propylitic alteration, gangue calcite, and caliche effectively neutralizes and mitigates any acid drainage that does develop. Also, the fairly deep level of oxidation (100–150 ft) in many mines destroyed sulfide minerals prior to mining, thereby minimizing the tendency to produce acidic, metal-rich drainage. The water and environmental quality at Midas is good despite geologic ingredients that might suggest concerns.

# Hilltop District

*Location.*—20 mi southeast of Battle Mountain, in the Shoshone Mountains of Lander County (figs. 2, 15). Features of this mining area are shown in figure 24.

*Major commodities.*— Au, Ag, Cu, Pb, Zn; Sb; Ba

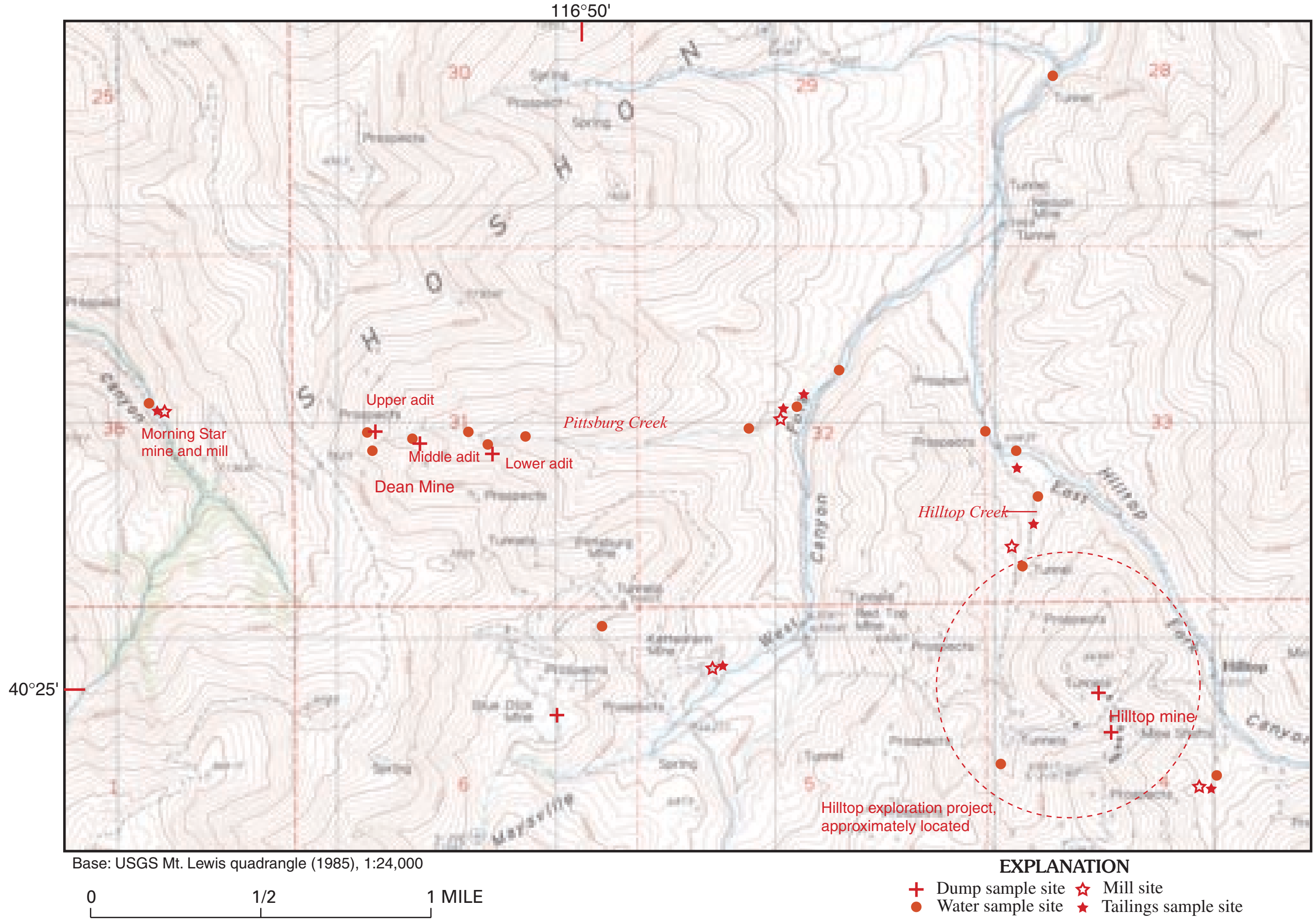


**Figure 24.** Features of the Hilltop mining district, showing sample localities.

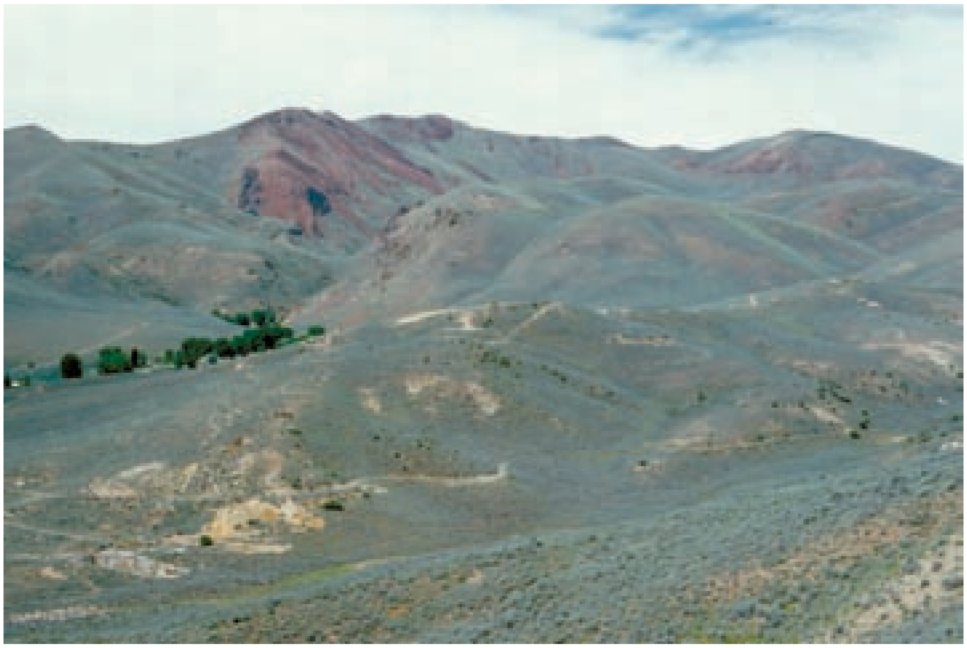
*Mining history.*—The first deposits were discovered in the mid-1860's, but major production did not come until 1887. Mining was fairly continuous through about 1951.

*Status of mining and exploration.*—There was no mining in the 1990's, but exploration is active at the site of the former Hilltop mine, and there was extensive exploration at the former Dean mine in the early 1990's. The "mineral inventory" at the Hilltop property is about 700,000 ounces of gold (Kirwin and Abrams, 1991); close-spaced drilling from 1995 to 2001 presumably increased the inventory. The resource is mixed oxide and sulfide types of unspecified grade.

*Production.*—Metallic production through 1951 is estimated to be about $811,000 from 18,000 oz Au, 358 oz Ag, 400,000 lb of Cu, and 540,000 lb of Pb (Stager, 1977). About 112 tons of stibnite ore were shipped during WWI and WWII. Placer gold production was about 120 oz Au. Barite production from 1930 to 1969 was more than 50,000 tons worth more than $300,000.

*Geology.*—Area geology was mapped by Gilluly and Gates (1965), but local controls on ore deposition have not been well established. The major deposits are in a complexly thrusted sequence of Ordovician quartzite, chert of the Valmy Formation, sandstone of the Silurian Elder Sandstone, and partly in one or more small sills, dikes, and stocks of Tertiary quartz monzonite composition. The gold-silver deposits are in quartz veins along fracture zones in brittle, siliceous rocks. Tertiary breccia pipes cut ore and also carry ore in places. Volcaniclastic rocks and lava flows overlie ore in a few places. The barite deposits, located north of the precious-metal mines, are in dark chert of the Devonian Slaven Chert.

*Ore deposits.*—The historical mines of the district are described by Stager (1977), but details of ore formation have not been published. The amount of hydrothermal alteration and abundance of sulfide minerals appear to be quite variable, possibly a function of local wall-rock composition (many rock types are unreactive). The district may be zoned from chalcopyrite and other base-metal sulfide minerals with pyrite-arsenopyrite in the center (Hilltop mine) to assemblages richer in antimony (tetrahedrite and stibnite) in the western deposits such as Dean, Kattenhorn, and Blue Dick. Recent work on exploration samples shows metal zonation (Kelson and others, 2000). Some of the variation may be masked by differences in



**Photograph 47.** The Gold Circle district, in low hills of the Snowstorm Mountains, is cut by several drainages that are dry most of the year. Cottonwoods thrive in the hamlet, fed by waters from Midas Creek. The Jackson mine and mill, lower left corner, placed tailings in the lowlands, and the tailings are only slightly eroded after more than 75 years. (A.R. Wallace photograph)

**Photograph 48.** The headwaters of Midas Creek, north of Miner's Gold mine, creates a small riparian zone in otherwise sage-covered hills. Midas Creek shows little or no chemical effects from altered rocks and mining. (A.R. Wallace photograph)

materials on mine dumps—ore minerals are sparse on the old dumps and abundant on dumps from the 1990's. I could not identify stibnite on dumps from the Blue Dick mine, but samples from that area are rich in Sb according to new analyses.

Veins carrying the Ag-Au ore are in structures that have steep dip and which supported mining for 500 to 925 ft vertically and 300 ft on strike (Stager, 1977). Oxidation extended only 100 ft below the outcrops. Quartz monzonite porphyry dikes are highly altered to clay minerals, and many contain more than 5 percent pyrite, considerably more than adjacent chert and quartzite. Although there are many differences, such as the limited amount of oxidation at Hilltop, one can speculate on similarities to the Marigold deposits, the prototype examples of distal-disseminated gold deposits related to adjacent porphyry intrusive bodies (Theodore, 1998).

Drilling and detailed studies at the Hilltop mine area (Kirwin and Abrams, 1991; Kelson and others, 2000) show that gold mineralization is hosted by thinly bedded cherts, quartzite, and argillite of the Valmy Formation. Most of the ore is in a tabular body between two thrust faults in the upper plate of the Roberts Mountains allochthon. Rocks in the ore zone are described as a "tectonic megabreccia." Exploration work suggests a relation to several regional features: (1) Roberts Mountains thrust; (2) Cortez rift; and (3) Mt. Lewis cauldron and Caetano trough. Breccia pipes carry a distinct style of narrow quartz veins that carry visible gold, with common pyrite, chalcopyrite, and lesser galena. From the spacing and extent of drilling, it is evident that a large deposit, on the order of a million ounces of gold, has been identified and will become an open-pit mine if engineering analysis and permitting process are favorable.


**Photograph 49.** Early mining at about 1900 focused on near-surface portions of veins and created relatively small amount of waste and disturbance, as shown here at the Gold Crown mine. (A.R. Wallace photograph)

## Mineral-Environmental Conditions

There are a number of environmental concerns related to past mining in this district, including drainage of acidic, metal-rich water from mine portals and mine-waste dumps and metals released from several mill tailings. Mine drainage is probably the biggest source of concern to the environment, but the effects of unconfined mill tailings at five sites also could be significant in a major storm event.

*Mineralized rocks and ores.*—Oxidation prior to mining was much less pervasive in this district than in most parts of northern Nevada. Mine dumps both from deep shafts and from shallow adits tend to contain abundant sulfide minerals. These sulfide minerals, combined with higher amounts of precipitation and snow, produce more acid mine drainage than in most districts studied. The mine drainage water is especially degraded where drainage from tunnels is allowed to react with sulfidic waste on dumps. New chemical analyses of historical dump rocks, tailings, and altered rocks show them to have high concentrations of many base and precious metals, including Ag, As, Bi, Cd, Cu, Hg, Mo, Pb, Sb, Se, Te, Tl, and Zn. Arsenic in waste rocks ranges from 160 to 3,000 ppm and Se ranges up to 60 ppm. Leach tests on three dump samples produced leachates with pH values of 3.0, 3.6, and 5.7; metal concentrations in the leachates are proportional to the acidity. The acidic leachates carried high concentrations of Al, Cd, Cu, Fe, Mn, Se, and Zn.


**Photograph 50.** Numerous mine workings of the Pittsburg/Dean mine complex are in this headwater basin, which is underlain by siliceous rocks at higher elevations and limestone at the elevation of the photo. The upper mine workings generate acid and metals, and there is no neutralization capacity in the wall rocks. Lower mine drainages and springs are alkaline and effectively neutralize the acidic drainage over a distance of about 500 feet (foreground).

*Mills and tailings.*—Mining through the 1920's was supported by at least five mills that are described in the literature and located in the field (fig. 24). Tailings were present near the five mill sites. The smallest mill, with stone foundation, operated below the Kattenhorn mine, probably before 1900. Two mills served the Hilltop mine area, the larger of which has a concrete foundation and is located west of the deep tunnel under the hill. According to Vanderburg (1939) this mill closed shortly after it was built in 1922, which is consistent with the modest amount of tailings to the north of the mill. The western part of the district, which includes the Philadelphia and Morning Star (Dean) mines, was served by two mills. In the 1890's, a tram carried ore from the Pittsburg mine complex north to the mill above the west fork of Rock Creek, and tailings were placed on two elongate piles near the junction of a side tributary (Pittsburg Creek) with the West Fork (photo 51). These tailings, possibly amounting to about 50,000 tons, were reprocessed one or more times as technology improved (Vanderburg, 1939). An equally large tailings impoundment is at the Morning Star portal of the Dean mine complex in Dean Canyon (photo 56). The tailings in this district reflect the sulfidic character of the veins: they are yellow

**Photograph 51.** Tailings from the Pittsburg mine and mill complex were placed near the junction of the West Fork of Rock Creek and Pittsburg Creek (left side of photo).

**Photograph 52.** A small mill on the east side of the Hilltop district created a few thousand tons of tailings, placed in an intermittent creek that joins the East Fork of Rock Creek.

**Photograph 53.** This concrete foundation marks the site of a small mill in the center of the Hilltop District; it received ore from a tunnel that went under the Hilltop and adjacent mines. This relatively modern mill may have operated in the 1920's.

**Photograph 54.** Several exploration adits in the Dean mine area from the early 1990's created acidic mine drainage that ran across sulfidic mine waste. The pH at this upper tunnel was 2.7 in 1997. The siliceous wall rocks have no acid neutralization capacity.

to ocher and contain fairly high concentrations of base metals. Leach tests on three samples produced solutions with a wide range in pH (3.7 to 8.4); the acidic leachate solutions were high in Cu and Zn and very high in Pb, whereas the alkaline solution was very high in As and Sb.

Water flowing through and below mill tailings piles at four sites was tested several times to determine possible inputs from the tailings. Small seeps (about 1 gal/min) from the Morning Star tailings have pH values of 3.2; concentrations of Cd, Cu, Se, and Zn are elevated but only Se exceeded the aquatic wildlife standard. Measurements on Pittsburg Creek above and below the two Philadelphia tailings piles did not indicate any significant changes associated with the tailings. The three other tailings impoundments did not appear to produce significant changes in nearby streams as compositional variations could not be distinguished from numerous other sources of contamination.

Mercury is high in samples of tailings from this district, with concentrations ranging from 14 to 1,690 ppm in five of six analyzed solid samples. Highest concentrations in dump materials are 5 to 8 ppm Hg; thus, much of this Hg appears to be added during milling—which is not unexpected when

**Photograph 55.** Mine drainage from this small exploration tunnel reacted with sulfidic dump rocks to create the dark red-brown water in the pool, which then flowed into the unnamed creek to the left. Water in that creek had a pH of 3.3–3.6 for several hundred feet, until it was neutralized by spring inflows north of the gray mine dump (limestone from the lowest mine tunnel workings).

**Photograph 56.** The Morning Star mill, at the west end of the Dean mine complex, placed its tailings (light color) near Dean Creek in the Lewis Canyon watershed.

amalgamation was used to recover gold. The high values are associated with virtually all of the tailings sites, not just one unusual mill and tailings pile. The observed Hg values were in the range found for calcine from mercury retorts. The Hg enrichment in mill tailings could not be traced to surface water because my water samples were not analyzed for Hg. The observed high Hg values in tailings solids suggest that additional studies are warranted to monitor possible mobilization into surface water.

*Surface water.*—There is more water in and near the historical mines of this district than in most of the districts studied. The East and West Forks of Rock Creek have substantial flow and probably flow throughout the year, whereas some of the tributaries probably flow for only a few months. Because the surface waters were widespread and diverse in composition, more samples (44) were collected here than in any of the studied districts, and several of the sites were sampled two or three times. A total of 35 water sites were sampled, most of which are in or near mines. The pH values of the water ranged from 2.4 to 8.4; seven of the sites are characterized by high to very high conductivities. Most of the sites were visibly contaminated by the effects of mining, as shown by red to ocher precipitates on the streambed, but the highly acidic sites appeared to be clear and “clean” because iron and other metals were held in solution. Chemical analyses show that about half of the sites are contaminated by metals from the mined rocks.

Analyses show the following metals to be high or very high (relative to other mine water in this study) at many sites: Al, As, Cd, Cu, Fe, Se, and Zn. Lead was not found to be high in any water sample. As described later in detail, the mine drainage water that starts with pH values of 3 or less, and very high metal concentrations, evolves to circum-neutral and relatively low metal concentrations over distances of 0.5–1 mi.

Most mine workings in the central part of the district are dry, in part because they were shaft operations, but one tunnel that emerges near the old mill releases water to a nearby stream that I call Hilltop Creek (fig. 24). The small flow from black, carbonaceous, cherty rocks of the tunnel has a pH of 3.06 and conductivity of 1,540 $\mu$S/cm—indicating that the water has not been neutralized by carbonate strata or alteration minerals. This mine drainage later flows over mill tailings and mixes with a larger stream from the east. The beneficial mixing reactions are described in a later section on evolution of surface water.

Several mine adits from the Dean exploration venture of the early 1990’s released acidic mine drainage, but that was effectively stopped in 1998 when the tunnels were plugged. The upper mine levels, in quartzite and porphyry dikes, earlier released highly acidic (pH 2.6–2.8) and metal-rich water, but the lowest adit in limestone released water with a pH of 8.1. Additional acid was generated as the mine water reacted with the sulfidic waste on dumps. Pittsburg Creek, a northward-flowing intermittent stream that has no formal name, had prominent rusty iron oxide coatings and the pH was 5.8 below the lowest Dean dump. The evolution of this contaminated mine water is described in a later section.

The Morning Star mine adit is dry, but the tailings below it are wet much of the year from snowpack and rain. Water seeping from the tailings has a pH of 3.2 and carries high concentrations of several metals. This seep mixes with the higher flow of water in Dean Canyon Creek, causing the pH to rise and form a white precipitate of Al-Zn-oxyhydroxides. The abundant and alkaline water in Dean Canyon Creek appears to effectively dilute and mitigate the small drainage from the Morning Star tailings; no downstream sample was analyzed to confirm that metal concentrations are low.

*Summary.*—The Hilltop district produced some of the most highly contaminated mine water in the study area from high sulfide ores in siliceous rocks with low acid-neutralizing capacity. However, other rocks in the district, as well as alluvium, contain carbonate; this allows for natural mitigation of acid-mine drainage within about 1 mi of the source. Reclamation work in 1998 greatly improved water quality. Some useful lessons can be learned from this area: (1) Sulfide minerals exist near the surface, suggesting that mechanical erosion is more active than chemical weathering at this position high in the Shoshone Range; (2) siliceous sedimentary rocks and silicified dikes have little acid-neutralizing capacity to mitigate the acid formed when sulfide minerals oxidize; (3) carbonate-bearing strata in the sedimentary section and caliche in alluvium help mitigate acidic drainage, but in this area there is less neutralizing capacity than in many parts of the study area, and water quality remains degraded for longer distances of flow than in other areas. Water leaving the mining area has relatively good water quality, adequate to support fish in several miles of Rock Creek.

## Imlay District

*Summary.*—The Imlay mining district, on the west side of the Humboldt Range, midway between Lovelock and Winnemucca (figs. 2, 15), was one of the early silver producers in the region. It was active again in the 1930’s at the Standard gold mine, and in recent years at the Florida Canyon open-pit mine and large red heap-leach stack that is visible from I–80. Aspects of the Standard mine were described by Nash (2001).

## Iron Point District

*Location.*—Humboldt County, 20 mi east of Winnemucca (fig. 2 ).

*Major commodities.*— Ag; minor Mn, Pb, Zn, Au

*Mining history.*—The Iron Point district is not well described in the literature. A small amount of silver was shipped from the Silver Coin mine prior to 1920. Other mines in the central part of the district appear to have been productive prior to about 1950; dumps and works are of modest size, and the amount of metal produced probably was not large.

*Status of mining and exploration.*—No mines were active in 1997. Several exploration programs were active, including substantial amounts of drilling.

*Production.*—Total production figures are incomplete. The size of dumps suggests that the amount of silver and associated metals was relatively small. Manganese production prior to 1940 also was small.

*Geology.*—Basement rocks are Cambrian quartzite and phyllite that have been overridden by two thrust-faulted plates of limestone, shale, and metavolcanic rocks. These packages of rocks were intruded by several small stocks and numerous dikes of Cretaceous granodiorite. Tertiary basalt lavas cap the range. The silver-bearing polymetallic deposits are in deformed rocks adjacent to thrust faults. The manganese deposits are chemical facies (lenses) within Permian-Pennsylvanian marine strata.

*Ore deposits.*—Good descriptions of the silver deposits are not published. Dumps are unusually dark colored from black chert, manganese oxides, and probable carbonaceous matter in shales. These black rocks are cut by veinlets of white quartz and calcite, and sulfide minerals are sparse or absent. The mined deposits probably were oxidized prior to mining, but the black manganese oxide coloration masks the usual brown iron oxides. Ores of this character are not common in northern Nevada; one similar occurrence is the silver-rich ores of the Betty O’Neal mine, Lewis District. These deposits could be classified as polymetallic veins or distal-disseminated type, either of which is related in concept to the adjacent granodiorite pluton.

The manganese mines and prospects follow lenses of manganese oxide minerals in cherts. These are submarine hot-spring deposits that formed syngenetically with the enclosing sediments. The known deposits in this district are quite small.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Fairly large areas of fractured and altered rocks enclose the silver deposits (Erickson and Marsh, 1971; 1974). According to the geochemical survey by Erickson and Marsh (1971), the altered rocks contain high concentrations of metals, such as As (greater than 100 ppm), Cu ( greater than 100 ppm), Hg (greater than 1 ppm), Pb (greater than 100 ppm), and Sb (greater than 20 ppm). New chemical analyses of two dump samples show them to have high concentrations in many metals; one had high concentrations of the suite Ag-As-Hg-Sb-Tl and the other was high in Cd-Cu-Tl-Te-Zn. Leach tests on a dump sample from the Silver Coin mine yielded a pH of 6.2 and high concentrations of As and Sb in the leachate.

*Mills and tailings.*—No mill site or tailings were recognized in this district.

*Surface water.*—No drainage was noted at mines or prospects, and the surface was dry in May of 1997 when streams and springs were flowing in most other districts.

*Summary.*—Mined rocks in this district were mostly oxidized and do not generate acid-rock drainage. Dumps are locally rich in base metals, but these do not appear to be mobile. Stormwater could possibly transport As and Sb for relatively short distances.

# Ivanhoe District

*Location.*—Western Elko County, about 40 mi north of Battle Mountain (fig. 2). Features of the district are shown in figure 25.

*Major commodities.*—Hg, Au, Ag

*Mining history.*—There was no mining in this district until 1915 when mercury was discovered and brought into production. Most Hg production was between 1929 and 1943, and there has been minor intermittent production since then. The largest mining operation began in 1990 at the Hollister gold open-pit mine, but mining ceased in 1992 before the announced resource was mined out. The heap-leach facility continued operation through 1996, and in 1997 much of the mine area was reclaimed.

*Status of mining and exploration.*—There was no mining activity in 1997. Exploration for gold was widespread in the district. The many mercury mines are considered by many to be favorable sites for potential hot-springs gold, as at the Hollister mine.

*Production.*— One of the more productive Hg districts in Nevada with more than 2,000 flasks. The Hollister mine produced only a small part of the announced reserve/resource of more than 1 million oz Au.

*Geology.*— Basement rocks in the district are quartzite, argillite, and chert of the Ordovician Valmy Formation, unconformably overlain by a thick sequence of Miocene and younger volcanic and volcaniclastic rocks. The Valmy has not been productive in mines to date but has been prospected as a host for Carlin-type gold deposits and contains gold-bearing zones in the deepest part of the Hollister mine. Tertiary rocks are highly varied in composition and mode of deposition: some are always barren, whereas certain kinds are predictably favorable for Hg or Au when intercepted by feeder structures. Bartlett and others (1991) and Wallace (2003) show the physical and chemical selectivity of tuff and andesite flow units for gold and mercury in the district. Gold and mercury mineralization formed at about 15.2 to 14.9 Ma at and near the paleosurface in tuffaceous sediments above relatively impermeable volcanic and Paleozoic rocks.

*Ore deposits.*—Two ore types at Ivanhoe, mercury and gold, are related in general, if not in detail. Both are associated with hot springs activity that altered volcanic rocks and deposited huge amounts of opaline silica at or very close to the surface. The mercury deposits are classified as hot-springs type, and the Hollister gold deposit is classified as hot-springs type gold. The Hg deposits are distributed over a broad area (9 by 6 mi), whereas the known gold deposits are in a smaller central area of about 2 $mi^2$. The Hg deposits are relatively small tabular zones, elongate along feeder structures, with open-pit lengths of about 500 to 2,000 ft. The Hollister open-pit mine was planned to mine several lenses of gold-bearing rock containing about 18 million tons of ore for heap leaching (Bartlett and others, 1991), but mining stopped short of that goal. Although the tonnage for the Hollister gold mine was much larger than for the Hg open-pit mines, it was much smaller than the large to huge open-pit mines on sediment-hosted gold ores in northern Nevada.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Geochemical descriptions of rock alteration and ores by Bartlett and others (1991) and in this study show enrichments in the epithermal suite of elements (As, Hg, Sb, Te, and Tl) to tens or hundreds of parts per million. The widespread rock alteration originally included sulfide minerals, especially in the more iron-rich (basaltic) rocks, but the primary abundances (about 1 to 3 percent) were not high compared to many deposit types in the region, and most primary sulfide minerals have been oxidized within 300 ft of the surface. This suggests that acid-rock drainage should not cause concern in this district, and this is confirmed by my reconnaissance observations.

New chemical analyses of 15 samples of dump rocks and retort calcine show they contain high concentrations of Hg, Sb, Tl, and scattered high concentrations of Bi, Mo, and Sb. Leach tests on three samples (two calcine) show these materials generate alkaline solutions (pH 7.0 to 8.9) with very low

Base: USGS Tuscarora (1982), 1:100,000

**Figure 25.** Features of the Ivanhoe mining district, showing sample localities.

**Photograph 57.** The Standard Mine was probably the first bulk-mined sediment-hosted gold mine in Nevada. This view shows the southern of two open cuts that are small in comparison with recent gold mining operations elsewhere in Nevada. There was no recent mining here.

**Photograph 58.** As a fairly large gold producer, the Standard Mine also created a substantial pile of mill tailings that were placed at the west edge of the mountain range. These fine-grained materials are deeply eroded, but dams contained most of the tailings.

concentrations of all metals. No reliable Hg determinations were made on the leachates because a special aliquot was not taken (as described for water sampling and analysis).

*Mills and tailings.*—There are numerous retorts of simple to complex design and numerous associated piles of calcine near mines in this district. Only small seeps or puddles of water are present in wet seasons; most of the time these mines and calcine piles are dry. There are no perennial streams within a mile of these features. Leach tests on two samples of calcine produced solutions with pH values of 7.0 and 8.9 and low concentrations of metals relative to other leachate solutions in this study. The highest risk at these abandoned mines may be ephemeral puddles that can collect runoff water enriched in mercury and a few other metals that could be unhealthy to wildlife over long periods of time. Tests have not been made to determine if the puddle water might have concentrations sufficiently high to be acutely toxic in a few hours of exposure.

*Surface water.*—There is very little surface water in the Ivanhoe district. Three sites (springs and a small pond filling an exploration pit) showed pH values in the range 7.7 to 8.2, indicating that the altered volcanic rocks in this area are not generating acid. The conductivities at these sites were less than 300 μS/cm, suggesting normal chemical contributions from the nearby rocks and soils. Chemical analyses show the three samples to contain low to very low concentrations of metals (relative to other districts).

*Summary.*—There do not appear to be significant mineral-environmental concerns in this district. The suite of elements in the altered rocks and ores are considered to be toxic, but the metals are not mobile in the prevailing dry climate. Oxidation of most sulfide minerals in the mineralized zones minimizes the tendency to generate acid-rock drainage and associated metal mobilization. Mineral-related contamination does not appear to extend beyond mining claims.

There is reason for concern regarding human activity in the vicinity of mercury mines and dumps. There are no residents in the district, but visitors to mines leave well-worn trails. In 1997 there were few restrictions of human traffic on private or public lands that had been mined for mercury. Exposure to mercury in rocks, soils, dust, or vapors should be minimized. The practice of using mercury retort calcine for surfacing roads should be curtailed to prevent spread of possibly toxic materials.

## Lewis District

*Location.*—15 mi southeast of Battle Mountain, in the Shosone Mountains of Lander County (fig. 2).

*Major commodities.*—Ag, Au, Pb; lesser Cu, Zn

*Mining history.*—Silver was discovered in 1867, and the largest mine (Betty O'Neal) was discovered in 1880; production decreased after several fires in the 1880's but was revived in the 1920's with a new mill and mine complex at Betty O'Neal. The Dean (Morning Star) mine workings and mill in upper part of Dean Canyon are discussed in the section on the Hilltop district, which adjoins to the northeast.

*Status of mining and exploration.*—There was no mining activity in 1996–98 and little to no exploration. The extensive exploration in the 1960's at Betty O'Neal and eastward up Lewis Canyon apparently failed to locate sufficient ore to support a new mine.

*Production.*—Total production is estimated at about 5 million oz Ag, 20,000 oz Au, 2 million lb Pb, 330,000 lb Cu, and 13,000 lb Zn, worth about $4 million. By far, the greatest production and values were from Betty O'Neal mine (about $3 million).

*Geology.*—The complex geology was mapped in detail by Gilluly and Gates (1965). This part of the Shoshone Range is a melange of thrusted Ordovician and Silurian sedimentary rocks, including prominent sections of Valmy Formation (chert, siltstone, quartzite, and limestone) that is the chief host for ore. Several Tertiary stocks intrude the sedimentary rocks, and volcanic rocks cap several ridges. Breccia pipes, mapped in detail by Gilluly and Gates (1965), are related to the Eocene(?) intrusive complexes. The pipes are locally mineralized.

*Ore deposits.*—The largest deposit in the district, Betty O'Neal, has unusual mineralogy for the region: it is rich in silver, as tetrahedrite and other sulf-antimonides, but relatively low in Cu-Pb-Zn for a polymetallic deposit. Siliceous host rocks show very little alteration; silicification probably was most common, and there is relatively minor pyrite gangue. There may be similarities to the structurally similar deposits to the northeast in the Hilltop district, except that those deposits are much richer in gold. Some of the breccia pipes are mineralized with pyrite and gold, but the results of exploration have not been published.

New chemical analyses of samples of dump rocks and tailings from the Betty O'Neal mine show them to have high concentrations of Ag, As, Cd, Cu, Mo, Pb, Sb, Se, Tl, and Zn.

## Mineral-Environmental Conditions

There is no obvious acid rock or mine drainage in the district, and the largest dumps and tailings piles at the Betty O'Neal mine seem to be stable. The ores in this district appear to be low in pyrite; thus, waste and tailings probably generate relatively small amounts of acid.

*Mineralized rocks and ores.*—Waste dumps are few and small in this district, except for the fairly large piles at the Betty O'Neal mine. Visual inspection of the Betty O'Neal waste suggests is it much lower in sulfide minerals than most polymetallic vein deposits. Two dump samples of hand-picked sulfidic chunks (not typical material) showed surprisingly low concentrations of As, Cu, Pb, and Zn but high Ag (and very low Au). The black coatings on waste imply that Mn is high; carbonate gangue minerals are probably more abundant here than in most polymetallic deposits.

*Mills and tailings.*—The 1880's production from the Betty O'Neal mine was processed by the Star Grove mill at the mouth of Lewis Canyon. A stone foundation remains at the site (photo 62), but only a few tailings could be located. The mine was reopened in 1922 with a new 100-ton-per-day flotation mill, which stands today. This mill evidently operated for only a few years (Vanderburg, 1939), which is consistent with the modest volume of tailings (50,000 to 100,000 tons). These tailings probably were reprocessed in the 1930's, and an attempt was made in recent years to leach these materials in situ. An analysis of the tailings shows low concentrations of As and base metals relative to most polymetallic deposit tailings. The tailings sit on a gentle slope distant from any stream and away from any canyon that might focus stormwater. A leach test on the tailings produced a pH of 5.7 and low (relative to the study median) metal concentrations. These tailings appear to pose few if any hazards.

*Surface water.*—No drainage was evident at the Betty O'Neal mine. Water in the extensive mine workings must infiltrate bedrock or alluvium somewhere along the haulage tunnel, but the water probably is alkaline and relatively

**Photograph 59.** Mercury ore at the Silver Cloud mine occurs in select layers of tuffaceous rocks that have been intensely altered to opaline silica. Part of the ore came from an open pit and part from small underground workings that followed mineralized layers.

**Photograph 60.** Large piles of calcine remain near the retorts at the Silver Cloud mine. Because the siliceous ore was crushed to the size of gravel before heating, some of the calcine has been removed for use on roads—thereby spreading mercury contamination.

benign. Lewis Canyon Creek was not sampled; there are no iron coatings on the bed, and the water appears to be clean.

*Summary.*—The relatively narrow alteration zones, the generally low pyrite content of the veins, and the high acid-neutralizing capacity provided by sedimentary rocks and vein-filling carbonate minerals suggest low risk for metal contamination from mines and prospects in this district. The vein deposits high in Dean Canyon are known sources of contaminants and are discussed as part of the "Hilltop District" section.

## Majuba District (Antelope)

*Summary.*—This mining area located 45 mi southwest of Winnemucca has a history of modest production of base metals and silver and prospecting for unusual deposits of

**Photograph 61.** This rotary kiln, much like that used to create cement or lime, was used to process relatively large amounts of mercury ore. The last mercury mining in the Ivanhoe District, in the 1970's, used bulk mining methods and large-capacity kilns in an attempt to reduce costs.

**Photograph 62.** The 1880's mining in the Lewis District was supported by a 40-stamp mill at the mouth of Lewis Canyon. This stone foundation may be that mill site. Only traces of tailings could be found along the creek.

uranium, tin, and molybdenum in the last 40 years. See descriptions by Nash (2001).

## Merrimac District (Lone Mountain)

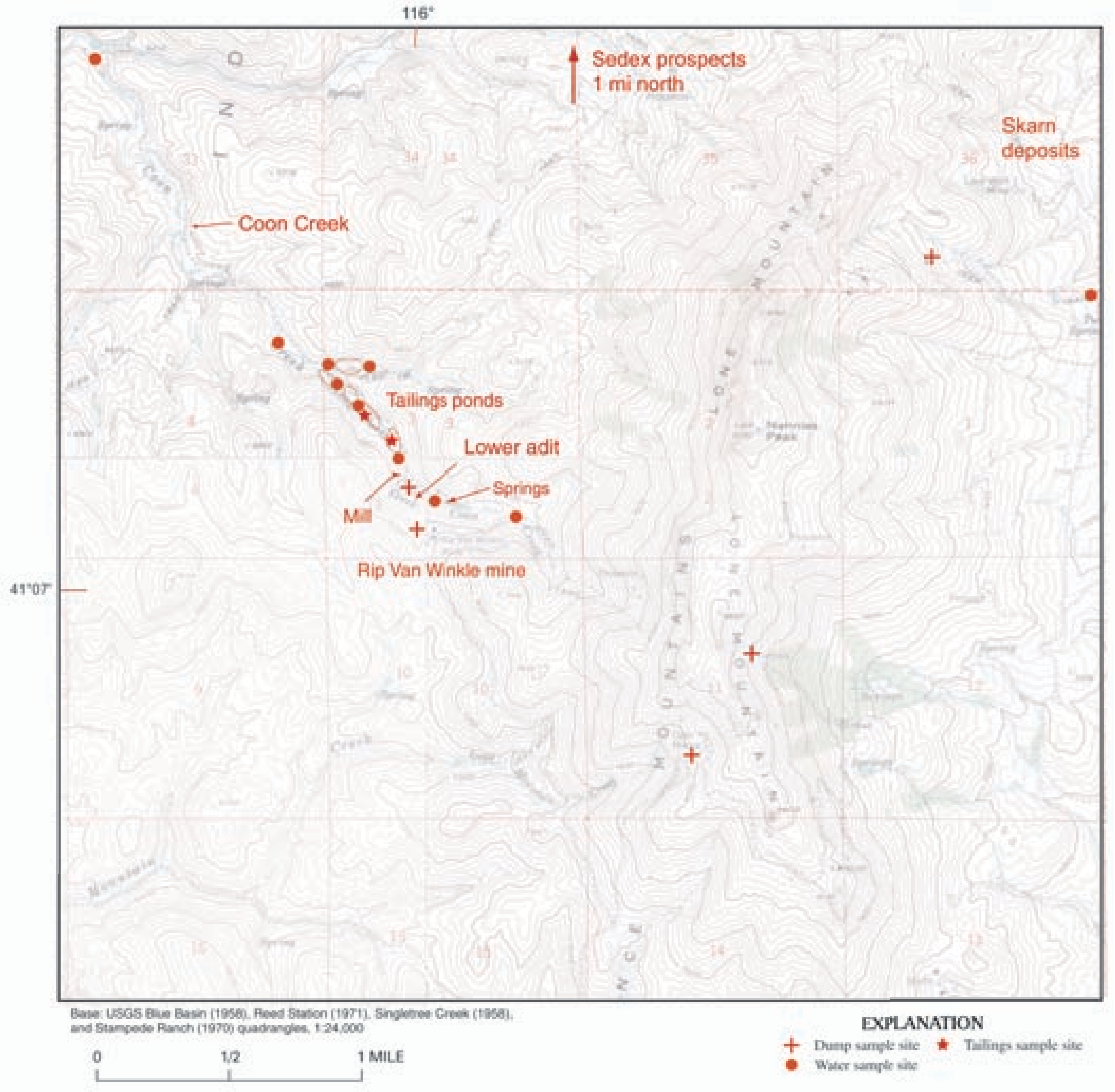
*Location.*—The Merrimac district is about 25 mi northwest of Elko in Elko County (fig. 2). Features of the district are shown in figure 26.

*Major commodities.*—Pb, Zn, Cu, Ag, Au; minor Ba, W, Fe. Largest Zn producer in Elko County. Total production slightly more than $1 million.

*Mining history.*—Ore was discovered in 1866 but there was little production until after 1900. Production was episodic from 1912 to the 1950's. The largest mine, the Rip Van Winkle, was active from 1938 to 1951. Judging from the waste piles and from production figures (LaPointe and others, 1991), the small mill at Rip Van Winkle created about 100,000–200,000 tons of tailings. Other workings and waste piles are small.

*Exploration and mining status.*—There was little exploration activity in late 1990's. Exploration in the 1970's and 1980's was widespread but apparently did not find sediment-hosted base metal or gold deposits.

*Geology.*—The district is dominated by craggy outcrops of a 38-Ma dikelike intrusive body of intermediate composition (quartz monzonite). Related dikes east of Lone



Base: USGS Blue Basin (1958), Reed Station (1971), Singletree Creek (1958), and Stampede Ranch (1970) quadrangles, 1:24,000

**Figure 26.** Features of the Merrimac mining district, showing sample localities.

Mountain have associated zones of mineralized rock that haves been prospected. Much of the district is underlain by carbonate rocks of Silurian-Devonian age, in thrust contact with Ordovician-Devonian siliciclastic rocks and chert. The latter rocks host sedex (massive sulfide) lenses of Zn-Pb-Ag in the northwest corner of the district, whereas the carbonate rocks are common hosts for skarn mineralization. The largest deposit, Rip Van Winkle, is localized along a north-striking reverse fault (steep west dip) and mostly covered by Eocene welded tuff on the western flank of Lone Mountain.

*Ore deposits.*—Deposit types that have been prospected or mined include (1) Cu-Fe skarns; (2) W skarns; (3) polymetallic deposits of Pb-Zn-Ag, as at Rip Van Winkle; (4) sediment-hosted (sedex) massive sulfide lenses; and (5) sediment-hosted gold deposits and associated jasperoid alteration that were prospected and drilled, but no prospects have been mined.

Siliceous alteration of sedimentary rocks (jasperoid) is common. Base-metal sulfide deposits are deeply oxidized, perhaps enhancing silver values in the early days of mining.

**Photograph 63.** The intrusive complex at Majuba creates this peak that rises above the countryside. The roads up the mountain go to two mine tunnels and to several exploration targets. Copper was the chief commodity mined, but several others have been sought, including uranium and molybdenum. The amount of disturbance is relatively small compared to many other districts.

**Photograph 64.** The lower tunnel of the Majuba mine creates a small amount of drainage for a part of the year. This drainage has a pH of 7.4 and low metal concentrations. Drainage like this is typical of the ephemeral mine drainage in northern Nevada.

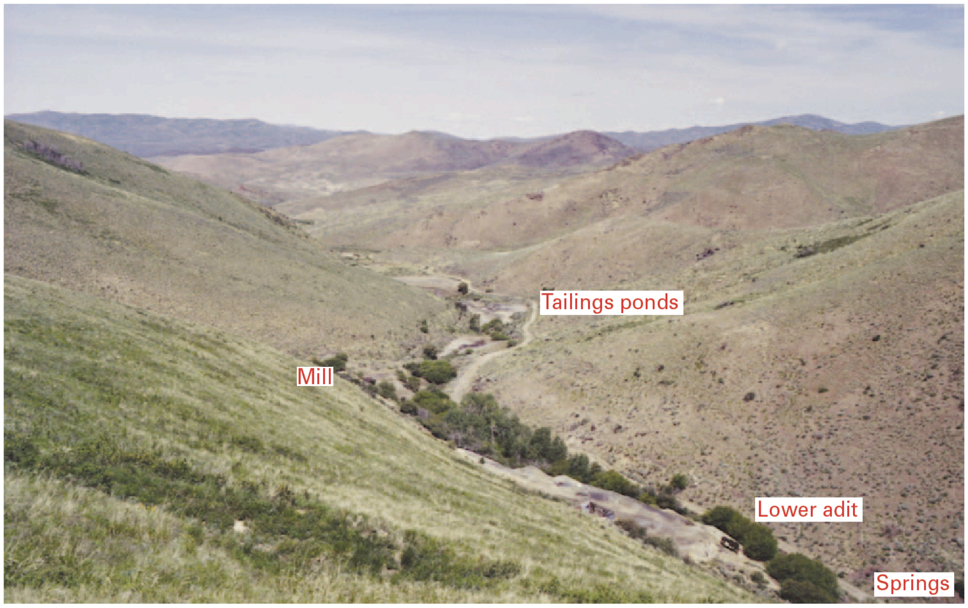
The Rip Van Winkle deposit was thoroughly oxidized, creating oxide and sulfate minerals that were unconventional for mining in the 1940's–50's. New chemical analyses of dump rocks and tailings from the Rip Van Winkle mine show them to be high in Ag, As, Cd, Cu, Hg, Mo, Sb, Se, Te, Tl, and Zn; concentrations of Ag, Pb, Sb, and Zn are very high in some samples.

Hypogene base-metal deposits are presumably related to the 38-Ma intrusive complex, and deposits of that age are crudely zoned. The amount of alteration in the intrusive rocks and adjacent country rocks is much smaller in size and in intensity compared with other complexes in the region (such as Battle Mountain). Hydrothermal conditions in the Lone Mountain igneous complex did not reach those of a porphyry-type mineralizing system.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Most of the mines and prospects are so small as to pose few problems, especially in this area of abundant carbonate rocks. The magnetite skarn deposits on the east side of the district show no signs of acid-rock drainage and are probably unreactive, similar to the larger iron deposits of the Modarelli and Safford districts.

The massive sulfide prospects in the northwestern part of the district have the potential, in theory (Taylor and others, 1995), to create mineral-environmental problems. The lenses are oxidized and there are no indications of acid-rock drainage or other harmful conditions in the surficial environmental that here is generally dry.



**Photograph 65.** The Rip Van Winkle mine and mill complex extend along Coon Creek. The lower adit and mine waste are at the right, and the mill is at left center, followed by five tailings impoundments to the left (west). Aspen groves are located near a series of springs which are the main source of Coon Creek.

**Photograph 66.** Pyritic waste rocks on dumps from Rip Van Winkle shafts produce acidic runoff that kills vegetation. This local effect appears to be much less significant than the contaminants from mill tailings in Coon Creek.

**Photograph 67.** The mill tailings extend across Coon Creek and are eroded by the stream. Coon Creek flows for about 6 months per year. The flow seen here in June of 1997 is relatively high. White sulfate mineral crusts form on the surface as the tailings dry. The rusty streaks in the streambed form from acidic seeps, explained in photo 68.

**Photograph 68.** Small seeps of red-colored pore waters can be found locally in the wet tailings. Here the red water fills a hole made by a hoof; it has a pH of 1.9 and extremely high metal concentrations. The red pore fluid mixes with alkaline surface water, producing a thin film of iron oxyhydroxides.

Ores, waste, and tailings from the Rip Van Winkle mine are rich in zinc and other base metals. The ores were partly oxidized prior to mining, which may reduce their reactivity. Dumps from shafts in the mine complex are of moderate size and high sulfide content and create kill zones several hundred feet long (photo 66). A leach test on one sample of waste yielded a pH of 2.8 and high to very high concentrations of many metals, as discussed below for tailings samples. The acidic runoff that kills vegetation may occasionally reach Coon Creek, but the effects are probably minor compared to effects of the mill tailings in the creek channel.

*Mills and tailings.*—A small flotation mill near the Rip Van Winkle lower tunnel (100 tons/day capacity) released tailings to five or more ponds in the valley of Coon Creek (photo 65). Tailings ponds about 15–20 ft deep were created with dams across the creek, forcing the ephemeral creek to flow over or through the tailings (photo 67). Gullies cut the tailings, but erosion has removed only about 10 percent of the materials. There is no evidence to suggest a dam failure in the past.

Because the tailings are of substantial volume (about 200,000 tons) and placed in the creek channel, I visited the area several times and took a large suite of tailings and water samples for analysis. There is both good and bad news from these geochemical studies: water in Coon Creek shows only traces of metals related to the mill tailings, but the tailings have the potential to generate acid and release the base metals, especially zinc and cadmium, if conditions were favorable. Leach tests on three samples yielded solutions with pH values

**Photograph 69.** The Rip Van Winkle tailings are saturated during spring runoff and seeps are common. Some seeps, like this one in foreground, are slightly acidic (pH 5–6) and moderately enriched in metals. Coon Creek, in background, flows over the tailings with only a small amount of reaction.

**Photograph 70.** Tailings placed in a side drainage, north of Coon Creek, also are extensively eroded.

in the range of 3.0 to 3.3 and very high concentrations of Cd, Cu, Pb, and Zn and high concentrations of As, Sb, and Se. Long-term reactions in the tailings are best shown by the extremely concentrated pore fluids in the tailings. The pore water in the tailings is highly acidic (pH less than 2) and has extremely high concentrations of Cu, Fe, Zn, and Cd (photo 70). However, several tests show that Coon Creek below the tailings impoundments has a pH of 7.9–8.2 and metal concentrations that are elevated but meet the standard for aquatic life. The zinc concentration may be high enough to be of concern, depending upon the regulatory standard applied.

The water quality in Coon Creek may seem to be inconsistent with the chemical properties of the mill tailings. This paradox might be explained by high clay content in the tailings that makes permeability very low and minimizes reactions. Also, metals may be adsorbed onto the clays. An indication of the low permeability is the toughness of the tailings: attempts to drill into the tailings with a hand auger failed at 6 inches depth, which is rare in my experience. These tailings are rich in cohesive clays that appear to minimize erosion and chances of failure in an extreme storm.

In the summer of 2000 a contractor for the BLM made engineering studies of the tailings and a plan for reclamation work. As at most sites, these tailings need to be isolated as much as possible from surface water.

*Surface water.*—This hilly area is quite dry, despite the elevation, but there are several ephemeral springs, one of which is the source for Coon Creek that runs west of the Rip Van Winkle mine and over five tailings impoundments. Many of the 30 samples collected from this district are considered to be background samples with little effect from mining, but 16 samples from 12 sites show the contributions from mined materials. The pH values ranged from 1.8 to 8.5 in the Rip Van Winkle mine area samples. Pore water from mill tailings, with pH values in the range of 1.8 to 2.1, contain very high concentrations of Al, As, Cd, Cu, Fe, Mn, Mo, Pb, Se, U, and Zn, including some of the most extreme values measured in this study. Surface water in the Rip Van Winkle mine area with pH values 6.6 to 8.2 (and having input from the mine and tailings) are less metal rich, but high concentrations of Al, As, Cd, Cu, Fe, and Zn are present in some of these samples. The evolved water in Coon Creek, after dilution and reactions, contained 128 and 199 ppb Zn in 1997 and 1999, respectively.

*Summary.*—Abundant and widespread carbonate minerals in sedimentary rocks and alluvium, weak development of sulfide mineral deposits and alteration, and deep oxidation of sulfide minerals combine to make a healthy environment with only a few signs of potential geochemical problems. The high elevation range collects substantial amounts of snow, which feeds a network of springs, and the waters are invariably clear and useful for livestock. The Rip Van Winkle mine area is a significant source of contamination in sulfidic waste dumps and tailings piles in the flood plain of Coon Creek. Acidic and metal-rich water is produced locally in these piles, but the metals do not migrate far. The mill tailings in Coon Creek are potentially one of the worst sources of contaminants in the study area, but high clay content and low permeability appear to minimize reactions and output of acidic pore water. Reclamation work should be done to isolate the tailings from surface water and to prevent contamination of the Class A water of Maggie Creek.

## Mill City District

*Summary.*—The Mill City district in the Eugene Mountains, 30 mi southwest of Winnemucca (fig. 2), had a history of small mines until large tungsten skarn deposits were identified and mined intermittently from 1918 to the mid-1980's. The large mill tailings piles are described briefly by Nash (2001); one leach test showed that high concentrations of Mo are released in the alkaline leachate that is buffered by calcite. Molybdenum is well known for its mobility as an oxyanion (molybdate) but is not expected to be released from tungsten mill tailings. Additional testing is needed to document the mobility of Mo in this situation because these tailings are less than 4 mi from the Humboldt River.

## Mineral Basin District

*Summary.*—Iron was mined in this district from the 1940's through mid-1960's when high-grade ore was needed for war efforts. The deposits are small compared to world iron deposits, but the open pits and waste piles are large relative to historical mines in Nevada. This area 20 mi east of Lovelock was briefly described by Nash (2001).

## Modarelli District (Frenchie Creek)

*Location.*—Cortez Mountains, Eureka County, 40 mi southwest of Elko (figs. 2, 15).

*Major commodities.*—Iron (hematite)

*Mining history.*—Iron was discovered in 1905, but there was very little activity until 1951 when an open-pit mine was developed. The Modarelli mine operated from 1951 to 1961. Several other iron prospects in the district were not productive.

*Status of mining and exploration.*—There has been no mining in the past 30 years and no exploration for iron. Several recent drill holes in the Modarelli pit probably were testing for Olympic Dam type ore.

*Production.*—Total production was about 396,000 long tons of $Fe_2O_3$ (1951–61).

*Geology.*—Rocks in this part of the Cortez Mountains are chiefly metamorphosed Mesozoic felsic volcanic rocks (Muffler, 1964). Cretaceous(?) stocks intrude the metavolcanic rocks near the Modarelli mine, and a large granitic pluton dominates the central part of the range 5 mi to the southwest. Faults of several ages cut the plutonic and metavolcanic rocks.

Hematite deposits occur as replacement bodies in Mesozoic rhyodacite flows adjacent to altered Cretaceous(?) intrusions.

*Ore deposits.*—Only one type of ore is known in this district, hematite replacements of volcanic rocks. Hematite is the dominant iron mineral; textural studies show that the hematite formed from magnetite to make what miners call “martite,” which is nonmagnetic. The average grade of ore shipped was 57.8 percent iron. Some investigations determined as much as 7 percent phosphorus, a serious contaminant, in the ore. The replacement bodies are controlled by intersecting northwest- and northeast-trending high-angle faults. Muffler (1964) proposed that the iron was released during deuteric alteration of Cretaceous(?) plutons and transported into the metavolcanic rocks by hydrothermal fluids rather than formation by magmatic segregation processes suggested for other iron deposits of this type. The deposits in this district are small compared to most of their class and also have the economic disadvantage of high phosphorus and low magnetism (which hinders milling). As such, they cannot compete in the world iron-ore market but possibly could have value for some special properties such as pigment.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—These iron-rich ores and waste appear to be stable in the environment and benign. Some ores of this type contain pods of pyrite, but no pyrite was observed in the Modarelli pit or waste dumps; thus, there seems to be no risk of acid-rock drainage. Concentrations of potentially toxic metals are very low. A leach test on an iron-ore sample showed it to be one of the least reactive rocks from this study; the leachate had very low metal concentrations. The leachate attained a pH of 8.2 with a high concentration of As.

*Mills and tailings.*—A small ore-processing facility at Modarelli probably served only to crush the ore. There are no fine-grained materials at the mine site and no processing wastes that contain harmful materials.

*Surface water.*—The area and the open-pit mine are dry. A spring southeast of the mine that provided water for the mining camp has a pH of 8.2 and low dissolved solids, and all metal concentrations are low.

*Summary.*—No geochemical contaminants are produced by the iron ores. Hematite and associated minerals are stable in this climate and no harmful elements are released to the environment.

## Mount Hope District

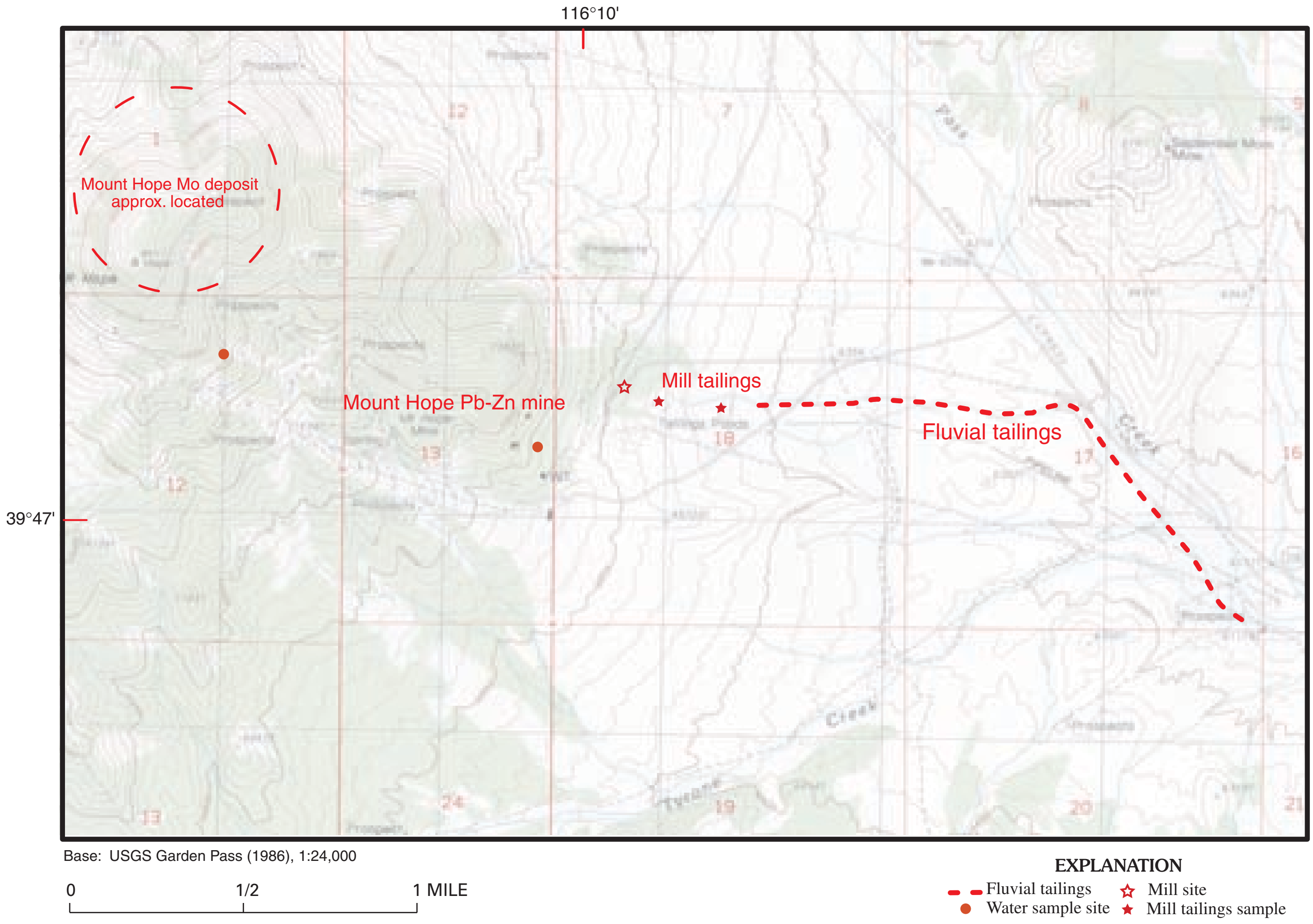
*Location.*—The Mount Hope district is located in a small mountain range about 20 mi north of Eureka in Eureka County (fig. 2). Features of the district are shown in figure 27.

*Major commodities.*—Ag, Zn, Pb, Cu, Au; Mo resource.

*Mining history.*—Discovered in 1870, mining at the Mount Hope mine was opened in 1890 and worked intermittently in the 1920's and 1940's. A fire in 1947 forced closure of the mine, and it never reopened.

*Status of mining and exploration.*—There was no mining in the 1990's. Drilling in the 1980's identified a significant Mo deposit of the Climax type.

*Production.*—Production in the early years apparently was relatively small but during the 1940's amounted to more than $1.3 million after a flotation mill was constructed. Zinc



Base: USGS Garden Pass (1986), 1:24,000

**Figure 27.** Features of the Mount Hope mining district, showing sample localities.

**Photograph 71.** These soft mill tailings that cover tens of acres south of the mill at Mill City are the most visible legacy of tungsten mining more than 50 years ago. Seemingly benign because they look like sand and contain few sulfide minerals, these materials may be releasing molybdenum because the leachates are alkaline.

**Photograph 72.** The Modarelli mine produced hematite iron ore from this small open pit in the 1950's. The hematite is unreactive and creates no acidic or metal-enriched drainage.

was most abundant by weight. The drill-defined resource of Mo is about 560 million tons of ore averaging 0.10 percent Mo; there has been no mining of Mo.

*Geology.*—Predominant rocks are chert, shale, and limestone. These rocks were intruded by a 38-Ma rhyolite stock complex composed of multiple intrusions that generated the Mo deposit (Westra and Riedell, 1996). The historical Pb-Zn replacement deposits are in limestone, southeast of the rhyolite intrusive complex that forms the Mount Hope summit.

## Mineral-Environmental Conditions

The chief concern in this district is the mill tailings from the Mount Hope Pb-Zn ores. The district was visited very briefly to examine the tailings; there were no investigations of the unmined Mo deposit and associated alteration.

*Mineralized rocks and ores.*—The Pb-Zn replacement ores are described as very rich in sphalerite. An assay of 13 wt. percent Zn in a composite sample (Roberts and others, 1967) may be typical. The composition of waste materials on dumps is not known, but presumably is high in Zn, Pb, Cd, Cu, and associated metals typical of polymetallic replacement deposits.

*Mills and tailings.*—One metal building that may have been part of the mill is standing. Two tailings impoundments are on the hillside to the east of the lower tunnel and mill (fig. 27). The impoundments are relatively small, on the order of 1 acre each, and show moderate amounts of erosion (photo 73). A long swath of fluvial tailings fills the arroyo east of the mill

**Photograph 73.** The Mount Hope zinc mine placed its tailings in two impoundments on the hillside near the mill. The dams are eroded, as seen here, but are mostly intact.

**Photograph 74.** The arroyo east of the Mount Hope mine and mill contains fluvial deposits of mill tailings several feet thick, as seen on the right side of this photo. These fluvial tailings attest to a storm event, possibly while the mill was active in the 1940's.

(photo 74) to the main highway and then south for another 0.5 mile. The volume of fluvial tailings, spread up to 3 ft thick in a narrow arroyo for about 1.8 mi, is difficult to estimate but probably exceeds that retained in the two impoundments. Because the volume of fluvial tailings is larger than the eroded channels in the impoundments, it is possible that the fluvial tailings reflect a dam failure in the early 1940's while the mill was in operation, and subsequent production was used to rebuild the impoundment wall. Such failures during operation are fairly common when the tailings are saturated with water and unconsolidated (Smith and Connell, 1979; Nash, 2002b). Leach tests on two tailings samples produced solutions with pH values of 6.4 and 9.8, very high Al (2 solutions) and As (1 solution) and high concentrations of Cu, Pb, Mo, and Zn. The effects on water resources are difficult to evaluate. There are no residences in the vicinity. Shallow ground water tapped by a windmill that produces water for livestock might be influenced by metals leached from tailings, but the ground water could not be sampled.

*Surface water.*—The area is dry and has very little surface water. The lowest mine tunnel releases a very small flow of water, and there are a few springs high on Mount Hope. Samples were collected in June of 1999 from the collapsed tunnel and a spring in altered rhyolite. The mine drainage had a pH of 6.8 and carried high concentrations of Mn and Zn. The spring, distant from mining, had a pH of 6.7, and an analysis showed high concentrations of Al, As, Cd, Cu, Fe, Mo, Pb, and Zn. These are good examples of the mitigating effects of carbonate in wall rocks and of unmined, altered rocks producing metal-rich water.

*Summary.*— The polymetallic ores in sedimentary host rocks are rich in base metals, but due to prevailing pH conditions and little water, there is little metal mobility from the mine or waste dumps. The altered siliceous rocks associated with the unmined molybdenum deposit may be more reactive than the polymetallic ores because the siliceous rocks have lower acid-neutralizing capacity. The largest source of contaminants in this district may be the fluvial tailings that are spread for about 1.8 mi down an arroyo. Episodic flows of water would likely leach metals such as Zn, Mo, and As that are mobile in neutral to alkaline water. Such processes could contaminate shallow ground water in the valley.

## National District

*Location.*—Santa Rosa Range, 60 mi north of Winnemucca, in Humboldt County (figs. 2, 15). Features of the National mine area are shown in figure 28.

*Major commodities.*—Au, Ag, Hg; minor Cu, Pb, Zn

*Mining history.*—The very rich bonanza gold deposits at National were discovered in 1907, but veins and prospects were known on Buckskin Mountain and nearby areas for many years prior to 1907. Records were not kept for individual properties, but Lindgren (1915) estimates that in only 3 years (1909–11) the National mine produced about $4 million in gold. Total production was about 175,000 oz Au and 457,000 oz Ag from 1909 to 1936. Production from the Buckskin National mine (Bell vein) was 24,000 oz Au and 300,000 oz Ag. Mercury production from Buckskin Mountain was minor.

*Status of mining and exploration.*—There has been no mining for many years and no signs of active exploration. The Buckskin National property was reclaimed in 1997.

*Production.*—The National mine was small in tonnage but extremely rich in gold, accounting for most of the $6 million reported from the district. The Buckskin National mine was larger in tonnage but ore was of lower value.

*Geology.*—Basement rocks are Mesozoic metasedimentary rocks (phyllites) in the canyons southwest of Buckskin Mountain. The mineral deposits are in a sequence of Miocene felsic lavas, tuffs, and associated small intrusive bodies. A large volume of siliceous sinter caps Buckskin Mountain. High-angle normal faults with relatively small displacements control some of the veins. Most features of these relatively simple ore systems are remarkably well preserved.

*Ore deposits.*—The important ores of this district are epithermal vein-type, but these may have more base-metal sulfide minerals than most examples in Nevada and may have chemical tendencies approaching the polymetallic vein class (as defined here). The sulfide minerals, including pyrite, marcasite, arsenopyrite, galena, sphalerite, stibnite, and chalcopyrite, occur in the veins (Lindgren, 1915) but also occur in altered wall rocks (thus are on mine dumps). Adularia occurs in the veins, as do bladed forms that once were calcite (now replaced by quartz); argillic alteration of wall rocks along veins is relatively narrow.

The shallowest of the deposits, on Buckskin Mountain, are associated with sinter that is considered a classic example of hot springs deposition (Vikre, 1985). Mercury is associated with parts of the hot springs sinter. The mercury mines were not very productive.

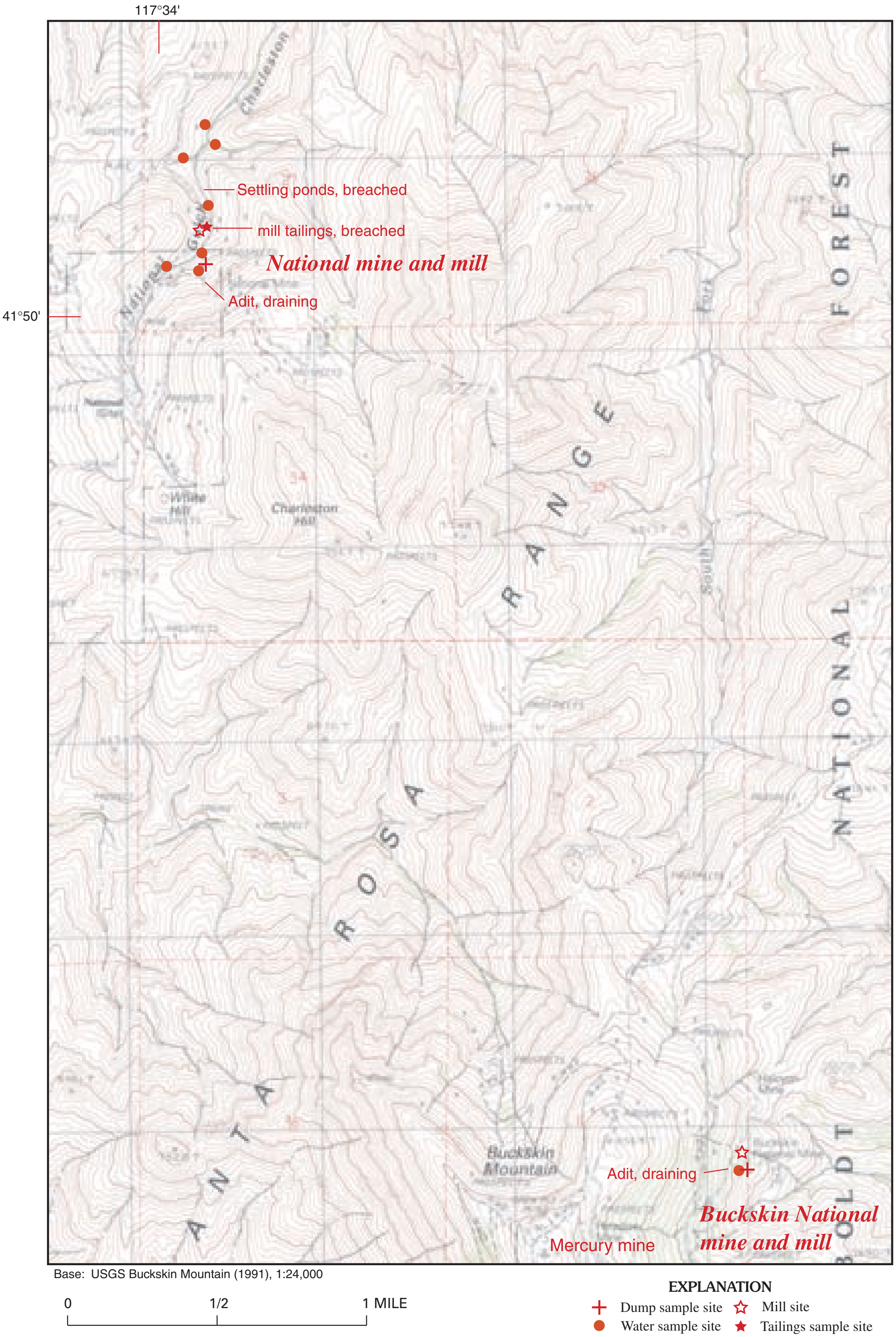
## Mineral-Environmental Conditions

These vein deposits, chiefly quartz with a small percentage of sulfide minerals, might be predicted to be relatively benign compared to other deposit types in the region that are larger in size and richer in sulfide minerals. However, there are several conditions that combine to create some of the most acidic water in the area: (1) Higher amounts of precipitation; (2) a high water table within 40 ft of the land surface in 1911, according to Lindgren (1915); (3) much less pre-mining oxidation of ore than in most districts; and (4) a lack of carbonate in rocks and veins and apparently little or none in alluvium at this elevation, resulting in less neutralization capacity.

*Mineralized rocks and ores.*—Rocks on waste dumps are not visibly rich in base-metal sulfide minerals but pyrite is commonly present (or iron oxide minerals and jarosite that have formed in place of pyrite during weathering). New chemical analyses of seven samples show that the Buckskin National and National mine dumps are higher than median concentrations in Ag, Sb, Se, and Tl, and As is very high; some dump samples are high in Bi, Cu, Mo, Pb, or Zn. Silica rock (sinter) on a mine dump near the top of Buckskin Mountain is high only in Hg. Two samples from the mercury mill at the base of Buckskin Mountain are rich Hg, with some high values for Sb, Se, and Tl.

Leach tests on three dump samples yielded pH values of 3.0, 5.8, and 6.0. The leachates were high in As and Zn and the very acidic leachate (National mine dump sample) was high in Cd, Cu, Fe, Mo, Sb, and Se.

*Mills and tailings.*—There were several mills at various stages of mining, with two of moderate size serving the National and Buckskin National mines after 1920. Tailings from these mills were essentially unconfined and allowed to mix with mine waste and mine water. Analyses show the tailings to be high or very high in Ag, As, Sb, Se, and Tl; some are high in Cu, Bi, Mo, Pb, Sb, or Zn. Leaching tests show they generate acids (pH 3.7 to 5.5). The most acidic leachate (National) was high in As, Cu, Sb, Se, and Zn, whereas the moderately acid leachate (Buckskin National) was high in As, Fe, Sb, and Se. The leach test results seem to be supported by field measurements of pH and conductivity, which suggest that reaction of mine-drainage water with tailings further degrades water quality.



Base: USGS Buckskin Mountain (1991), 1:24,000

**Figure 28.** Features of the National mining district, showing sample localities.

**Photograph 75.** The Buckskin National mine and mill produced polymetallic ores under arduous conditions, high on Buckskin Mountain. Tailings, placed on mine waste on this steep slope, are very difficult to reclaim but has been done in places (lower right corner of photo).

**Photograph 76.** The Buckskin National mine tunnel creates acidic drainage (pH is 3.0), shown by the ocher water. Reclamation in 1997 reduced the flow and channeled most of it into a pipe (drain in center of photo) to minimize reactions with waste rocks and tailings.

Four mills are recognizable in the district: at National, at Buckskin National, a small one southwest of the National mine called the Birthday mine and mill, and a mercury retort facility on the road to Buckskin Mountain. The Buckskin National cyanide mill, high on the mountain, placed its tailings on a steep slope of talus mixed with mine waste (photo 75). The tailings have been eroding for years, and parts were wetted by mine drainage from the adit. The adit was reclaimed in about 1997, improving the flow of water, but the tailings were not moved and remain exposed to precipitation. The National stamp mill, not far from the lower adit of the National mine, used amalgamation and tables to collect gold. It was surrounded by mine-waste dumps and placed its tailings in the headwaters of a small stream; the crude dam was breached years ago. The National tailings are wetted both by mine drainage, which is highly acidic, and the stream. Features that appear to have been catch ponds on the creek north of the mine and mill have been breached. Engineering studies have been made to determine reclamation options on this private site; as of June 1999, no work had been done. The Birthday

**Photograph 77.** These craggy, siliceous rocks at the top of Buckskin Mountain contain mercury mineralization. Mining of mercury has been attempted on a relatively small scale at several times. Most of the mercury ore appears to have been hauled down the mountain for processing in retorts.

**Photograph 78.** The National mine site looks like many mines in Nevada, but it contained some exceptionally rich pockets of gold. The richest ores were mined from 1910 to 1920. Located high in the Santa Rosa Range, the mine area receives more snow and rain than most areas, and this is expressed as acidic drainage from the collapsed lower tunnel (brown feature in center of photo).

mill near National appears to have been a small stamp mill with small production. The Birthday tailings sample yielded a leachate solution with high As concentration, but the volume of tailings is small, relatively stable, and distant from creeks.

*Surface water.*—The high peaks of this district receive much more snow and rain than adjacent valleys. Streams from the east flank of Buckskin Mountain flow east to the Little Humboldt River, a tributary to the Humboldt River. Drainage from the National mine area flows north to Charleston Creek, then to Eightmile Creek, which flows into the north-flowing Quinn River. Two mine adits release acidic drainage. Mine water from the Buckskin and National mines are described by Price and others (1995). Their measured pH's of 2.5, 2.6, and 3.3 are among the most acidic in their study of Nevada mines; metal concentrations are high, but the analytical methods used did not cover most trace elements and thus are not readily compared to results in this study. My sampling on two visits in June of 1997 and June of 1999, at the end of snowmelt, yielded 11 samples from 9 sites. My samples had pH values in the range of 2.8 to 8.7, and conductivities from 200 to 1,460 $\mu$S/cm. As for other areas, metal concentrations correlate closely with acidity: the two acidic adit drainages with pH values less than 3.0 had high to very high concentrations of Al, As, Cd, Cu, Fe, Mn, Pb, Se, and Zn. As these waters mixed and reacted with other surface water, the metal concentrations decreased sharply, as will be discussed later. Evolved water

**Photograph 79.** Mine drainage from the National mine with a pH of 2.9 and very high metal concentrations picks up additional metal concentrations from reactions with mine waste and mill tailings.

below the Buckskin-National mine was not sampled, but the evolved water north of the National mine improves to concentrations below or near the ALWS (Zn is 100 ppb) as described later.

*Summary.*—Several factors combine to create highly degraded water in this district: precipitation is much higher than at lower elevations, the deposits were only slightly oxidized prior to mining, and the highly silicified rocks have low buffering capacity. Mine workings generate moderately to strongly acidic drainage, and that drainage is further degraded by reactions with mine waste and mill tailings, especially below the National mine. Reclamation at the Buckskin National mine diverts most mine drainage from dump rocks and tailings. Brief studies at these sites did not disclose evidence for carbonate in rocks and alluvium; mine drainage did not appear to be undergoing natural mitigation within hundreds of feet of the mine portals as it does in many districts in the study area. The net effect is greater on water quality than in most districts, even though the scale of mining at these sites is not large. More studies are needed at these mine sites, including documentation of variations in water flow through the year and possible changes in water composition through the seasons.

## North Battle Mountain District

*Location.*—The Sheep Creek Mountains, 6 mi north of Battle Mountain in Lander County (fig. 2).

*Major commodities.*—Ba, Ag, Pb, Au, Cu

*Mining history.*—Silver in the North Battle Mountain district was discovered in 1906, but most mining of the silver-rich ores was done from 1928 to 1938.

*Status of mining and exploration.*—No mines were active in 1996, and prospecting was minimal.

*Production.*—A few mines produced a small amount of silver-lead in about 200 tons of ore. The barite production, less than 100,000 tons, was small compared to many other mines in the region.

*Geology.*—Basement rocks are siliceous sedimentary rocks (chert, shale, sandstone, minor limestone) and greenstone of Ordovician-Devonian age, overlain by cliff-forming Miocene lavas. The basement rocks are highly deformed, sheared, and faulted.

*Ore deposits.*—Two types have been mined: (1) polymetallic deposits rich in silver, as at the Snowstorm mine and (2) bedded barite, as at the Rimrock mine. The polymetallic deposits were worked by a series of shallow shafts and adits. The veinlike deposits have not been studied much; they could be related to plutons, as in the Battle Mountain District, or might be related to metamorphism. The bedded barite deposits are like many others in the region that formed in submarine sediments of Ordovician to Devonian age (Papke, 1984).

### Mineral-Environmental Conditions

*Mineralized rocks and ores.*—The silver deposits are locally rich in base metals, but the amount of workings and dumps is small. In theory, these mineralized rocks could pose the same concerns as those of similar composition in the Battle Mountain district, but the amount here is so small that the effect is likely to be insignificant. There is no evidence of oxide coatings in arroyos to suggest that metals have been mobile.

Mining of barite deposits created a series of narrow pits and waste dumps of moderate size. The processing plant was located well down the alluvial fan, close to the railroad, and

**Photograph 80.** Fluvial mill tailings cover a large swath east of the Getchell mine, just east of the new road to the Twin Creeks mine. The gray tailings are up to 3 feet thick and average about 1 foot thick over an area 100–450 feet wide by 9,000 feet long. There was essentially no channel for these flood deposits.

that site has remnants of stockpiles and impoundments of reddish-brown claylike material that was produced by the washing and concentrating processes. The waste dumps and mill tailings are rich in iron-oxides, but the content of base metals is low and no cause for concern is evident.

*Mills and tailings.*—The processing facility on the lower slope was for barite. The pinkish materials that remain in several large impoundments are "slimes" generated during the processing of barite. The metal concentrations are low in the slimes, and the high clay content probably minimizes permeability and leaching reactions.

*Surface water.*—This district is very dry. No surface water or springs were noted, and no mine workings release water.

*Summary.*—Metal mines of this district created small disturbances and release little or no contaminants in the dry environment. The barite mine and processing plant created substantial disturbance, but they appear to release no significant metal contaminants.

## Potosi District

*Location.*—Eastern Humboldt County, on the flank of the Osgood Mountains (figs. 2, 15).

*Major commodities.*—Au, W, Ag, As

*Mining history.*—This district was the site of tungsten mines of moderate size and the large Getchell gold mine. The mining and milling of tungsten fluctuated relative to the Getchell gold mining as the same mill was used. The tungsten mining was most active during the war years of 1942–47 and 1951–57. In the past 20 years, several very large open-pit gold mines have been developed: Preble, 1985–90; Pinson, 1988—; Chimney/Rabbit Creek/Twin Creeks, 1987—; Getchell Gold, 1987—; and production will continue for many more years. Historical mill tailings from the Getchell mine complex are the only aspect investigated here. The Getchell gold mine was one of the most productive in Humboldt County through 1960 and was famous for abundant arsenic minerals. The mill with 400-tons-per-day capacity was built in 1937, when power was brought in from Winnemucca.

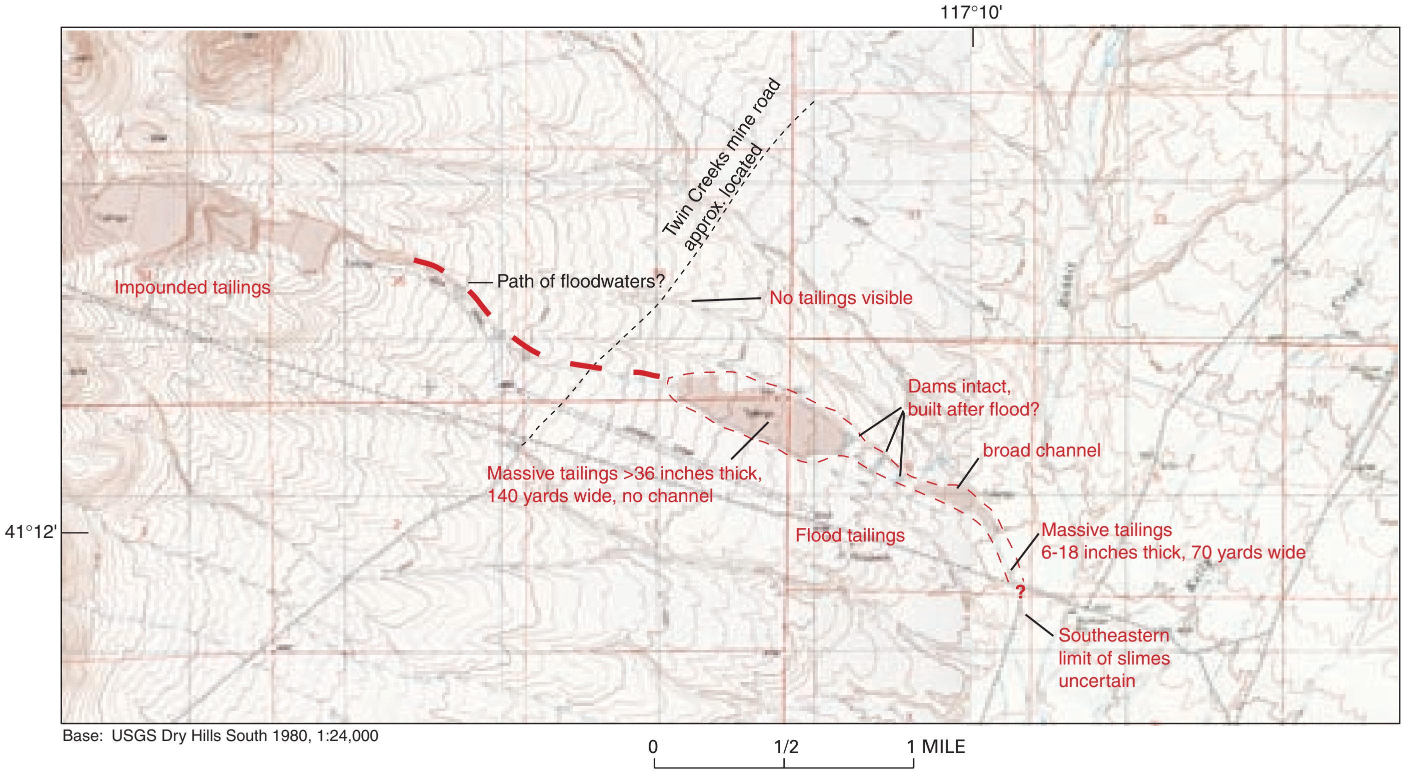
*Status of mining and exploration.*—This mining area contains some of the largest gold mining complexes in northern Nevada. The tungsten mines have not been active for 40 years.

*Geology.*—Paleozoic sedimentary rocks (shale, quartzite, limestone) are intruded by a Cretaceous granodiorite stock and overlain by Tertiary volcanic rocks and alluvium. Major fault structures bound the east side of the range.

*Ore deposits.*—Tungsten deposits are of the skarn type, adjacent to the stock. The Getchell mine worked vein deposits of gold on the east side of the stock. The gold veins are unusually rich in arsenic-sulfide minerals (orpiment and realgar) and the genetic relations to the stock and to the tungsten deposits have been much debated. The more recent disseminated gold discoveries are generally believed to be variants of the Carlin-type sediment-hosted gold deposits.

## Mineral-Environmental Conditions

*Mills and tailings.*—The topic of concern in this study is the area of fluvial tailings east of the Getchell mill, which are partly on BLM lands. The tailings impoundments and fluvial tailings are sufficiently large to be shown as several ponds on the USGS Dry Hills South 1:24,000 topographic



Base: USGS Dry Hills South 1980, 1:24,000

**Figure 29.** Location of fluvial tailings east of the Getchell mine, Potosi district.

map (fig. 29). In the early 1990's Gary Raines (U.S.Geological Survey, Reno Office) noticed an unusual dark feature on remote sensing images of the Getchell area; field investigations by Raines and Vic Dunn (Bureau of Land Management, Winnemucca office) identified a substantial area of tailings east of the impoundments and partly on BLM lands. Samples were studied in detail to understand the behavior of arsenic, which is highly enriched in these materials (Leventhal and others, 1996). Selective leaches by weak acids showed high solubility of the arsenic phases. My passive leachate tests on two samples, using deionized water, yielded pH values of 5.3 and 7.7 and solutions containing very high concentrations of As and high amounts of Mo, Pb, and Zn.

Field studies of the eastern redistributed tailings in 1999 and 2001 revealed a wide swath of flood-deposited materials on the gentle slope east of the main road to the Twin Creeks mine that extends as far as Rabbit Creek (fig. 29; Nash, 2002b). The fluvial tailings are difficult to locate on the broad slope but are distinctive on the topographic map and aerial photographs. The ephemeral stream channel that carried the tailings has a broad channel, hundreds of yards wide and only slightly incised. Apparently, all flow was down one wash—nearby washes do not appear to contain fluvial tailings. The deposit of redistributed tailings (photo 80) ranges in thickness to more than 30 inches, is 150–300 yards wide and 1.8 mi long. It is located 1.5 to 3.3 mi east of the main impoundment. The redeposited tailings are massive to faintly laminated, and coarse-grained sand and cobble layers are rare to absent within or below the tailings layer. The absence of other clasts and lithologies suggests that only one source—the tailings impoundments—was involved. The fine sand fluvial tailings can be traced to Rabbit Creek, but it is possible that tailings slimes were carried by floodwater farther east and south into Kelly Creek.

*Surface water.*—Hydrogeochemical studies of the Osgood Mountains were undertaken by R.B. Wanty and others (U.S. Geological Survey, written commun., 2003), with particular attention to structural controls on ground-water flow and expression in springs. No geochemical studies of water were done as part of this study.

## Railroad District (Bullion)

*Location.*—Pinon Range, 15 mi south of Carlin, in Elko County (fig. 2). Features of the central part of the Railroad district are shown in figure 30.

*Major commodities.*—Cu, Pb, Zn, Ag, Au, W, Mo, Ba

*Mining history.*—The district was discovered in 1869 and soon had two of the first smelters in Nevada (photo 82); bonanza ores of copper-lead-silver were recovered through 1887. New workings yielded base-metal sulfide ores through 1968. Exploration in the 1980's onward shifted to sediment-hosted gold deposits with discovery and mining of the Rain deposit.

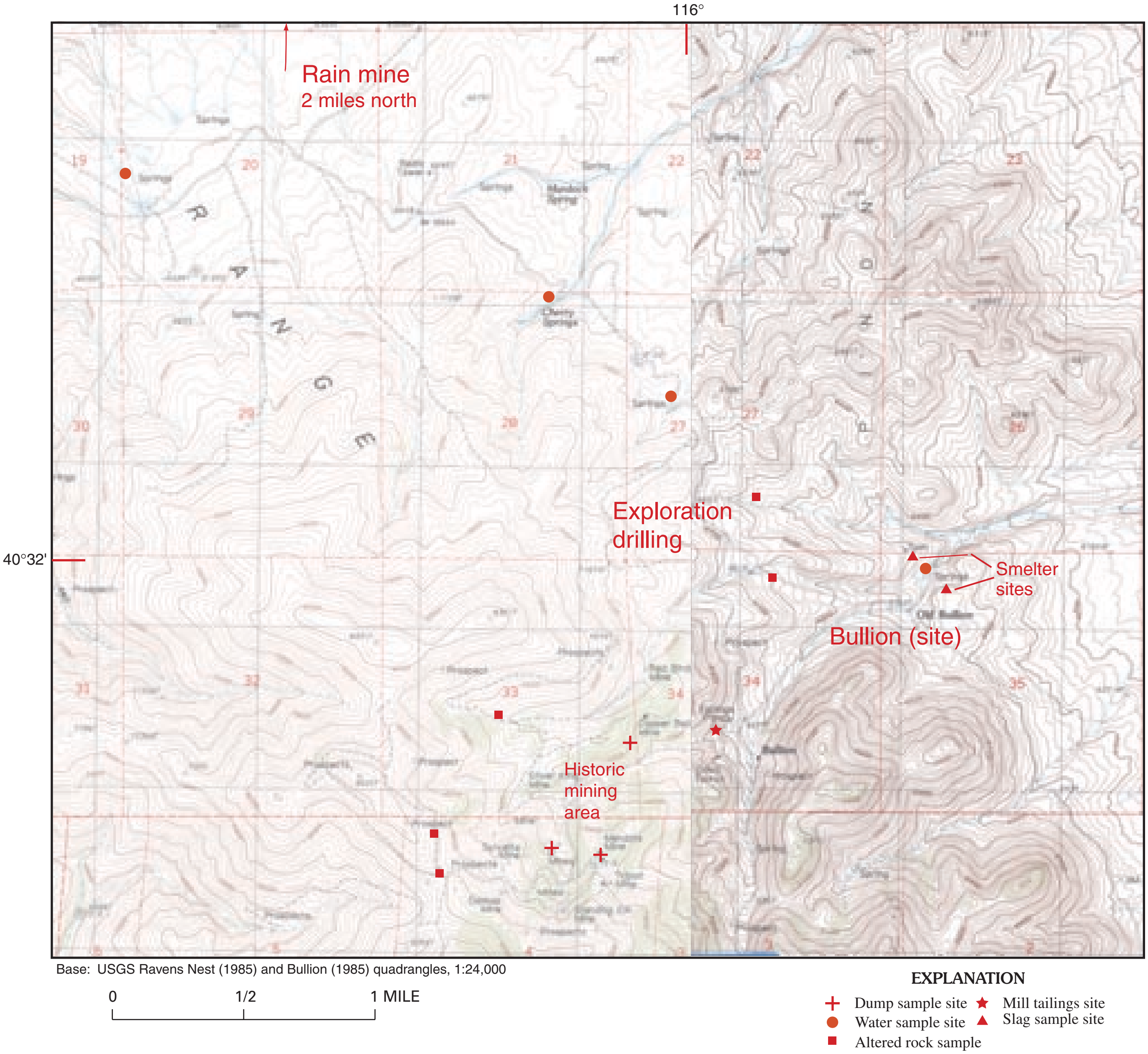


**Figure 30.** Features of the central part of the Railroad district, showing sample localities.

*Exploration and mining status.*—No mines were active after 1996. In-fill drilling at several sediment-hosted gold prospects continues, and mining plans have been submitted for ore bodies near the Rain open pit. Drilling has been done in recent years at several of the disseminated gold prospects.

*Production.*—Underground reserves in base-metal deposits on patented claims are not known. The pre-production reserve for the Rain ore body was 686,000 oz Au; average grade was 0.083 oz/t Au (Knutsen and Nichols, 1986); this reserve was later increased to more than one million ounces (Dean and others, 1991). The first stage of mining at Rain was completed in 1996. Four deposits in the Rain subdistrict (Rain, Emigrant Springs, Gnome, and SMZ ) together contain a geologic resource of about 1.6 million oz Au at an average grade of 0.042 oz/t Au (Thoreson, 1991). Published reserves or resources for as many as six other sedimentary-hosted gold deposits in the district suggest fairly small size (less than 1,000,000 oz contained Au at less than 0.1 oz Au/t) relative to deposits in the Carlin-trend to the north.

*Geology.*—Ore geology in this district is more diverse than most because thrusted and folded Paleozoic sedimentary rocks and Tertiary igneous rocks are involved. The area was mapped by Ketner and Smith (1963). A thick section of Silurian-Devonian carbonate rocks is an important hosts for traditional base-metal vein and replacement ores. The carbonate section is unconformably overlain by Mississippian

**Photograph 81.** The distal end of the fluvial tailings deposit is still more than 100 feet wide and about 6 to12 inches thick. Here the flood deposits are curving to the south, into the Rabbit Creek drainage.

**Photograph 82.** Two smelters were located at Bullion east of the mines in an area of springs. The smelters operated in the 1870's. Two modest piles of slag on the south and north sides of the creek and some steel pipes are all that remain at these sites.

argillite and siltite of the Webb and Chainman Formations, locally the host for disseminated gold mineralization at Rain and other new prospects. A zoned, multistage Tertiary (33 Ma) stock occupies the center of the district and is the apparent source of the polymetallic ores.

*Ore deposits.*—Several types of ore are known, but genetic relationships have not been established. The historical ores were rich in Cu-Pb-Zn and more valuable for silver than for gold. Depending on structural setting, these ores had skarn to pipe or replacement affinities (photo 83). The composite intrusion was tested for molybdenum deposits, but results and details are not known. The texture and geometry of the porphyry stock look favorable. In the past 10 years most work has been on gold deposits in fine siliciclastic rocks and jasperoids of the Webb and Chainman Formations in association with high-angle structures. The Rain deposit has been mined out

**Photograph 83.** Historical mines and prospects at Bullion were adjacent to a porphyry intrusion that created skarn-type deposits that have been oxidized, producing the red rocks in the foreground. Numerous small prospects attempted to find ore, but no large ore bodies could be identified.

(by open pit), two or more nearby prospects may be mined, and work continues on at least three other gold prospects north and south of the central intrusive complex (which may or may not be a factor in the gold deposits).

The Rain ore body was localized along two high-angle faults, mostly in the Webb Formation (argillized siltstones and shales and sandstone [Knutsen and Nichols, 1986]). A high- grade "throat" zone, with grades averaging 0.14 oz/t Au, is subparallel to the high-angle faults and extends below the main ore zone into the Devils Gate Limestone. Alteration consists of argillization, silicification, and decarbonatization. In the nearby Emigrant Springs deposit, As, Sb, and Ba are anomalous along with gold (Jackson and Ruetz, 1991). Pre-mining soil and rock geochemistry over the Rain ore body showed some very gold- and barite-rich jasperoids, and As-rich soils. Upper parts of the ore bodies are oxidized to alunite, jarosite, and iron oxide minerals, whereas deeper parts are unoxidized and carbonaceous (Thoreson, 1991)

Base-metal ores, rich in Ag and Au, probably are zoned and telescoped relative to the composite intrusive body, but relations to outboard gold deposits have not been postulated. Large changes in stratigraphy and structure, among other factors, complicate analysis of district-scale genesis. Based on essentially no facts from the gold ores, one can speculate that they are candidates to be "distal-disseminated" type as in the Battle Mountain district. At least parts of the model are right: the district has a porphyry system at its core, and this multistage intrusive complex generated highly saline fluids (shown by halite-bearing fluid inclusions) as called for in the distal-disseminated model (Theodore, 1998).

## Mineral-Environmental Conditions

*Altered rocks and ores.*—The disseminated gold prospects in the southern part of the district are enriched in many of the "pathfinder" elements typical of well-studied sediment-hosted deposits, including As (to 2,600 ppm), Sb (to 1,190 ppm), Hg (to 49 ppm), Tl (to 14 ppm), Ag (to 49 ppm), and Mo (to 14 ppm) according to analyses of drill cuttings (Putnam and Henriques, 1991). Similar samples of rotary cutting from the Trout Creek prospect (south of Bullion) show many of the same enrichments (Jackson and Ruetz, 1991); reported mean values include: As (336 ppm), Sb (109 ppm), Hg (2.5 ppm) and Ag (4.0 ppm). Soil samples over the Trout Creek prospect are reported to be enriched in As and other pathfinder elements; Hg is enriched to as much as 8.1 ppm in linear trends thought to reflect leakage along structures. My samples of five altered sedimentary rocks (drill cuttings) show low base metal concentrations, 200–500 ppm As, 1.1–2.6 ppm Se, and less than 1 ppm Hg—similar to the industry results.

*Mills and tailings.*—Mills and tailings are surprisingly hard to find in this district, considering its $4.7-million production (LaPointe and others, 1991). One mill is located at the lower tunnel, and it has only a small tailings impoundment. Possibly tailings from early years of milling were removed for reprocessing, as is known for other silver districts.

In the 1870's two smelters were in operation: the slag, stone foundations, and yellow rose bushes from those operations can be seen at Old Bullion (photo 82), a mile northeast of the mines. Springs near the smelters do not show contamination by the slag piles.

*Surface water.*—Several substantial streams that are important for livestock have their sources in the Pinon Range. These streams and their source springs flow through altered sedimentary rocks. No mine workings release water to the surface. Eight samples from six sites had pH values of 7.5 to 8.4 and conductivities of 80 to 380 $\mu$S/cm that are suggestive of good water quality. Analyses show very low metal concentrations—much lower than from most mining areas but slightly elevated relative to water from basins in unaltered sedimentary rocks. Samples collected from springs and headwater creeks near drilled alteration zones show only

**Photograph 84.** Silver ores in the Rochester district are in oxidized rocks like these at the Nevada Packard mine. Because sulfide minerals were destroyed by weathering, these rocks do not create acidic drainage. This open cut was created in the 1890's in an attempt to bulk mine low-grade ore for a heap-leach operation.

**Photograph 85.** The mill for the Nevada Packard mine was at the base of the hill and placed its tailings on this flat area. Episodes of flooding in a small arroyo carried tailings nearly a mile to the west (right side of photo). The yellowish area with no vegetation (left center) is a heap-leach pad from a 1980's operation (the heap was placed on top of the tailings impoundment).

slight metal enrichments, such as 10–18 ppb As and 2–4 ppb Zn. Although the altered rocks are enriched in many metals, as described above, the metals do not appear to be moving at these pH values.

## Rochester District

*Summary.*—Rich silver ores of this area on the west flank of the Humboldt Range, 15 mi northwest of Lovelock (figs. 2 and 15), were mined from 1912 through the mid-1930's. Since 1986, bulk-mining methods have been applied to previously mined vein systems to make Rochester the first or second largest silver producer in Nevada, with more than 6 million ounces a year (Tingley and LaPointe, 2000). Because the originally sulfidic ores are deeply oxidized (photo 84), they are amenable to heap-leaching, and waste from both the old and new styles of mining and milling create fewer environmental concerns than if they were unoxidized. The early mills created large tailings piles in major drainages (Nash, 2001). The historical tailings impoundments are deeply eroded (photos 85, 86), and overbank tailings deposits downstream suggest that floods breached the dams, probably during the period of active milling (Nash, 2002b).

**Photograph 86.** A mill in Lower Rochester Canyon placed its tailings in an impoundment that covers more than 40 acres. Erosion has cut through the tailings, which are about 8 feet thick.

## Safford District

*Location.*—Cortez Mountains, Eureka County, 35 miles west of Elko (figs. 2, 15).

*Major commodities.*—Fe, Ag, Cu, Pb

*Mining history.*—Iron was discovered prior to 1869 along the Humboldt River. Silver was discovered in 1881. Iron at the Barth mine was produced at several periods through the 1960's and possibly more recently. Silver-bearing veins were mined intermittently from the Zenoli and Onondaga mines from 1907 to the 1960's.

*Status of mining and exploration.*—There was no mining in 1997, but stockpiled magnetite ore from the Barth mine continues to be shipped. There are few signs of exploration activity in recent years, but there are some newly posted claims.

*Production.*—Total iron production through 1964 was about 1,100,000 long tons with a grade of about 63 percent Fe. The silver-bearing veins produced about 37,000 oz Ag, 50 oz Au, and less than 50,000 lb each of Cu and Pb, worth about $35,000.

*Geology.*—Basement rocks are Mesozoic metavolcanic rocks, and these are unconformably overlain by Miocene tuffs and andesitic lavas. A thick sequence of Miocene volcanic rocks is exposed in the Palisades north of the Humboldt River. A quartz monzonite intrusive body is reported 1,800 ft west of the pit; by analogy to other parts of the Cortez Mountains, this may be Cretaceous(?).

*Ore deposits.*—Two types have been productive: (1) magnetite in metavolcanic rocks and (2) silver-bearing sulfide-barite veins.

The iron deposit at the Barth mine consists of massive replacement bodies of hematite and magnetite in Mesozoic andesite. Ore in the 1950's was described as hematite, but stockpiled ore at the site in 1997 is predominantly magnetite. The ore body extended under the Humboldt River, so the river was diverted in 1960 to allow mining of the northern portion. This ore is classified as volcanic-hosted magnetite, as in the Modarelli district.

The silver-bearing veins contain prominent barite and calcite and several sulfide minerals (galena, sphalerite, chalcopyrite, pyrite). The silver mineralogy is not known; only small amounts of gold are present. At the Zenoli and Onondaga mines there are numerous adits and shafts, and each mine complex had more than 2,000 ft of workings. The veins strike northwest and dip steeply to the west and east. Surface exposures suggest the veins have sharp walls and are fairly narrow (a few feet wide). Some of the vein ore is oxidized. These appear to be fairly normal polymetallic deposits, but barite is more abundant than in most veins of this type in Nevada. Andesites outside of the mine workings are variably argillized and chloritized, and many of the hills are capped with limonitic soils.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—The iron-rich rocks and ores of the Barth mine contain very low concentrations of toxic metals. No pyrite was observed on the stockpiles and waste piles, thus no acid-rock drainage is likely. These rocks should be stable and cause no geochemical problems.

*Mills and tailings.*—No mill or tailings were found for the silver ores. The iron ore is processed through a simple plant that grinds the ore and probably makes a magnetic concentrate; the stockpiled ore is sand-sized material that appears to be primarily magnetic magnetite. These materials do not appear to be chemically reactive.

*Surface water.*—The hills in the district are dry, but the Humboldt River and a small creek flow through the district. Safford Creek, which flows by the silver mines, shows no visible signs of pollution; the pH at two sites was 8.6 and 8.8. The alkaline pH would appear to reflect the propylitic alteration of andesitic rocks. Water analyses show very low metal concentrations; the value of 3 ppb Zn is notably low for a stream leaving an area of alteration and mining.

*Summary.*—Mines and mine waste appear to have no adverse effects on water quality or other aspects of the natural environment.

## Scraper Springs District

*Location.*—Western Elko County; 10 miles northeast of Midas (fig. 2).

*Major commodities.*—There are prospects for Ag, barite, and zunyite (Al-silicate)

*Mining history.*—There has been no production and no significant mining.

*Status of mining and exploration.*—Modest exploration in the 1980's for zunyite as a possible ore of aluminum and for sediment-hosted gold.

*Production.*—None.

*Geology.*—Basement rocks are Ordovician Vinini Formation, unconformably overlain by Oligocene andesite flows and siliceous tuff. Structure is seemingly simple, with only a few high-angle faults.

Ore deposits.—Prospects are of two types: (1) silver-barite veins in volcanic rocks, a variety of epithermal type for which details are lacking; and (2) zunyite in argillized and silicified volcanic rocks. Elsewhere, zunyite is part of a high-temperature, acidic alteration assemblage associated with shallow intrusions but here the zunyite seems to have a tabular geometry, 12 to 62 ft thick in drill holes, which suggests to the author that it may have formed in a less dynamic, less structurally controlled environment such as a hot-springs apron.

### Mineral-Environmental Conditions

*Mineralized rocks and ore.*—Zunyite and associated alteration including alunite and pyrite in acid alteration of volcanic rocks, as at Summitville and Red Mountain in Colorado, can create natural acid-rock drainage with high metal content (Plumlee and others, 1999). Brief inspection of the Scraper Springs zunyite locality revealed no evidence for such conditions in the Nevada climate; for instance, there is no vegetation kill in the zunyite alteration zones. Leach tests of zunyite-bearing rock in the laboratory showed minimal acid generation and very low metal concentrations in the leachate. The leachate pH's of 7.1 and very low total base-metal concentrations are strikingly different from leachates of alunite-bearing acid-altered volcanic rocks (Nash, 2002a). There is no evidence to suggest that this zunyite occurrence is affecting surface water; a nearby stream has a pH of 8.1 and low dissolved solids.

The small silver-barite veins were not examined in detail. No evidence for effect on the environment was observed.

*Surface water.*—There are several springs in the district and small ephemeral streams that appear to be of good quality (there are no visible Fe-Mn-oxide coatings suggestive of metal transport by acidic water). The water has pH values near 8; no chemical analyses were made of the water. Rock alteration and small prospects do not appear to be degrading water quality.

*Mills and tailings.*—None.

*Summary.*—No evidence for significant effects. Altered rocks (unmined) also have minimal local effect.

## Seven Troughs District

*Summary.*—This area 25 mi west of Lovelock (fig. 2) was the site of silver mining from 1905 to the mid-1930's. The town and mills were devastated by a flash flood in 1912, and a later unrecorded event caused the failure of a tailings impoundment (see Nash, 2001, 2002b).

## Star District

*Summary.*—This silver mining area boomed in the 1860's, but the bonanza ores played out and there was only minor production in the last 125 years. Located on the west flank of the Humboldt Range (fig. 2) in an area of carbonate rocks, the small historical mine workings would seem benign, but the mines may release enough copper to harm fish in the Class A water of Star Creek. This water is described by Nash (2001) and discussed later in this report.

## Swales Mountain District

*Location.*—Elko County, about 15 miles north of Carlin (figs. 2, 15).

*Major commodities.*—Ag, Au, Cu, Pb, Zn; Ba

*Mining history.*—Date of discovery is not known. Mining has been minimal, with no record of any ore shipped.

*Status of mining and exploration.*—The was no mining in 1997, but there were some signs of recent exploration, including a few drill holes. Considering the proximity to Carlin area, the exploration activity was very low.

*Production.*—None recorded.

**Photograph 87.** Underground mining operations in the Seven Troughs district created relatively small waste piles, as shown here. Two mills were located near the stream in Seven Troughs Canyon, foreground, one of which is shown here. Floods in 1912 carried away the mill tailings and destroyed one mill, causing the release of cyanide into the floodwaters.

**Photograph 88.** Fluvial mill tailings from a flood extend far out on the alluvial fan and onto the playa east of the Seven Troughs range. The tailings are as much as 40 inches thick and contain virtually no coarse sand or gravel interbeds. After the first quarter-mile on the fan, there was essentially no channel for the tailings-rich floodwaters.

*Geology.*—Many similarities to the Carlin area led to mapping by Evans and Ketner (1971) and to exploration efforts since the 1970’s for Carlin-type sediment-hosted gold deposits. Ordovician to Mississippian cherts, shale, and limestone are present in thrust slices. The thrusted rocks are intruded by several small, dikelike bodies of porphyritic rocks of intermediate to felsic composition. The Eocene (38 Ma) intrusive rocks are very similar to those of the Merrimac (Lone Mountain) district 13 mi to the north. Eocene-Miocene volcanic rocks and sandstone unconformably overlie the intrusive and older rocks. Structure is complex, with three thrust faults, two sets of folds, and Oligocene and Miocene high-angle faults (Evans and Ketner, 1971).

*Ore deposits.*—Two types: (1) Ag-Au with base metals in veins and replacement zones in limestone, generally near intrusive contacts; and (2) bedded barite lenses in Ordovician Vinini Formation. These were tested by small prospect workings.

The metal deposits tend to be highly oxidized and rich in manganese oxides but originally were sulfidic. Some of the prospects are in monzonite porphyry and some are in calc-silicate rock (thin zones adjacent to the intrusions), but most are in limestone. The deposits are probably best classified as polymetallic vein and replacement; some grade into skarnlike deposits, but the skarns are only weakly developed and carry spotty occurrences of mineralization. The High Top mine, the largest in the district, has very small workings and dumps. Despite seeming to have all the "right" kinds of rocks to make a good ore deposit, the known mineralized zones at Swales Mountain are even smaller than the small ones at Lone Mountain.

### Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Altered rocks were extensively sampled in 1967 by Ketner and others (1968) who show anomalous zones of base metal concentrations near intrusive contacts and thrust faults. Concentrations of Cu, Pb, and Zn were commonly greater than 2,000 ppm; no data for As were reported. In my brief examination it was evident that pods of mineralized rock or mined dump rock are very rich in Fe-Mn-oxide minerals (gossan), but these are very small (tens of tons). Sulfidic zones are present but do not create acid-rock drainage. The polymetallic deposit dumps contain high concentrations of base metals; the tonnage is so small and the climate so dry that metals do not appear to be mobile. Analysis of a sample of limonitic waste on a typical mine dump shows very high Pb, Zn, Cd, and Ag—typical of this deposit type. If any acid-rock drainage is generated in storms or spring runoff, it would be mitigated by carbonate-bearing rocks and alluvium. Although the geologic setting (porphyry intrusions, skarn) and deposit types (polymetallic deposits) might suggest adverse mineral-environmental conditions (Plumlee and others, 1999), mine-related contamination does not develop. This mineralizing systems was very small, alteration halos were extremely small, and very little sulfide remains after deep oxidation.

*Mills and tailings.*—None.

*Surface water.*—This area was totally dry when visited in June of 1997. One spring on the east side of district is developed for stock, but it was not sampled. There are no visible indications of metals moving in surface water or arroyos.

*Summary.*—No adverse effects are evident. This intrusive system produced very small pods of mineralized rock, and the base metals are not mobile because of the deep oxidation and the dry climate.

## Tenabo District (Bullion)

*Location.*—Lander County; 25 mi southeast of Battle Mountain (fig. 2).

*Major commodities.*—Ag, Au, Cu, Pb; barite, turquoise

*Mining history.*—Silver was discovered about 1869, creating one of the early mining camps (Lander). Mining in the subsequent 3 decades was chiefly for silver. Gold was discovered in 1905, but the first major gold mine opened in 1935 at Gold Acres (converted to open pit in 1942). Production from Gold Acres mine was initially about 1.5 million tons, and open-pit mining resumed in the 1990's. The Pipeline and South Pipeline deposits were discovered in the early 1990's. Production from several mines operated by Cortez Joint Venture exceeded 1 million ounces Au from 1999 to 2002. Reserves as of 2000 at Pipeline and South Pipeline were about 151 million tons with an average grade of 0.047 oz/t Au (Tingley, 2001). Barite was discovered in the 1930's, and production started in 1954. Some of the best turquoise mines in Nevada are in this district.

*Status of mining and exploration.*—Exploration was intense in this district in the 1990's following the discovery of the two Pipeline deposits. Excavation at the Pipeline open pit commenced in April of 1997, and mining continued through 2002, with high-grade gold ore being hauled across the valley to the Cortez gold mill. Exploration also has been active at several other historical mines, attempting to define gold reserves sufficient for mining.

*Production.*—Historically, more than $1 million was produced at Gold Acres (gold-silver), Greystone (barite), and Blue Sky (turquoise) mines; 10 other mines produced more than $100,000 (gold or turquoise) prior to 1980. Tonnage and value from the huge disseminated gold deposits mined from 1985 onward dwarfs the historical production.

*Geology.*—The Shoshone Range in the vicinity of Tenabo is underlain chiefly by Ordovician and Devonian siliceous sedimentary and volcanic rocks that are complexly thrust faulted (Gilluly and Gates, 1965). Tertiary intrusions are present on the west edge of the district, and thick Miocene andesites are prominent on the eastern side. A window of carbonate rocks is present in a small area and are the important host rocks at the Gold Acres mine. Large bedded barite deposits have been mined at several places in the district from Devonian chert-carbonate rocks. The historically important silver ores are in veins and contact zones associated with granitic intrusions.

*Ore deposits.*—There are three types of metallic deposits: (1) Sediment-hosted gold of the Carlin-type at Gold Acres and Pipeline; (2) pluton-associated polymetallic vein deposits at Altenberg Hill and Grey Eagle; (3) pluton-associated skarn and related deposits at Robertson and part of Gold Acres. There also are large barite deposits of the bedded, stratiform type.

New chemical analyses of six dump samples from polymetallic vein deposits show them to have high concentrations of Ag, As, Bi, Cd, Cu, Mo, Pb, Sb, Se, Te, Tl, and Zn. A sample of tailings was high in these metals and especially high in Se.

### Mineral-Environmental Conditions

*Mineralized rocks and ores.*—Outcropping veins, altered rocks, mines, and prospects were extensively sampled in the mid-1960's by Wrucke and others (1968). Based on multi-element results for 1,875 samples, three northwest-trending belts were defined. Highest values for As, Bi, Cu, Pb, and Zn were determined near the Tenabo townsite and Altenburg Hill and near the Gold Acres mine; highest values for Ag and Au also were in these areas. Concentrations of As in mineralized rocks commonly exceeded 3,000 ppm. Although the metal concentrations are high, their occurrence in metasedimentary rocks that contain calcite may limit their mobility. A leach test on a sample of mine waste in calc-silicate rock from Altenburg Hill yielded a pH of 7.5, and only As, Cu, and Mo were highly concentrated in the leachate.

Recent exploration and mine geochemical studies at the Gold Acres mine and Pipeline mines to the south of Tenabo confirm and extend the earlier work by Wrucke and others (1968). Sediment-hosted gold ores at Gold Acres are enriched in an "epithermal" suite of elements (As, Sb, Hg, Tl), whereas skarn rocks above the gold zone are enriched in a base-metal suite (Ag-Cu-Bb-Zn-Mo) (Hays and Foo, 1991). These skarn rocks with low gold content now presumably are on waste dumps. The gold ores at Pipeline and South Pipeline are enriched in As, Hg, Sb, and Tl; some rocks in these deposits contain elevated Pb and Zn, but the base metal contents are generally low (Foo and others, 1996). The Pipeline and South Pipeline ores were originally rich in pyrite, but oxidation is widespread and in places pervasive. Oxidation is surprisingly deep: to 1,800 ft at South Pipeline and to 1,100 ft at Pipeline. Environmental impact reports for these mining projects give abundant data and plans for handling waste. From a geologic perspective, I infer that the combination of abundant calcite and carbonaceous matter in the ores and waste rocks, and the extensive oxidation of sulfide minerals, would suggest that acid-rock drainage from waste-rock dumps will be minor and that most metals will be relatively immobile. Mobility of Zn, As, and a few other metals will require monitoring, as is done by industry.

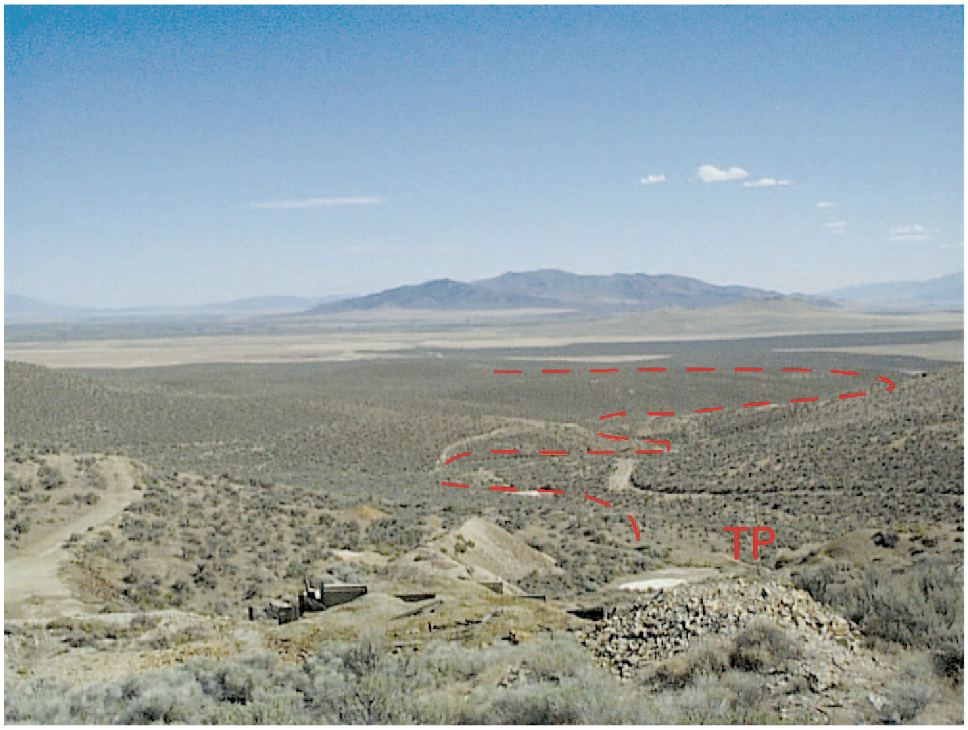
**Photograph 89.** Rugged Star Canyon carries water east from the Humboldt Range. The mouth of the canyon was a natural location for a mill in the 1870's. The light-colored mill tailings are piled on the edge of the stream but are relatively stable.

*Surface water.*—Most of the small mines in the district seem to be dry and do not create mine drainage. A small amount of water seeps from the portal of the Grey Eagle mine, which is at higher elevation and gets more precipitation than the central Tenabo area. This water has a pH of 6.7 and contains relatively high concentrations of As, Fe, Sb, Zn, and total base metals.

Ground water is encountered in the deeper stages of open-pit mining of the Pipeline and South Pipeline mines. That water was described in the environmental impact reports for those operations. A pond was created to collect pumped water and to encourage both evaporation and infiltration of mine water. Pumped water from these two large mines is part of a separate hydrographic basin from the main Humboldt River Basin; thus, dewatering and disposal activities are not likely to influence the main Humboldt River.

*Mills and tailings.*—The small part of this district that was studied contains at least two historical mills, at Grey Eagle (to the west) and at Indian Creek (northeast). The latter appears to have been a custom mill for miscellaneous ores that were hauled from distant mines. The mill has been dismantled, but a modest volume of tailings exists at the site. A leach test on these tailings produced a leachate with a pH of 3.8 and very high Al, As, Cd, Cu, Se, and Zn concentrations. The relatively small volume of tailings is in an arroyo and has been partly eroded by stormflows. The location on a relatively gentle slope with a wide channel suggests that the tailings have a better chance of surviving an extreme storm than a site in a canyon.

The Grey Eagle mine was a modest producer of polymetallic sulfide ores, with a small mill located at the lower mine tunnel. The mill is typical of the small (about 50 tons per day) mills of the 1920's–1940's. The tailings, however, are noteworthy for the large amount of erosion that has taken place. Based on brief observations, I surmise that there was at least one failure, and tailings were carried down the canyon to the south for more than a mile. The few tailings remaining in the breached impoundment and the fluvial tailings to the south, probably are releasing acid and base metals when wet, based on tests on similar tailings, but no chemical studies

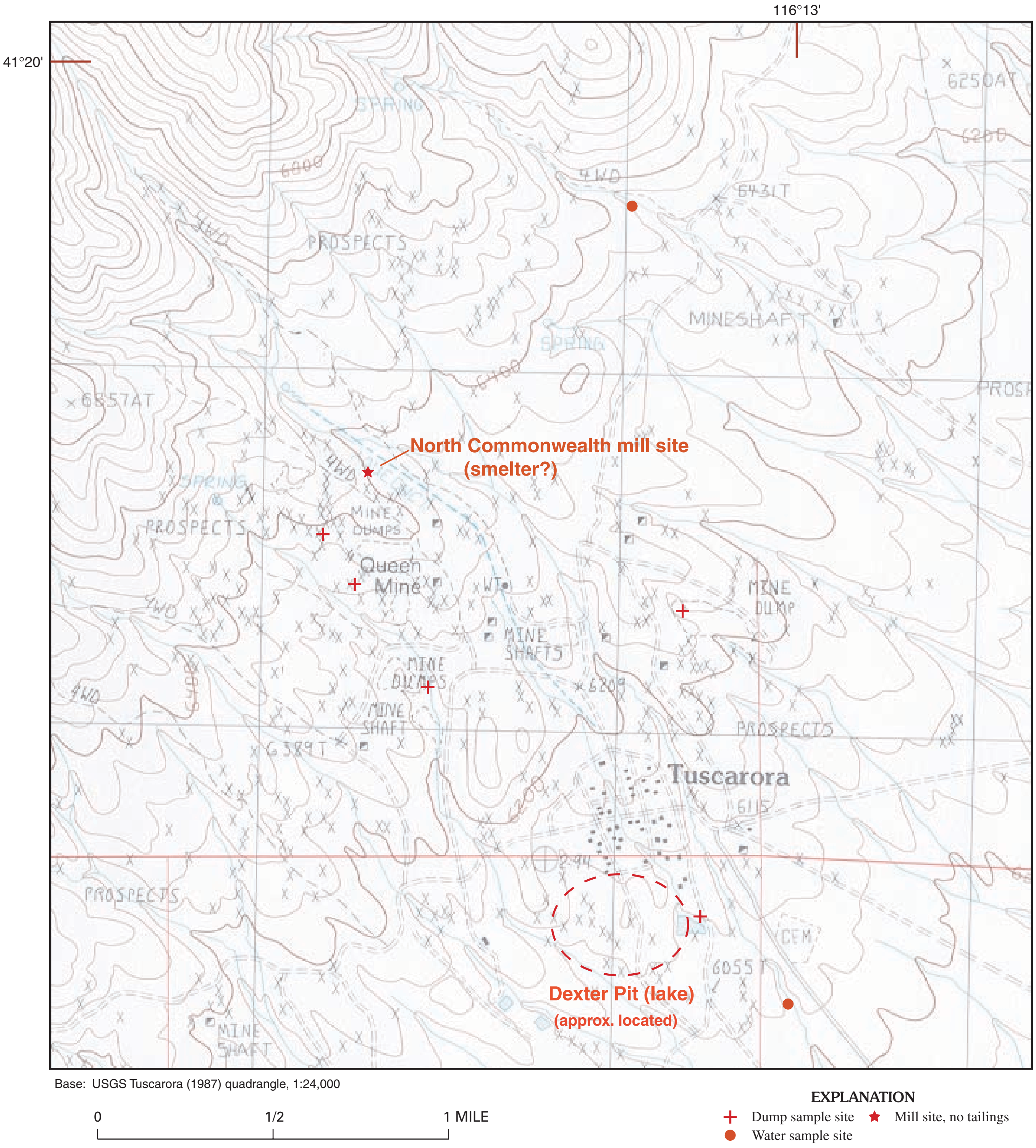


**Photograph 90.** This view, looking south from the top of the Pansey Lee mill site, shows the tortuous channel that the floodwaters must have taken from mill. Only one small area of fluvial tailings could be found north of the area of fluvial tailings.

**Photograph 91.** This swath of fluvial tailings occupies a shallow drainage more than 2 miles south of the Pansey mill. The tailings in this view range from about 6 to 30 inches thick and up to 80 feet wide.

were made of these tailings. They do not appear to be a threat to human health because the there are no residences for many miles, and their effect on wildlife would be for brief periods at most.

The Gold Acres mine, one of the first open-pit gold mines in Nevada, started production in 1936 with a cyanide mill (Vanderburg, 1939). Water was in short supply and tailings were processed in ways that conserved water. Tailings were hauled in mine cars and dumped on piles east of the mill, as shown on old topographic maps. These tailings have been covered by waste piles produced by mining over the past 15 years.



Base: USGS Tuscarora (1987) quadrangle, 1:24,000

**Figure 31.** Features of the Tuscarora mining district, showing sample localities.

## Ten Mile District

*Summary.*—This district located 10 mi west of Winnemucca was described by Nash (2001). The major concern in this area is a swath of fluvial tailings (photo 90, 91) that were released from the Pansey Lee mine (Nash, 2002b).

## Trinity District

*Summary.*—This mining area about 20 mi northwest of Lovelock (fig. 2) was the site of small silver mines that dated to 1860. There was a brief burst of activity at an open-pit mine with heap-leach in 1988–89 (Nash, 2001).

**Photograph 92.** The Dexter open pit is at the site of veins previously worked from shafts. The ore was treated on a heap-leach pad to the left of this view. The pit lake has good water quality, largely due to the beneficial effects of propylitically altered volcanic rocks.

## Tuscarora District

*Location.*—Elko County, about 50 mi northwest of Elko (fig. 2 ). Features of this district are shown in figure 31.

*Major commodities.*—Chiefly Ag and Au; much less Cu, Pb, Zn, Hg

*Mining history.*—Placer gold was discovered first, in 1867, then lode silver deposits, and later a silver rush in 1877. Production was minor after 1905, until the site of the Dexter lode was expanded into an open-pit mine with heap-leach in 1987–90. Two mercury deposits were mined in the 1940's and 1950's.

*Status of mining and exploration.*—There was no mining activity in 1996–97 and the operations at the Dexter mine were being reclaimed. Exploration in the 1990's resulted in little physical work.

*Production.*—Silver generally exceeded gold. A total of about 8.5 million oz Ag and 200,000 oz Au came from lodes and placers. Copper and lead were of minor value, and 12 flasks of mercury were produced.

*Geology.*—Basement rocks are quartzite, shale, and siltstone of the Ordovician Valmy Formation, overlain by a thick sequence of Oligocene andesitic breccias, lava flows, tuffs, and volcaniclastic siltstone. Two andesite stocks and numerous andesite dikes intrude the volcanic sequence. There is widespread propylitic (chlorite, calcite, pyrite, sericite) alteration in the volcanic rocks and more local adularia (potassium-feldspar) introduction near veins. Silicification of andesitic rocks bleaches them and makes them look like rhyolite. The age of hydrothermal adularia is 38 Ma, a good estimate of the age of vein deposition.

*Ore deposits.*—Four types of deposits have been mined in this district—silver-rich veins, gold stockworks, mercury veins, and gold placers—but only the silver veins and gold stockworks have been economically important. The silver veins filled northwest- and northeast-trending high-angle faults north of the townsite, whereas the gold stockworks are in pervasively fractured tuffs south of town. In the stockworks, gold (as electrum) occurs with quartz and adularia and ore has a silver:gold ratio of about 1:1. In the silver veins, the mineralogy is complex. Primary ores contained several kinds of silver-sulfur-antimony minerals, chalcopyrite, galena, sphalerite, pyrite, arsenopyrite, quartz, and calcite, whereas the oxidized ores contained enriched secondary silver minerals such as cerargyrite and native silver.

## Mineral-Environmental Conditions

*Mineralized rocks and ores.*—The high As, Cu, Pb, Zn, and other metals in the silver veins and associated waste rocks are potentially of concern. Several percent of pyrite and other sulfide minerals could generate acid-rock drainage, but this is countered by calcite and other minerals in green, propylitically altered rocks (Balistrieri and others, 2000). The net effect seems to be neutral pH water with low metal concentrations, according to some pH measurements on seeps near mine dumps and a lack of evidence for acid-rock drainage and metal transport (no oxide coatings and no kill of vegetation near mine dumps). The gold-breccia ores seem to have lower concentrations of sulfide minerals and base metals, as in many other Nevada hot-springs gold deposits (Nash and Trudel, 1996), and the rocks from the Dexter open pit were from the zone of oxidation. Thus, the gold ores and associated waste rocks are unlikely to create problems because the rocks are low in metals and contained sparse sulfide minerals prior to mining.

*Mills and tailings.*—The status of mills and tailings in this district is difficult for me to reconstruct. The foundation and stack of the North Commonwealth mill are prominent above the townsite, but I could not locate either slag or tailings related to this processing plant, which I presume processed much of the silver-vein ore. The mill tailings presumably were moved when they were reprocessed in 1979 to 1982 (LaPointe and others, 1991). Likewise, I could not locate any tailings elsewhere in the district. Whatever the explanation, there are no significant tailings piles today to cause concerns in this district.

*Surface and ground waters.*—There is very little surface water in this district,but the water table is close to the surface today—as shown by the lake in the Dexter pit. Most of the deposits were mined by shafts, not adits, in this area of relatively low relief. The shafts do not create drainage to the surface. The pH of four streams and seeps in the district ranges from 7.7 to 8.6. The mines and dumps could be contaminating ground water, but I did not sample ground water. Mineralogical evidence, reviewed previously, suggests that the mineralized rocks would produce little acid and low concentrations of most metals. Zinc and arsenic, abundant in the silver ores, could be mobile in near-neutral water and cause concern. Water wells could be sampled to check on these elements.

The pit and lake at the new Dexter mine has been the source of controversy, including a report in a national television program. Analyses of the pit water are reported by Price and others (1995) who cited several analyses by the owners. Reported pH's are in the range 7.5 to 8.98. Detailed studies of the pit lake water chemistry and water:rock reactions are in progress (Balistrieri and others, 2000). A stream, southeast and downgradient from the town, the lake, and the heap-leach pads, was sampled. There were no signs of acid drainage (in June of 1997) such as oxide coatings on cobbles, and the pH was buffered at 8.6; and the conductivity of 270 $\mu$S/cm was relatively low. Analysis of one sample shows that metal concentrations were very low.

*Summary.*—Water and environmental quality appear to be good at Tuscarora despite intense mining activity on deposits carrying high concentrations of base metals. All measured surface waters have alkaline pH values, indicating buffering by carbonate. This probably is related to calcite in propylitic alteration, calcite in basement sedimentary rocks, and(or) calcite (caliche) in alluvium. There is no evidence for acid-rock drainage or metal transport from pyritic volcanic rocks, which I attribute to the buffering action of propylitic alteration in these same rocks.

## Willard District

*Summary.*—This district, about 10 mi northwest of Lovelock, was the site of small mines in the early years. A silver deposit was bulk mined here from 1989 to 1993. Rocks in the pit, waste dumps, and heap-leach pile are mostly oxidized (photo 93) and appear to pose few concerns, as described by Nash (2001).

# Discussion and Interpretation

## Overview of Hydrogeochemical Results

Discussion of compositions of surface-water samples now shifts to the general trends observed in 275 analyses of water from 241 sites in northern Nevada. The total dataset of 275 analyses was used to characterize geochemical trends. The subset of 241 sites, used for characterizing sites, was

**Photograph 93.** Low-grade precious metal ore was mined from this open pit of the Willard mine. The host rocks are mostly oxidized and light in color, although a few zones of dark sulfidic rock were encountered deep in the mine. This pit does not collect water and the rocks are relatively benign because there are few sulfide minerals.

**Table 8.** Summary of surface-water compositions for three classes of acidity.

[Classes: Hi-Acid waters have pH values less than 3.0; Acid waters have pH 3.0 to 5.4; Near-Neutral waters have pH 5.5 to 9.4; ppb, parts per billion; >, greater than; Cond., conductivity, in microsiemens (µS/cm)]

| Variable | Hi-Acid (*n*=25) | | Acid (*n*=22) | | Near-Neutral (*n*=122) | |
|---|---|---|---|---|---|---|
| | Median | Maximum | Median | Maximum | Median | Maximum |
| pH | 2.6 | 1.7* | 3.4 | 3.0* | 7.9 | 5.5* |
| Cond. (µS/cm) | 1,570 | 4,590 | 910 | >2,000 | 510 | >2,000 |
| Al (ppb) | 75,000 | 1,800,000 | 23,900 | 1,627,000 | 21 | 24,160 |
| As (ppb) | 2,600 | 3,800,000 | 18 | 7,600 | 9 | 5,800 |
| Cd (ppb) | 360 | 26,000 | 200 | 26,000 | 0.3 | 63 |
| Co (ppb) | 280 | 4,400 | 141 | 495,000 | 0.7 | 1,800 |
| Cr (ppb) | 62 | 1,320 | 17 | 3,480 | 2 | 358 |
| Cu (ppb) | 5,760 | 792,000 | 1,050 | 3,900,000 | 4 | 820 |
| Fe (ppb) | 224,000 | >4,000,000 | 4,830 | 1,400,000 | 488 | 57,000 |
| Mn (ppb) | 9,980 | >3,000,000 | 5,900 | >3,000,000 | 22 | 39,000 |
| Mo (ppb) | 6 | 460 | 2 | 18 | 6 | 583 |
| Ni (ppb) | 460 | 6,650 | 255 | 172,000 | 5 | 1,200 |
| Pb (ppb) | 3 | 1,600 | 2 | 1,400 | 0.3 | 5,800 |
| Sb (ppb) | 5 | 1,660 | 1 | 15 | 1 | 140 |
| Se (ppb) | 18 | 1,340 | 7 | 1,030 | 2 | 829 |
| Th (ppb) | 13 | 1,960 | 0.6 | 39 | 0.1 | 1 |
| Tl (ppb) | 0.3 | 14 | 0.1 | 1 | 0.01 | 3 |
| U (ppb) | 15 | 760 | 5 | 664 | 1.6 | 214 |
| V (ppb) | 35 | 2,600 | 0.9 | 123 | 2 | 203 |
| Zn (ppb) | 8,900 | >2,000,000 | 6,330 | 1,900,000 | 20 | 18,000 |

*For pH, maximum pH is maximum acidity.

derived by averaging results of repeat sampling of 18 sites in 2 or more years and 11 replicate samples collected at the same time. The total of 241 analyses included results for the western part of the Humboldt River Basin (Nash, 2001) and sites outside of the basin. Element concentrations span 3 to 6 orders of magnitude (table 8), with the very high concentrations forming in some relatively rare puddles and small ponds that generally do not flow into streams. Median values (table 8) tend to be much lower than averages, which show the influence of a small number of extremely high values.

Compositions of grouped data have less variance if the analytical values are grouped by water type (such as mine drainage, tailings pond, dump puddle). Because the water samples collected in this study were generally from sites close to sources, the samples can be classified reliably on the basis of source. Subsequent discussion will evaluate compositional differences in water grouped by source, including mine workings, mine-waste dumps, mill tailings, and unmined altered rocks.

## Statistical Analysis of Hydrogeochemical Data

Several types of univariate and multivariate analyses were made of the data to look for relationships between variables or between samples that might add new insights to this large amount of information. Statistics can be used in many ways (Davis, 1986; Statistica, 2001) and with various degrees of rigor. The goal of the analysis here is to find patterns and tendencies that are consistent with geochemical theory or a priori understanding of the samples. To those ends, the author has selected only some of the results that seem most relevant to this study. The emphasis here is on geochemical patterns rather than statistical rigor. Compromises were necessary in the selection of appropriate samples and chemical data, often changing the database to include or exclude known extreme samples or variables with incomplete analytical results. Datasets with 160 or more samples and 35 or more variables were deemed appropriate for multivariate tests including correlation analysis, cluster analysis, factor analysis (three related statistical computations), and discriminant function analysis. The three first-mentioned analyses are basically related through the correlation test and no a priori knowledge or assumptions about samples, whereas discriminant function analysis examines relations based on some conceptual grouping of samples (male compared to female, mine dump compared to mill tailing).

Data from ICP-MS analyses of water and leachate solutions were used in statistical tests because they provide the most complete results for the most elements in the most samples. Elements of high geochemical interest that were not reported in all analyses from 1996 to 2000 include B, K, Li, Te, and U, as well as many others that are of less obvious relevance to this study (Br, I, Nb, Pt, and several of the rare earth elements [REE]). Because the analytical results for anions (Cl, F, $SO_4$) were available for only a small subset of the total samples studied, they were not included. Thus, for these computations the database comprised 50 elements (plus pH and conductivity values), of which more than 40 were determined in nearly all of the samples. Decisions could be made during multivariate tests whether or not to include some of the elements that were determined in only 60–70 percent of samples, and the software provided the options of replacing the missing data with the mean value or discarding that sample for the computations.

Two datasets were used in these tests: (1) surface-water samples, and (2) leachate solutions. The water dataset comprised 275 samples with analytical results for most of 52 elements, plus field measurements of pH and conductivity. Of the 275 samples, 115 were analyzed by the USGS. The leachate dataset comprised 167 samples, 80 of which were analyzed by a commercial laboratory. There are analytical results for most of 48 elements and data for laboratory measurements of pH and conductivity. Both datasets included codes for sample features such as sample type and deposit type to allow selection of subsets during multivariate tests. In both datasets some determinations were below or above the limit of determination and thus had qualifying codes of less than (<) or greater than (>); these codes were removed for the statistical analyses. In detail, the “qualified results” were simply changed to the limit of determination by removal of the qualifying symbol, but the values were not replaced by a number that is smaller or larger than the limit of determination, as is done in some analyses, because it was felt that the unqualified number was a fair approximation of the very low or very high concentration of that element. No statistical tests were made to examine possible differences between the two laboratories because that seems to be a quality-control issue that was addressed previously (Nash, 2000b); in the course of many tests there was no evidence for laboratory bias in the geostatistical trends.

Some unusual samples were known a priori to have extreme compositions that were outliers from the general distribution of values, and this was confirmed in univariate tests such as histograms. These extreme samples were treated in two ways: (1) removal of the sample prior to the test or (2) filtering of extreme values by a selection criterion during the analysis (for example, excluding samples with Cu greater than 10,000 ppb). In some tests it was informative to include the extreme samples in the analysis to determine if they influenced the patterns. In most cases it was deemed more relevant to exclude the extreme samples because the very high values in a few samples had too much influence and created patterns that did not hold for the more typical samples (with normally distributed values).

A derivative variable was created for pH after early tests showed weak correlation of metals with pH expressed as standard units (negative logarithm of hydrogen ion activity). The new variable is pH-rank, in which the most alkaline sample is given a value of 1 and the most acidic value is given the maximum value (275 for the water samples). The ranked values seem to correlate somewhat better with metal concentrations, as expected from solubilities but the pH associations in the datasets are not as strong as expected and may reflect the apples-and-oranges effects of comparing different numeric systems.

Many of the elemental associations indicated by multivariate tests are in accord with geochemical theory or simple observations of data tables but many are not. Some of the consistent associations (correlations) in both water and leachate datasets include Co-Ni, As-Fe, groups of REE, and Ca-conductivity. The weak associations of Cd-Zn and Cu-Zn were not expected, nor was the independent behavior of Ba and Pb relative to other elements.

## Relations Between Variables in Water Samples

The 275 analyses of water samples show a huge compositional range reflecting diverse conditions, from pristine water to water highly contaminated by mines or enriched by evaporation. Because the compositional range is so great, some relationships are dominated by extreme samples; clearer analyses can be made of some issues by eliminating the extreme cases or by testing subsets of one sample type (such as background or stream or mine related). Testing associations among 52 variables in 254 water analyses (extreme samples excluded) by correlation analysis or cluster analysis (which graphically portrays the correlations) suggests several groups of associated elements (fig. 32): Group A, consisting of 11 metals including Al, Be Cd, Co, Cu, Mn, Ni, Th, Tl, V, and Zn—a group of high interest in this study, and sub-group A′ (Fe, As, Bi, Ga, and In); Group B, 14 REE and alkaline-earth elements; Group C, 6 rock-forming elements including Ca, Mg, Na, K, Sr and Cr, plus Mo, Re, and Se (why the last 3 trace elements are included is not intuitive); and Group D, 3 elements of interest, Ba-Pb-Ag. Several elements behave independently, shown by long linkage distances for Si, U, and Sb (fig. 32).

Factor analysis shows the same trends as the correlation analysis and cluster analysis just described because it is based on similar computations and assumptions. For the dataset of water analyses excluding 16 extreme sample compositions, five factors explain 66 percent of the compositional variance among 52 elements. Some elements are not explained very well by the five-factor model: Be, Co, Li, Mn, Mo, Sb, Si, Sr, Tl, and U have communalities less than 0.5, and Cu and Zn also have relatively low communalities. A two-dimensional plot of factor 1 and factor 2 shows some of the relationships (fig. 33). Factor 1, explaining 29 percent of the variance, carries many REE and similar elements. Factor 2 (10 percent of variance) carries the alkali metals; and factor 3 (15 percent variance) carries Fe, As, Cd, Cu, Zn, and several other metals.

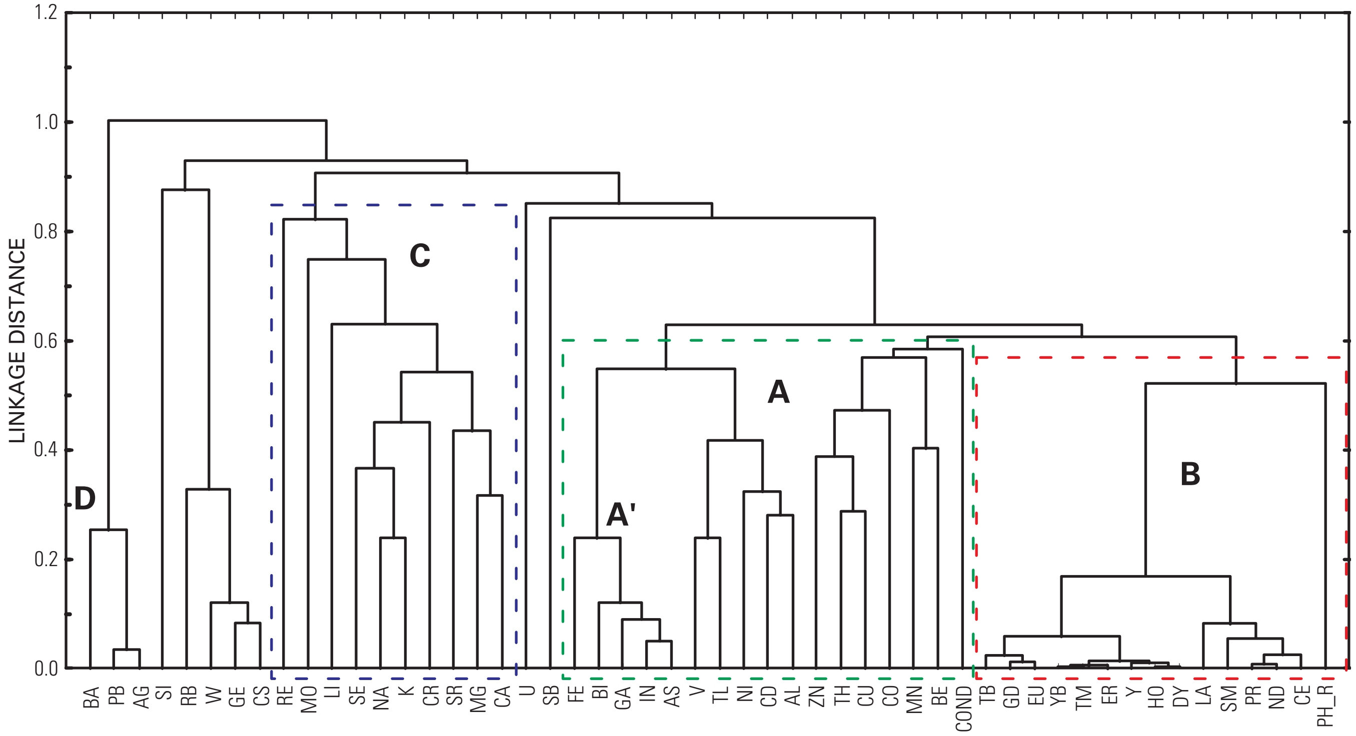


**Figure 32.** Cluster analysis tree diagram of element associations in 254 surface-water analyses. Samples having extreme concentrations of aluminum, copper, or zinc are excluded. Groups A to D are discussed in the text.

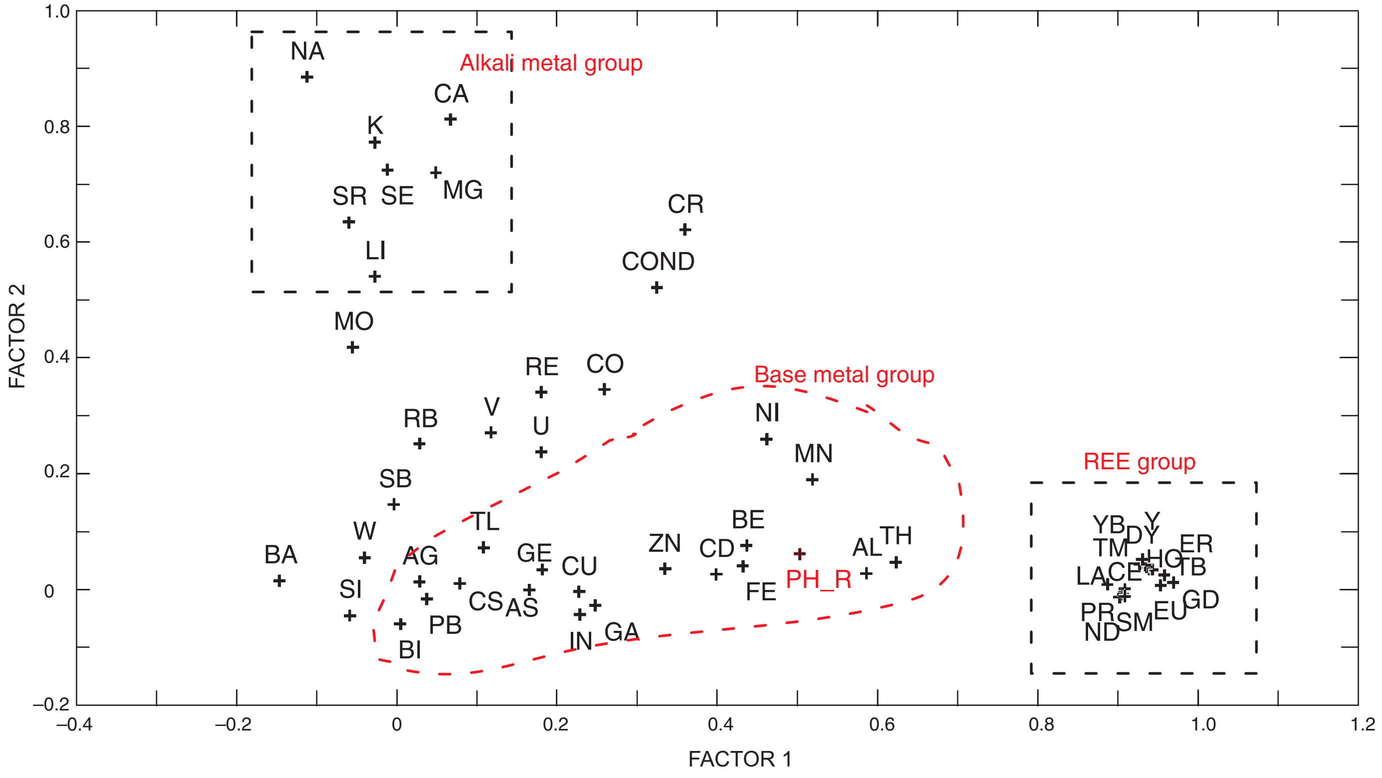


**Figure 33.** Plot of factor analysis scores for 254 surface-water analyses. Analyses with extreme concentrations of aluminum, copper, or zinc are excluded; varimax rotation.

The odd elements Ba-Pb-Ag that behave independently of other metals are heavily loaded on their own factor (which is typical of independent behavior). When the dataset is opened to all 270 samples (no exclusions), the factor model changes in some subtle ways and in detail seems to explain the range in metal concentrations better (the communalities for Cu and Zn are higher). When the samples with very high Cu and Zn concentrations are included, Cu and Zn are carried on factor 1 with the REE rather than on the factor with Fe-As. The field measurements of pH (or ranked pH) and conductivity are not well explained by any factor model; pH is independent of metals and metalloids, and conductivity is moderately loaded on the factor with alkalis.

## Relations Between Types of Water Samples

Geochemists often search for statistical trends between samples, in addition to trends between variables, because characteristics of the samples can help elucidate the geochemical trends. Also, examination of relations between samples can helps to focus on selected samples as a step toward understanding processes or areas. Q-mode factor analysis, cluster analysis (in sample mode), and t-tests have been used to investigate differences between types of water samples or between types of deposits and their significance. Classification of samples a priori by a trait, such as deposit type, helps in some of the tests. The discussion that follows will proceed from general aspects that are clarified by Q-mode factor analysis to specific questions answered by t-tests.

## Relations Between Water Samples

Statisticians normally use R-mode factor analysis but geologists find that Q-mode factor analysis provides information about samples. The computational aspects to R-mode and Q-mode factor analysis are similar, but the matrix is inverted (Davis, 1986); Q-mode highlights extreme sample end members. Most commercial software packages do not include Q-mode but software developed by scientists of the USGS in the 1970’s and 1980’s (Tidball, 1998) contains modules that still can be run in DOS-mode; they are computationally rigorous but unfriendly to users and lack graphics support. As mentioned previously, the total dataset of 270 analyses contains some extreme compositions in atypical samples: these extreme compositions tend to dominate several factors if left in the analysis. More useful results in Q-mode were obtained by a restricted dataset that excluded samples with more than 50,000 ppb Al, Cu, or Zn (11 samples), or samples lacking analytical results for several rare elements and REE. Also, the Q-mode software had a limit of 37 variables for its computations; thus, the dataset was trimmed to that number of variables by deleting those of low interest or low communality scores. Q-mode factor analysis run on a dataset of 209 samples and 37 variables required four or five factors to explain more than 95 percent of the information. The general results are:

1. Factor 1, which carries 81 percent of the information, characterizes samples with pH in the range of 6 to 9, conductivities of 230 to 600 $\mu$S/cm, and low concentrations of most metals (but moderate Ba and Mn concentrations). Most samples are from streams, springs, and weakly contaminated mine drainage. Samples with high loadings on factor 1 are typically background water, and samples having lower loadings on this factor (and conversely high loadings on other factors) reflect contamination from mined sources or unmined altered rocks.

2. Factor 2, which carries 10.4 percent of the information, characterizes samples with pH values in the range of 7.6 to 9.2, conductivities greater than 1,000 $\mu$S/cm, generally low metal concentrations, but moderate to high concentrations of Ba, Ca, Cr, K, Na, Mo, Se, or U. Samples come from all sources, including mine puddles and heap-leach pads. Samples with high loadings on factor 2 exhibit element enrichments typical of evaporative concentration, which may be the process that created these compositions.

3. Factor 3, carrying 4.8 percent of the information, characterized acidic water with pH values generally less than 3, conductivities of 1,500 to greater than 2,000 $\mu$S/cm, and high to very high concentrations of nearly all metals (especially Al, Cu, Fe, and Mn) that typically are carried in acidic water. All of the end-member samples are from mine drainages. Samples with high loadings on factor 3 are typical of acid-mine drainage, here and elsewhere, and the element suite is explained by the acidity. Moderate loadings on factor 3 are an indication of contamination by acidic water, generally with a source in mines or mine waste. Moderate factor 3 loadings are shown by background water samples collected in headwater basins underlain by unmined altered rocks.

4. Factor 4, which carries 2.0 percent of the information, characterizes water with a range in pH (3.9 to 8.3) and in conductivity (230 to greater than 2,000 $\mu$S/cm), low to moderate metal concentrations, but high Ca, Mg, and high Cu, Pb, or Zn. These samples are unusual ones from pit ponds and puddles. The number of samples in this group is small (six with substantial loadings) and may be a melange of different types of water, so interpretation is risky. Some of these waters may represent neutralized, formerly acidic mine-drainage water.

5. Factor 5, which carries 0.7 percent of the information, carries only two samples with extremely low metal concentrations: two deionized water blank samples that clearly are distinct geologically and perhaps should have been culled from the dataset.

The compositions of end-member samples on the four main factors are distinct and statistically significant. This can be tested by discriminant function analysis, as shown graphically in figure 34. The n-dimensional discriminating surface portrayed (fig. 34) is not intuitive but is real. The sources and processes controlling the compositions are suggested above but not uniquely defined by these multivariate tests.

The traditional t-test is an effective tool for testing differences among water sample types (spring, stream, background, mine-related) or water related to known deposit types

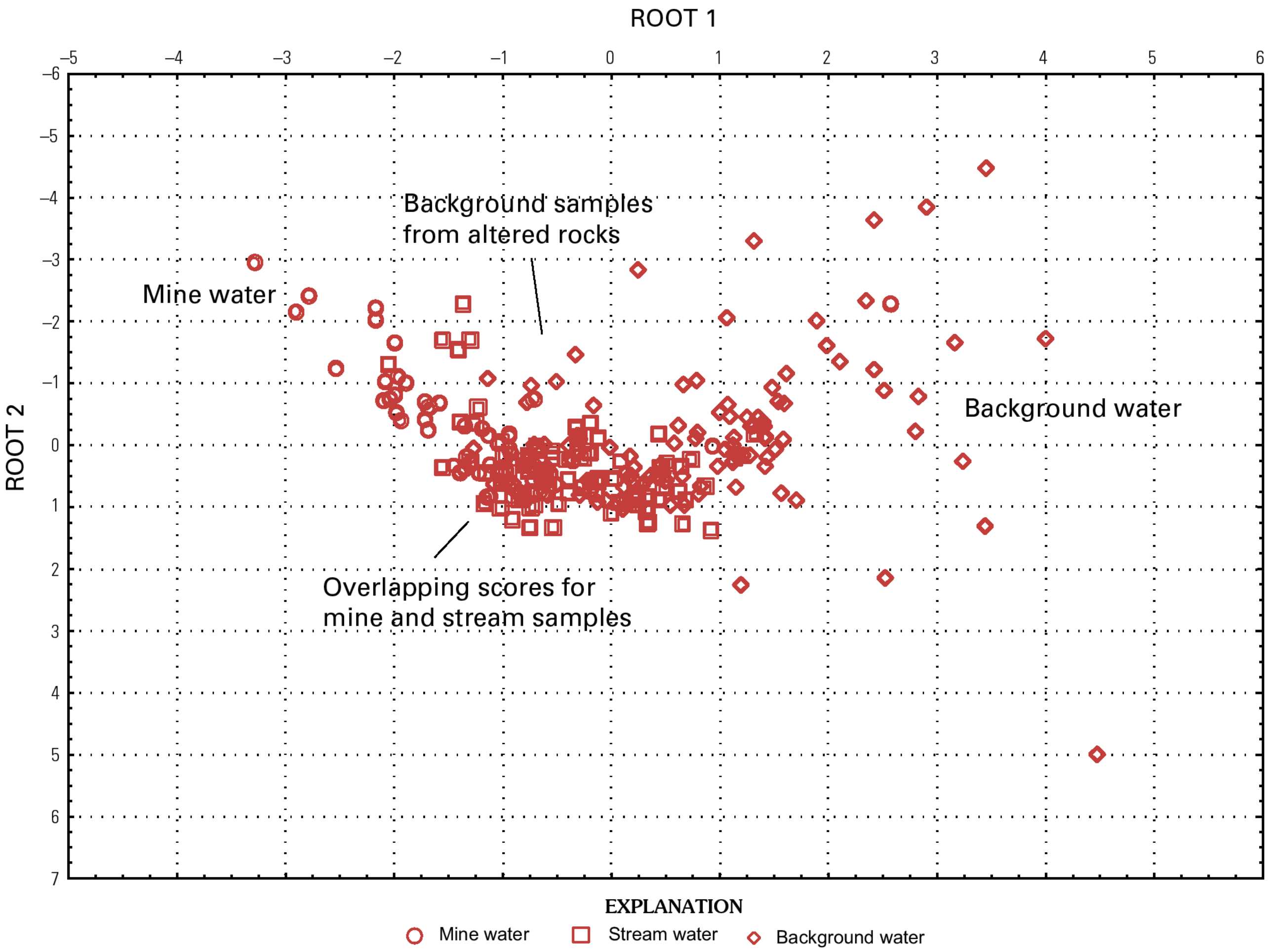


**Figure 34.** Plot of discriminant function scores of mine, surface, and background water compositions.

(epithermal vein, polymetallic vein, and others). It turns out that the compositional differences between groups are not significant at p = 0.05 (5 percent probability) for most elements, and in many cases even at 10-percent probability (which is very low for most statistical tests), elements of interest such as Cu, Pb, and Zn are not significantly different.

Surface water with a range of contaminants from mines and water closely associated with mines and mill tailings (the "mines" group) were compared using a t-test, which showed that many variables were significantly different at the 5-percent probability level: pH-rank, conductivity, Al, Be, Ca, Cd, Ce, Cr, Cs, Fe, Ga, Ge, La, Mg, Mo, Ni, Pr, Rb, Re, Sb, Se, Sm, Tl, U, V, and Zn (but not Ag, Cu, or Pb).[3] Comparing stream water (variably contaminated) with background water (thought to have no mine-related contaminants) shows that many variables are significantly different at the 5-percent level: pH-rank*, conductivity, Ag*, Ba*, Be, Ca*, Dy, Er, Eu, Gd, Ho, K, La, Li, Mn*, Mo*, Nd, Ni, Pr, Re*, Se*, Sm, Tb, Tm, W*, Y, and Yb (the variables with * are also significantly different at 1-percent level). For these classes, concentrations of Cu, Pb, and Zn and not significantly different even at the 10-percent level. The comparison of background and stream water, just reviewed, is one of the few in which variables are significantly different at the 1-percent level—in most cases the differences are not sufficiently distinctive to be significant at 1 percent.

Tests of water compositions associated with various deposit types show that for most cases there is no significant difference at the 1- and 5-percent probabilities. A t-test comparing water associated with epithermal veins with water associated with polymetallic vein deposits (30 and 76 samples, respectively) showed no significant differences until the 10-percent level at which Ce, Pb, and U are different. Comparing water associated with epithermal vein deposits and water associated with mercury deposits shows that Mg, Na, and Sb are significantly higher in the mercury deposit water. Comparing epithermal veins with sediment-hosted gold deposits shows that pH-rank, As, Re, and Tl are significantly different at the 5-percent level (As and Tl are higher and pH-rank is lower in

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[3] Elements identified by t-tests and by discriminant function tests tend to differ, probably because the discriminant function calculations used here eliminate similar-behaving elements that tend to explain similar chemical features. For example, Cd would not be part of the discriminant because that attribute would be explained by Zn.

association with sediment-hosted deposits). Comparing water from polymetallic deposits and acid-sulfate deposits shows that many elements are significantly higher in association with the acid-sulfate deposits, including Al, Cu, Co, Fe, In, Re, Th, U, and pH-rank. Comparing polymetallic deposits and massive sulfide deposits shows that Cu and Co are significantly different (but the samples from the massive sulfide environment may not be representative, in general). Comparing skarn deposits and sediment-hosted gold deposits suggests that only Bi is significantly different (again, the sample suites may not be representative).

What are the differences between types of water samples or between types of deposits, and are they significant? Many questions can be asked of the water dataset and tested using several univariate and multivariate analyses of samples grouped by an a priori criterion. With the large array of chemical variables in the dataset, the multivariate discriminant function analysis is an effective tool for differences in water-sample types (spring, stream, background, mine-related) or water related to known deposit types (epithermal vein, polymetallic vein, and others). Discriminant function analysis programs generally have options to classify unknown or uncertain samples relative to known training groups or to test classification of known samples to see if they may be misclassified. Posterior classification also can suggest if there is a range in element concentrations or overlap in geochemical character between two sample classes. Many classification questions have been tested, but only a few will be described here. A common outcome is that deposit types generally believed to be geologically or genetically different have compositions that are difficult to distinguish (that is, the ranges of metal concentrations overlap). The ore metals Cu, Pb, Zn, and As may seem to be the characteristic elements (for geologists) in these mining districts, but these objective multivariate tests demonstrate the important differences in numerous other elements including Al, Bi, Ca, Cd, Co, K, Mn, Mo, Th, U, and V when comparing various ore types.

What are the differences between samples collected as “background” and those taken at or near mines and mine waste? Another way to phrase this question is: how many chemical attributes are needed to distinguish mine water from background or unmineralized water? Discriminant function analysis indicates that 25 elements are significantly different between these two groups, starting with pH-rank, K, W, Ba, Ag, Re, U, Cr, and Mg. In stepwise discriminant function analysis, in which variables are entered one at a time, just two variables (pH-rank and K) properly classify 88 percent of the 146 samples in the test. Technically, discriminant function analysis defines a plane in n-dimensional space (here, n is 50 elements plus pH-rank and conductivity) that is difficult to visualize. More helpful are group statistics that show the mean and standard deviation for the groups to tell us that mine water has low pH, low Ba, but high K, Mg, and others, relative to background water. Posterior classification scores for the samples show that some background waters have mine-water affinities (fig. 33), which is in good agreement with the field observations that these water samples were taken in headwater basins with altered rocks but no mines. The elements that tend to be enriched in water from altered rocks include As, Fe, K, Mn, Mo, Na, Sb, Se, Sr, U, V, and Zn.

Differences between mine water and stream water prove difficult to compute and classify, probably because many of the stream compositions reflect contamination from mines. In a discriminant function analysis test of all mine and stream water (including the extreme compositions), the most effective discriminators are, in order, pH-rank, conductivity, Cs, K, Ba, Pb, Mo, Na, As, and Sb. The means of these variables are higher in the mine water, except Ba, which is lower; high pH-rank is equivalent to high acidity. The discriminant incorrectly classified 29 percent of stream samples and 33 percent of mine samples relative to the a priori assignments. There are many cases of overlapping compositions, and this is reflected in the discriminant plot (fig. 34). Posterior classification scores for samples indicate how well they fit the classification model. These values also can be considered as indicators of mixed compositions relative to model compositions: for example, a value of S-0.75 and M-0.25 for a sample suggests it is a stream water mixed with substantial (possibly 25 percent) mine-type composition.

What are the differences in water compositions associated with various deposit types? Discriminating between water associated with polymetallic deposits and epithermal vein deposits is fairly successful by discriminant function analysis that highlights the variables K, Cd, Co, Mo, Mg, Cs, Rb, and pH-rank. The mean value for water associated with polymetallic deposits is high in Cd, Mg, and pH-rank, and the other variables are high in association with epithermal deposits. Discriminating between polymetallic deposits and acid sulfate deposits can be done with 15 variables (Co, Cd, K, Pb, Ce, V, Al, Ni, pH-rank, Mn, Ag, conductivity, Cu, Cr, and Fe [listed in order of discriminant function]). In this test, mean values for Al, Ni, Mn, conductivity, Cu, Cr, and Fe are higher in the acid sulfate class. Comparing water associated with epithermal vein deposits and those with mercury deposits, discrimination can be done with 13 elements (Mg, Sb, Cu, Sr, Ca, Cr, Se, Cs, Dy, Y, U, Na, and Mo) in which the median values are higher for Mg, Sb, Sr, U, Cr, Ca, and Cs in the mercury deposit water. Discrimination between water associated with epithermal vein deposits and sediment-hosted gold deposits can be done with nine variables: (Mg, Sb, pH-rank, K, Ni, V, Cd, U, and Ca) to properly classify 92 percent of the samples. In this test, the water associated with epithermal veins are higher in Cd, U, V, and K and lower in Ca, Mg, Ni, and Sb relative to the mean for sediment-hosted gold deposits.

These discriminant function analysis tests confirm some intuitive concepts about water compositions in relation to deposit type and point out some subtle aspects of aqueous geochemistry. For instance, although a deposit type is rich in a certain element, such as Zn or As, the element may not be mobile under the local conditions. Also, some of the enriched elements in water are not those that we tend to think of as characteristic of the deposit type, such as the trace elements

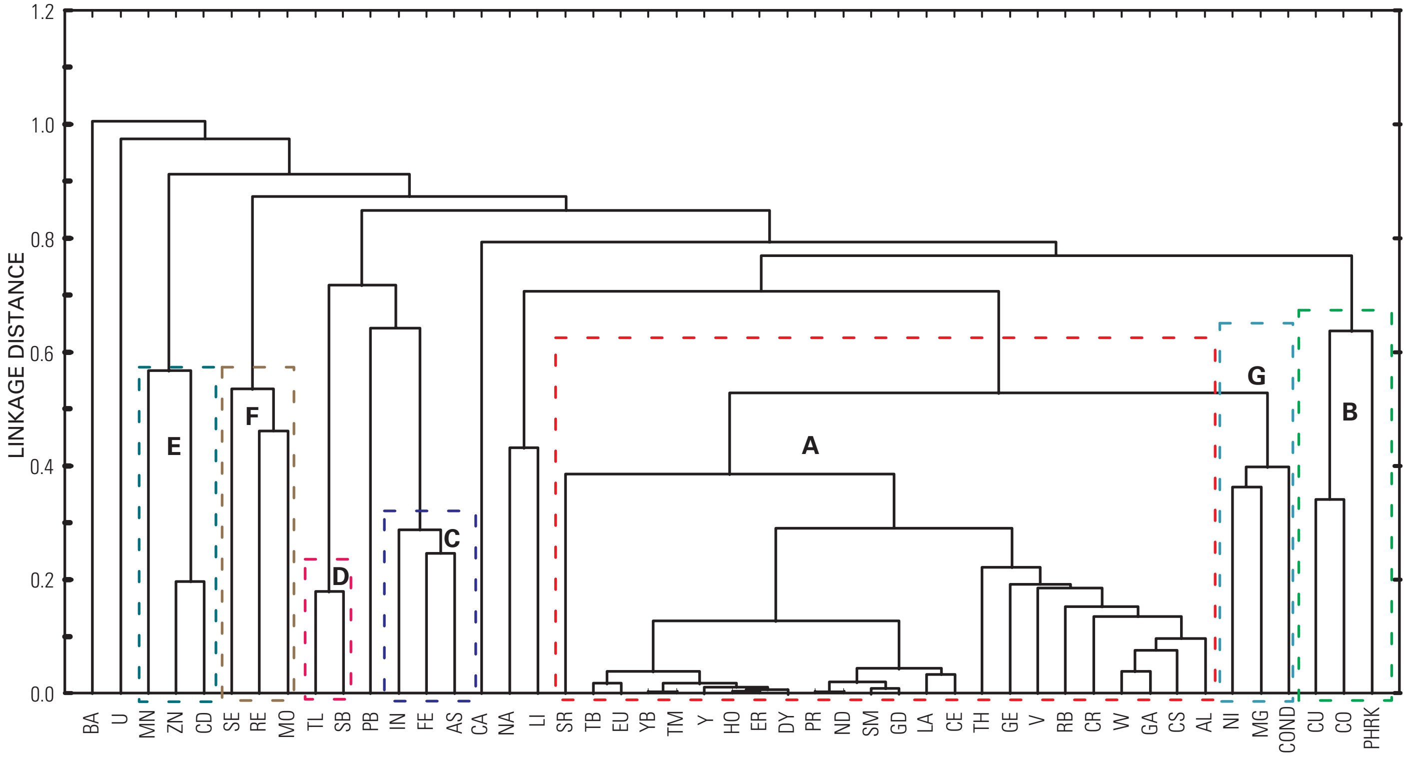


**Figure 35.** Cluster analysis tree diagram of relations between 47 variables in 153 leachate analyses. Eight analyses that have extreme concentrations of Al, Cu, or Zn are excluded. Groups A to G are discussed in the text.

(Co, Ni, U, or REE). Finally, these discriminant function analysis tests are only as reliable as the starting classifications and the quality of the samples in that class. Largely because of the arid conditions and deposit access, the samples from some deposit types may not be representative—chiefly in the cases of volcanogenic massive sulfide, skarn, sediment-hosted, and mercury deposits. Where the samples are deemed reliable and representative, they would be appropriate for a discriminant function analysis "training set" for comparison and classification of water from another study area.

## Relations Between Variables in Leachate Solutions

Analytical results for 161 leachate solutions span a very wide range, generally similar in magnitude to the results for surface water. Some of the extreme compositions were from samples of desiccation crusts, which were selected as atypical materials and expected to be highly reactive in leach tests. To avoid the effects of these outliers on the statistical tests, eight samples with extreme compositions were excluded from most computations. Cluster analysis of the leachate dataset yielded groups of variables that are generally similar to those described for the water samples (fig. 35). Group A is a large group (cluster) of 24 associated elements that are related to rock lithologies, including REE, alkaline earths, Al, Sr, V, and Th. Group B comprises Cu, Co, and pH-rank. Leachate conductivity is grouped with Ni and Mg. Group C includes Fe-As-In. Group D is Sb-Tl. Group E is Zn-Cd-Mn, and Group F is Mo-Re-Se. Many of these associations are logical on geochemical grounds, such as similar response to pH, but some, such as the uniquely strong association of Co and Cu with pH, are open to question. Many elements behave independently, as shown by low correlations or high linkage distance (fig. 35); elements showing independent behavior include Ba, U, Ca, Na, Li, Pb, Si, and Bi. Presumably, these clusters reflect both the availability of metals in samples and solubility relations that are largely controlled by pH: the clusters are not proof of processes but help in the interpretation of processes by identifying elements with similar behavior.

Relations between chemical variables in the leachate dataset were tested by factor analysis. A five-factor model explains 78 percent of the information after some extreme samples (very high values) and variables were removed. In the original model several elements were not described effectively, as shown by communalities below 0.4 for Ba, Bi, Li, Pb, Sb, Si, and U, and were not included in subsequent factor analyses. There could be many reasons for the low communalities, including independent behavior (reasonable) or analytical error. The five factors carry the following variables with high loadings:

factor 1: 17 elements (REE, Al, Cr, Na, Rb, Sr)

factor 2: 4 elements (Co, Cu, Mg, Ni) with moderately high loading of pH-rank and conductivity factor 3: 4 elements (As, Fe, In); Pb included here but has low communality

factor 4: 3 elements (Mo, Re, Se)

factor 5: 2 elements (Zn, Cd)

The tendency for higher numbered factors to carry fewer variables, as here, is typical of factor analysis in general and shown by the decreasing magnitude of eigenvalues and the amount of information (variance) that the vectors carry. Independent-behaving variables, such as Ba or U, tend to be carried on their own factor if more factors are allowed in the factor analysis. Or, these independent variables can be "forced" onto another factor in a factor model with fewer factors than are appropriate for that variable, as in the case of Pb in the previous example.

Inclusion of the eight samples with extremely high As, Cu, and Zn concentrations in the factor analysis changes the model in many ways. Copper is loaded more strongly on factor 2, and several REE are loaded on factor 2 rather than on factor 1. Factor 3 carries more information, with the addition of Zn and Cd, and a very strong loading for As. The 5-factor model of all 161 leachate analyses carries 84 percent of the information rather than 76 percent for the 153 more typical leachates. The model for 161 samples has the specifications (communalities, eigenvalues) that suggest it is a "better" model than for 153 samples. However, the eight samples with extreme concentrations are not typical geologically, and the extreme values are outliers (breaking the rule that data values have a normal distribution of values for reliable factor analysis).

## Relations Between Types of Samples

Knowledge of the materials used in the leachate analyses allows samples to be classified a priori according to sample type (mine dump, mill tailings, altered unmined rock) or by deposit type. Compositional differences between classes were examined by making t-tests on various class subsets of the dataset for 161 samples and 52 variables.

Are the leachate compositions systematically different among the three types of samples analyzed? Comparing the subsets for leachates from 70 dump samples and 58 mill tailings samples shows that, at the 5-percent level, pH-rank, Be, Ce, Dy, Er, Eu, Gd, Ho, Mg, Nd, Ni, Sm, Tm, Y, and Yb are significantly different. The variables are higher in the dump samples (pH-rank is more acidic). Comparing 70 dump leachates with 18 altered rock leachates shows that only pH-rank and conductivity are significantly different at the 5-percent level; at the 10-percent level, Be, Dy, Er, Eu, Gd, Ho, Mg, Ni, Se, Tm, Y, and Yb differ between the two classes. A similar comparison of leachates of mill tailings and altered rocks shows similar results; at the 10-percent level pH-rank, conductivity, V, and Yb are different between the two classes. No ore metals (Cd, Cu, Pb, Zn) are computed to be significantly different between any of the three classes. These vague distinctions between sample types reflect overlapping compositional ranges of leachate solutions, which seem logical considering that the materials attained their compositions by ore-forming processes of similar character but differing intensity.

Are the leachate compositions significantly different between the various ore deposit types? Comparing epithermal vein and polymetallic vein samples by t-test shows that at the 5-percent level none of the 52 variables are significantly different; at the 10-percent level Ce, Pb, and U are different. Comparing leachate compositions for samples from epithermal vein deposits and mercury deposits shows that pH-rank, As, Re, and Tl are significantly different at the 5-percent level (element concentrations and alkalinity higher in the mercury deposit samples). Comparing leachates of epithermal vein samples with those from sediment-hosted gold deposits shows that pH-rank, As, Re, and Tl are significantly different, with As and Tl concentrations higher and pH-rank lower (higher pH) in the sediment-hosted leachates. Comparing polymetallic vein and sediment-hosted deposit leachates shows very few clear distinctions: Sb is significant at the 5-percent level and Tl is significant at the 10-percent level. Comparing skarn deposit and sediment-hosted deposit leachates reveals that only Bi concentrations are significantly different (higher in skarn leachates). Comparing polymetallic vein and acid-sulfate deposit leachates shows that many variables are significantly different at the 5-percent level: pH-rank, Al, Be, Cd, Co, Cu, Fe, In, Re, Th, and U are higher in the acid-sulfate leachates. Comparing the polymetallic vein and massive sulfide leachates shows that only Co and Cu are significantly different at the 5-percent level.

Are the leachate compositions systematically different among the three types of samples analyzed? The simple answer is: maybe. Discriminant function analysis of leachates of tailings and of dump samples provided vague criteria. The most significant variables were Dy, Mo, Mn, pH-rank, Fe, V, Rb, Ge, Tl, Sr, As, Ni, Cs, Y, In, and Eu, but together these variables properly classified only 73 percent of the samples (57 percent of tailings). With altered-rock samples included in the discriminant function analysis of three sample types, the best multivariate discriminant misclassified all altered-rock samples. These computations imply that the character of the sample does not have a strong influence on the composition of the leachate (rather, it is the composition of the sample that is important). The fact that sample scores for mine dump and mill tailings samples overlap in n-dimensional discriminant space is not surprising: the materials are generally the same but have different grain size.

The different deposit types are reflected in generally different leachate compositions, although some leachate compositions are similar (they overlap). In a discriminant function analysis test of leachates from polymetallic and massive sulfide deposits, the variables Cu, Co, Se, Re, Ni, Sr, Al, Ca, Cd, pH-rank, Cr, Nd, Mo, Rb, and In were used in the discriminant that properly classified all 81 polymetallic samples and 7 of 12 massive sulfide samples. The '"misclassified"' massive sulfide samples were atypical samples of altered wall rocks and mill tailings.

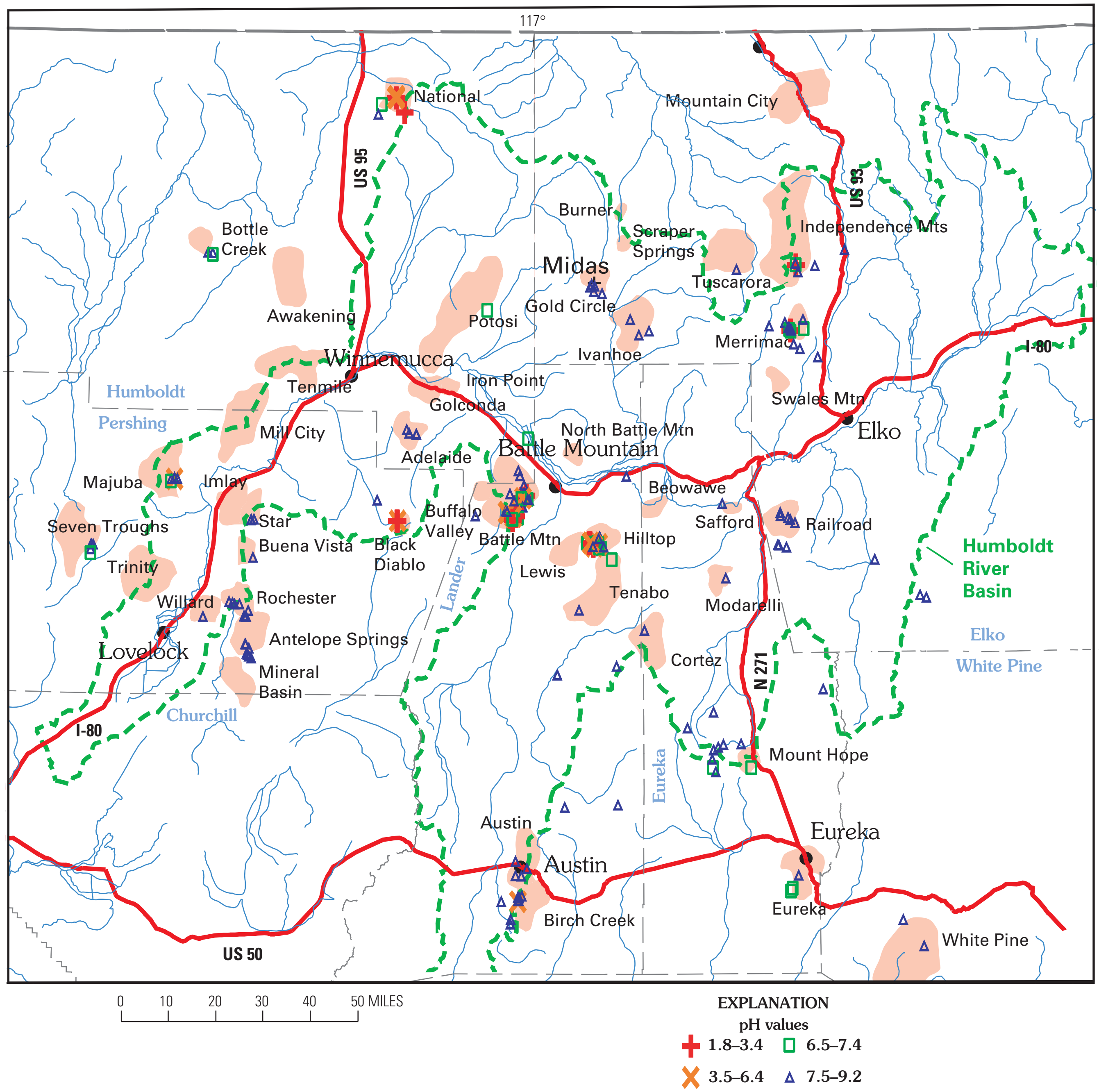


**Figure 36.** Location and character of surface-water samples. District outlines are from Tingley (1998); only studied districts are shown.

Distinguishing between polymetallic and sediment-hosted deposits is easy if Sb is included in the dataset: data for Sb, conductivity, and Cu are sufficient to properly classify 86 percent of the 86 samples. If Sb is excluded as a variable (behavior described above suggests that the results for Sb may not be appropriate for multivariate tests, perhaps due to analytical problems), seven variables are required for the discriminant (conductivity, Ca, As, Re, Se, Zn, and Cu).

Epithermal vein deposits (mined for silver and gold) and mercury deposits (also epithermal in character) are often thought to form in similar environments, but are there differences in the leachate compositions? According to discriminant function analysis there are significant differences in leachate pH-rank, V, Cr, Se, Mn, Al, Cs, and Mg; there are no data for Hg. These variables properly classify 92 percent of the 39 test samples. The mean values for mercury deposit leachates are higher for Cr, Mg, Se, and V, and leachate pH-rank is more alkaline relative to the epithermal vein samples.

## Mines as Sources of Contaminants

There are many potential sources of contaminants at a typical historical mine site, including mine workings, waste dumps, stockpiles, and mill tailings. Of the many contaminant pathways, only surface water has been investigated; dispersion into air (dust) and ground water are not considered here. Sources in unmined altered rocks near mines are mentioned in some of the district discussions and should be considered in any watershed evaluation, such as with TMDL's, but are not quantified in this study.

Mine sources can be tracked by hydrogeochemical sampling at watershed scale in humid climates, but sampling at sites miles distant from mines is generally not effective in Nevada because few streams flow that far (as will be discussed later). In this study, efforts have been made to observe and sample likely contaminants at the source; there is no effective alternative method if diagnostic information is required. The map of surface-water samples (fig. 36) shows mine samples and downstream sample sites. Many of the sites in figure 36 are background sample localities, thought to be uncontaminated by mining, that were studied for comparison with water in mining areas. The general trends and some of the processes involved in the formation and evolution of mine drainage water are discussed next.

### Mine Drainage Compositions

#### Abundance

How common is acid-mine drainage? Only a small number of historical mines in northern Nevada release mine drainage in amounts sufficient to be sampled. Using information from USGS 1:24,000 topographic maps, such as locations of mine adits, topography, locations of springs and streams, it was possible to anticipate likely sites of mine discharge. While in the field I searched for signs of mine drainage, which generally can be detected from a distance of hundreds of feet as telltale streaks of red iron coatings. I was able to identify only 16 mine adits with active discharge of water (sufficient to measure pH and collect a sample for analysis; photo 64). This is a very small number when compared to the thousands of mines and prospects in the districts that I traversed. Mill tailings interact with surface water (seasonal streams and ponds) at 12 sites (photo 94, 97). Small ponds and large puddles (greater than 50 feet wide) form occasionally at 9 sites (photo 98). Mine-waste dumps are wet from streams or mine water at 10 sites (photo 97). Although my reconnaissance study probably missed some mines that release drainage water, I believe I observed a representative selection of draining adits and possibly found most of the draining adits in the districts under study. Considering the large area studied (about 25 million acres) and the very large number of historical mines and prospects shown on topographic maps (estimated to be about 75,000 compared to 225,000 to 310,000 in all of Nevada [Price and others, 1995]), the number of wet, draining adits and mine dumps is small. From my observations I estimate that less than about 0.05–0.1 percent of historical mines and prospects release contaminated drainage during the wettest months of the year. This is similar to the estimate of Price and others (1995). The largest discharge was about 40 to 50 gpm during spring runoff, and most of the mine discharges are 5 to 10 gpm in wet seasons. The largest number of draining adits and associated wet dumps was in the Dean mine complex, western Hilltop district, and these were effectively reclaimed in 1998. The more problematic sites identified in this study, shown in figure 37, will be discussed later.

Some historical mines were described as being flooded by water a century ago when the workings were being excavated, but these mine workings appear to release little or no water today. Pumping of water was said to be complicated and costly in the Austin and Seven Troughs mining districts (Ross, 1953; Nash, 2001), leading to the construction of long haulage and drainage tunnels. These deep tunnels appear to be dry most of the time but may discharge water occasionally. For instance, the tunnel at Seven Troughs discharged a small amount of water in June 1994 but was dry in June of 1998. The Betty O'Neal mine had some water in it when I went underground in 1970, but no water was evident at the lower portal in 1998 and 1999. These brief comments are a reminder that flow of water into and out of underground mine workings is complex and difficult to predict.

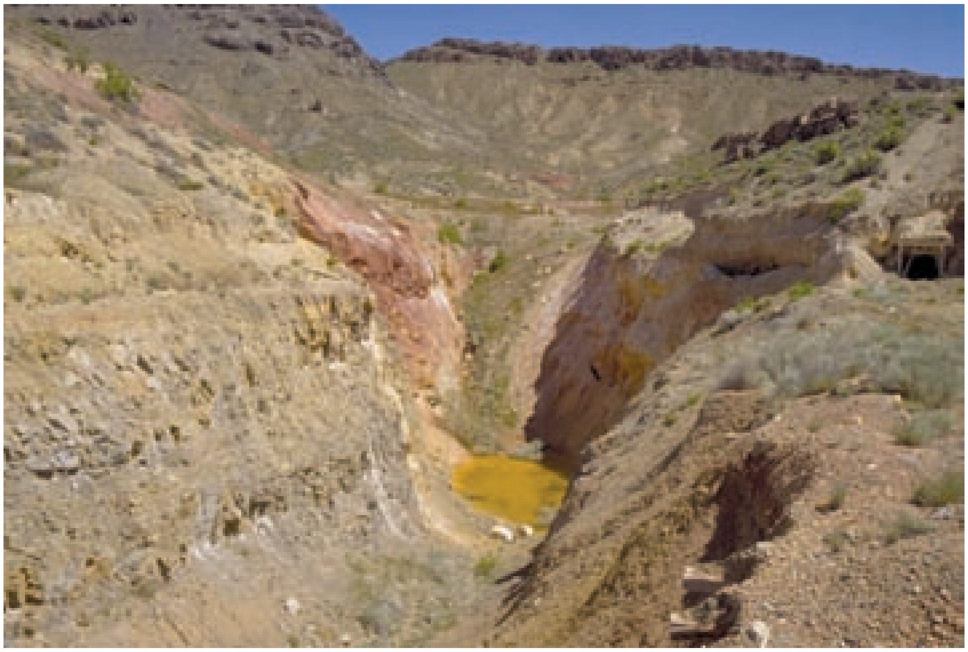
#### Acidity

The popular press asserts that mine drainage is typically acidic (for example,Watkins, 2000), but this is not generally true in northern Nevada. The pH of mine discharge water ranges from 2.1 to 8.3 with a median value of 3.4. Only 11 mine drainages have pH values less than 3, and 13 atypical mine-water samples, such as puddles and small ponds, have pH values of 1.7 to 3. Acidic water with pH values of 3 to 5.5 was present at seven mine sites and eight other sites such as tailings ponds, pit lakes, and puddles. The surface-water sample sites and pH values are shown in figure 36. All but a few of these acid sources appear to be seasonal, according to my observations of zero or low flow in September visits and comments from BLM staff.

#### Sources of Acidity

The sources of acid in the Nevada water possibly differ from typical acid-mine drainage elsewhere that is known to be

**Photograph 94.** Mill tailings commonly are placed in streams or arroyos where they react with episodic stormwaters. The white crusts on these tailings in Coon Creek dissolve within minutes, according to leach tests, and release metals to stormwaters, but these materials do not release much acid because they are calcareous.



**Photograph 95.** Trenches in mine dumps or mill tailings can collect runoff water with extremely high metal concentrations. This trench in the Antelope Springs district collects water with very high mercury concentration.

chiefly related to the oxidation of pyrite (Nordstrom and Alpers, 1999). In some places, such as in the 1990's Dean mine workings or at the National mine, pyrite and other sulfide minerals are abundant and there was relatively little pre-mining oxidation. At most mining sites there was deep pre-mining oxidation, and most of the historical mines operated above the water table. Mineralogic descriptions of the mined deposits include numerous reports of oxidized mineral species such as various oxides of iron and copper and base-metal sulfates. In the arid climate of Nevada, and with the prevailing deep pre-mining oxidation, formation of secondary sulfate minerals is widespread—and these sulfate minerals store metals and hydrogen ions that are readily soluble when contacted by water (Nordstrom and Alpers, 1999). Leach tests of oxidized and partially oxidized mine waste from Nevada and elsewhere (Nash, 2002a; Fey and others, 2000) show that iron-sulfate and other sulfate minerals are highly reactive and create acidic as well as metal-rich water. The ultimate source of acid is in sulfide minerals: some acid was created millions of years ago and some continues to be created in mines or within mine waste as the sulfides oxidize. Oxygen and water are required, and bacteria increase the rate of oxidation (Nordstrom and Alpers, 1999).

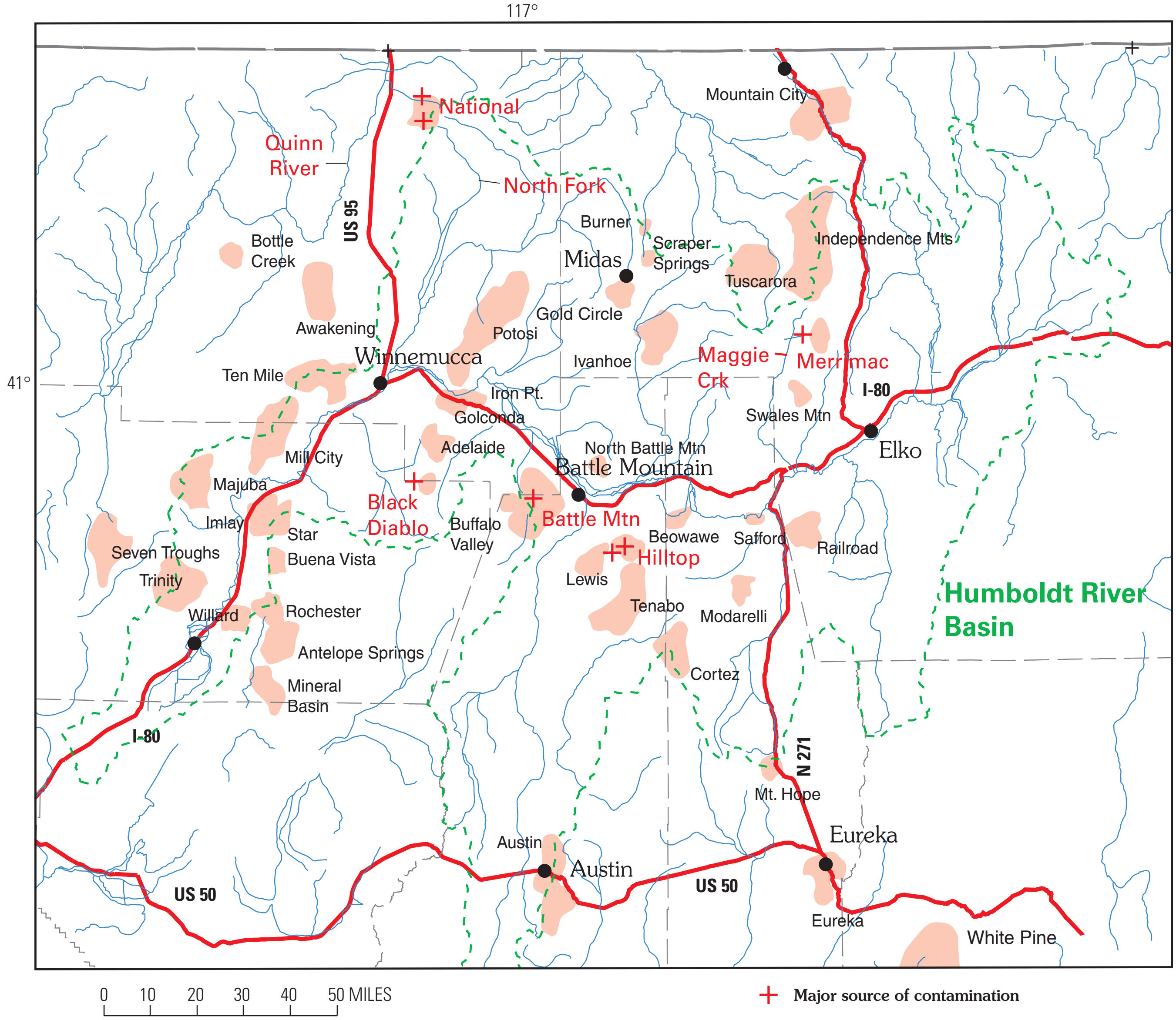


**Figure 37.** Location of mining areas with highly degraded water quality. District outlines are from Tingley (1998); only studied districts are shown.

## Metal Concentrations

Metal solubility and transport by mine water is largely a function of pH and Eh (oxidation potential). Numerous reports describe the sources of acid and the solubility relations of metals as a function of pH (Drever, 1997; Nordstrom and Alpers, 1999). The surface-water compositions observed in the Humboldt River Basin are similar to those of most hardrock metal-mining areas, including well-studied mining areas of Colorado (Plumlee and others, 1999; Nash, 2002a; Mast and others, 2000). At pH values below about 4, many potentially toxic metals are often highly to extremely concentrated (relative to water-quality standards for drinking water or aquatic life; Nevada Division of Environmental Protection, 2002). As in most metal mining areas, water released from adits, dumps, or mill tailings tend to carry high metal concentrations at the source, roughly in proportion to acidity (fig. 11).

The composition of surface water at 169 sites that may reflect contamination by mining is summarized in table 8; not included are samples of background stream water and spring water. The median value is perhaps the best guide to typical concerns, whereas the maximum value shows how concentrated and potentially toxic these waters can be at the sources. Table 8 and figure 11 show that metal concentrations in water are highest below a pH of about 3. Some mine-related water (adits, seeps, puddles, and pits) has pH values of 3 to 9, and concentrations of most metals in these waters are lower than the more acidic ones. At pH higher than 3 to 4, most base metals tend to hydrolyze, resulting in lower solubility.

**Photograph 96.** Mine drainage reacts with sulfidic mine waste and accumulates even higher amounts of metals. The red-wine color of this water is characteristic of high-acid, high-metal waters.

**Photograph 97.** Runoff from storms can be substantial in normally arid northern Nevada. Two days of rain and snow in June 1999 created runoff with pH values less than 2 at the Tybo mill tailings impoundment. Such events are poorly documented because they are rare and brief; the runoff from most storms stops flowing in a few hours.

Reactions with atmospheric oxygen as water emerges from mine workings tend to cause Fe to precipitate as fine-grained iron-oxyhydroxides that are capable of adsorbing many metals, including As, Cu, and Pb (Smith, 1999). Near-neutral pH water tends to carry relatively low amounts of most metals, but some potentially toxic metals (Zn and Cd) can be carried at these pH values. Near-neutral to alkaline water (pH 7–9) also can carry significant concentrations of metal-oxyanions (As, Mo, Se) and U.

The toxicity of metals varies greatly from metal to metal and receptor to receptor (Smith and Huyck, 1999; Kelly, 1999). Toxicity and exposure criteria are set relative to the health of humans and wildlife (Nevada Division of Environmental Protection, 2002). Human health tends to be more sensitive to some metals than wildlife; hence, drinking-water standards are quite low for As (50 ppb), Pb (50 ppb), and Tl (13 ppb). Aquatic wildlife is more sensitive than humans to other metals, including Cd (about 5 ppb), Cu (about 10 ppb), Hg (0.01 ppb), Mo (19 ppb), Se (5 ppb), and Zn (about 50 ppb).

The biology and chemistry of toxic metals are complex topics (Smith and Huyck, 1999; Kelly, 1999) that are beyond the scope of this report. In this report, a simplistic criterion of ALWS (table 6) has been used as an approximate framework for rating the degree of water contamination—with the assumption of long-term (chronic) exposure. However, one

**Photograph 98.** This pond on the Castleton mill tailings collects runoff and seepage from sulfidic tailings with pH 2 and extreme metal concentrations. Cycles of rain and evaporation enhance the concentrations.

unusual situation involving possible acute exposure for wildlife needs to be described. Some ephemeral ponds of water located on mine dumps and tailings impoundments are even more metal-rich than mine-drainage water, attaining extreme compositions by collection and evaporation of runoff water (photo 98). These waters can contain more than 10,000 ppb of several metals, including Cu and Zn, and also are rich in other elements including As, Cd, Hg, Se, and U. Compared to commonly applied water-quality standards, values for these metals are 200 to more than 75,000 times higher than the regulatory standard. These ephemeral ponds are not typical of mine-related water but are mentioned as a special concern because of possible acute toxicity in short-term exposure. Further evaluation of these ephemeral water bodies by wildlife biologists and reclamation specialists could be valuable.

### Relation to Ore Type

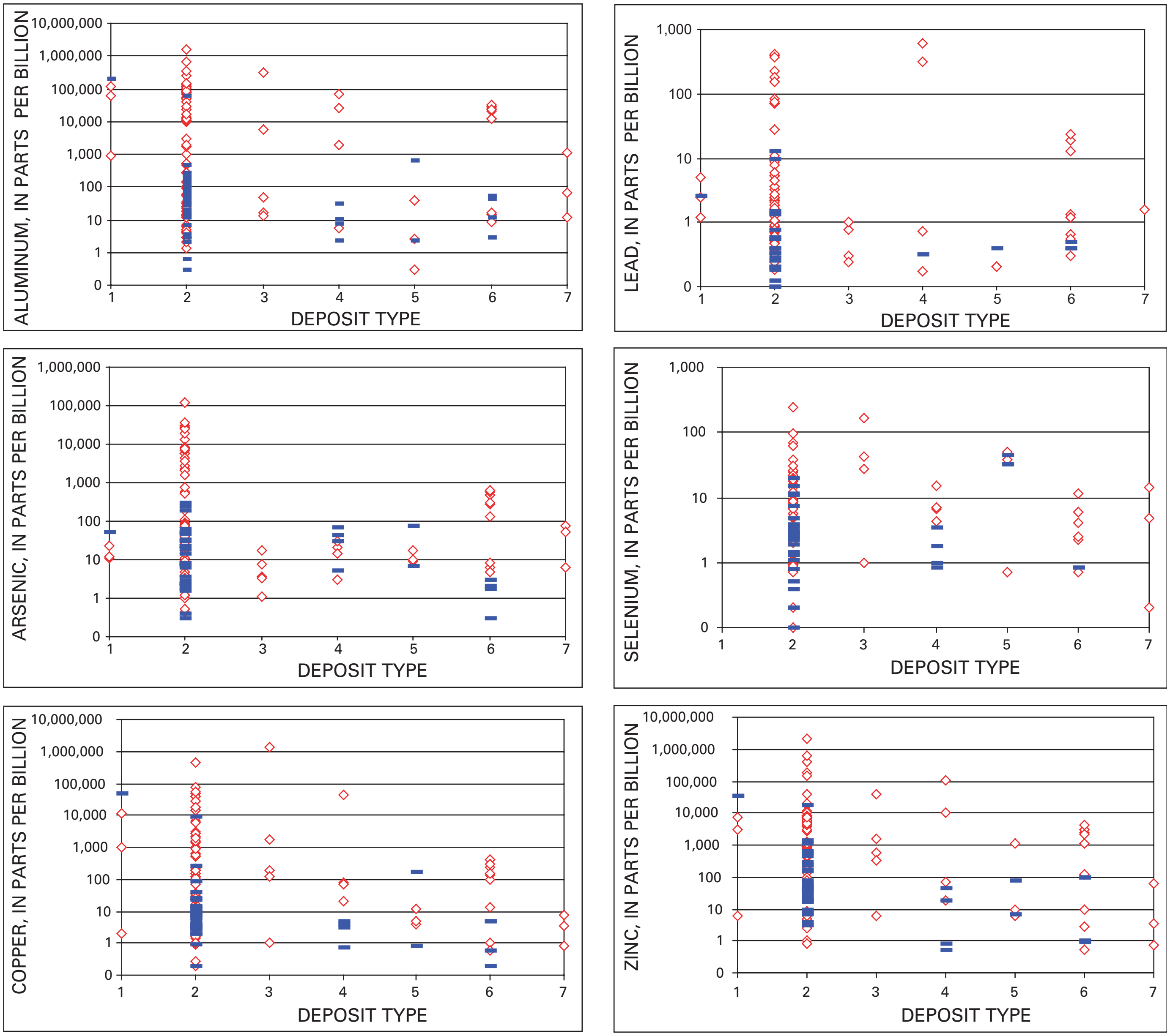
The mineralogy and chemical composition of metallic ore deposits and their host rocks would logically determine the composition of mine water from those deposits (Plumlee and others, 1999; duBray, 1995), but in my experience the wide range in water compositions from a deposit type blurs the distinctions between deposit types (Nash, 2001; Nash, 2002a). Compositions of mine water from northern Nevada plotted by deposit type (fig. 12; figs. 38, 39) are not as distinctive as postulated by others. Some trace metals of concern, such as Se and U, can be elevated in acidic mine water even from deposits that are not normally considered to be enriched in those elements. Acidic mine water is capable of mobilizing a wide array of elements, including some such as Al and Ti that are often considered “immobile” by geochemists.

Anions were determined in less than 50 percent of the water samples collected in this study and are not as diagnostic of contamination as metal analyses. Anion concentrations are shown in figure 39 as a function of deposit types. Variations in Cl and F do not appear to relate to sample type or deposit type, although more definitive studies by Tuttle and others (2003) show significant enrichment in F in some porphyry systems. Chlorine appears to be enriched chiefly in evaporative settings and is enriched in some small ponds and heap-leach water. Sulfate concentrations span a substantial range and commonly are higher in mine water than in springwater and surface water distant from mines. Subtle differences in background surface water from altered unmined rocks, relative to unmined rocks with no prospects or alteration, discussed previously, include higher sulfate concentrations.

The most effective predictor of metal mobilities in mining-affected water is acidity. The converse is that neutralization is the most effective process to mitigate metal-rich mine drainages. In many settings in Nevada, host-rock lithologies provide sufficient acid-neutralizing capacity to dominate acid production, producing neutral to alkaline waters that are capable of transporting only low concentrations of most metals (but locally high concentrations of a distinct suite of elements that includes As, Cd, Mo, Se, U, Zn, and occasionally Cu). Sedimentary rocks, especially calcareous shales and limestones, commonly provide the required neutralizing capacity, and in other terranes caliche in alluvium is effective.

## Evolution of Surface Water Within Mining Areas

The composition of mine-drainage water changes downstream from the sources in response to several processes that generally improve water quality. The one exception is the case of mine water reacting with mine dumps, which generally results in added acidity and metals, but this case really is included under mine drainage. In Nevada, attenuation of



**EXPLANATION**

▬ Mixed water—sampled in stream below mines or mill tailings

◇ Mine water—sampled at adit or mine dump

DEPOSIT TYPES

1, acid-sulfate

2, polymetallic vein

3, massive sulfide

4, skarn

5, sediment-hosted gold

6, epithermal vein

7, mercury

**Figure 38.** Relations of metal concentrations in mine drainage to deposit types.

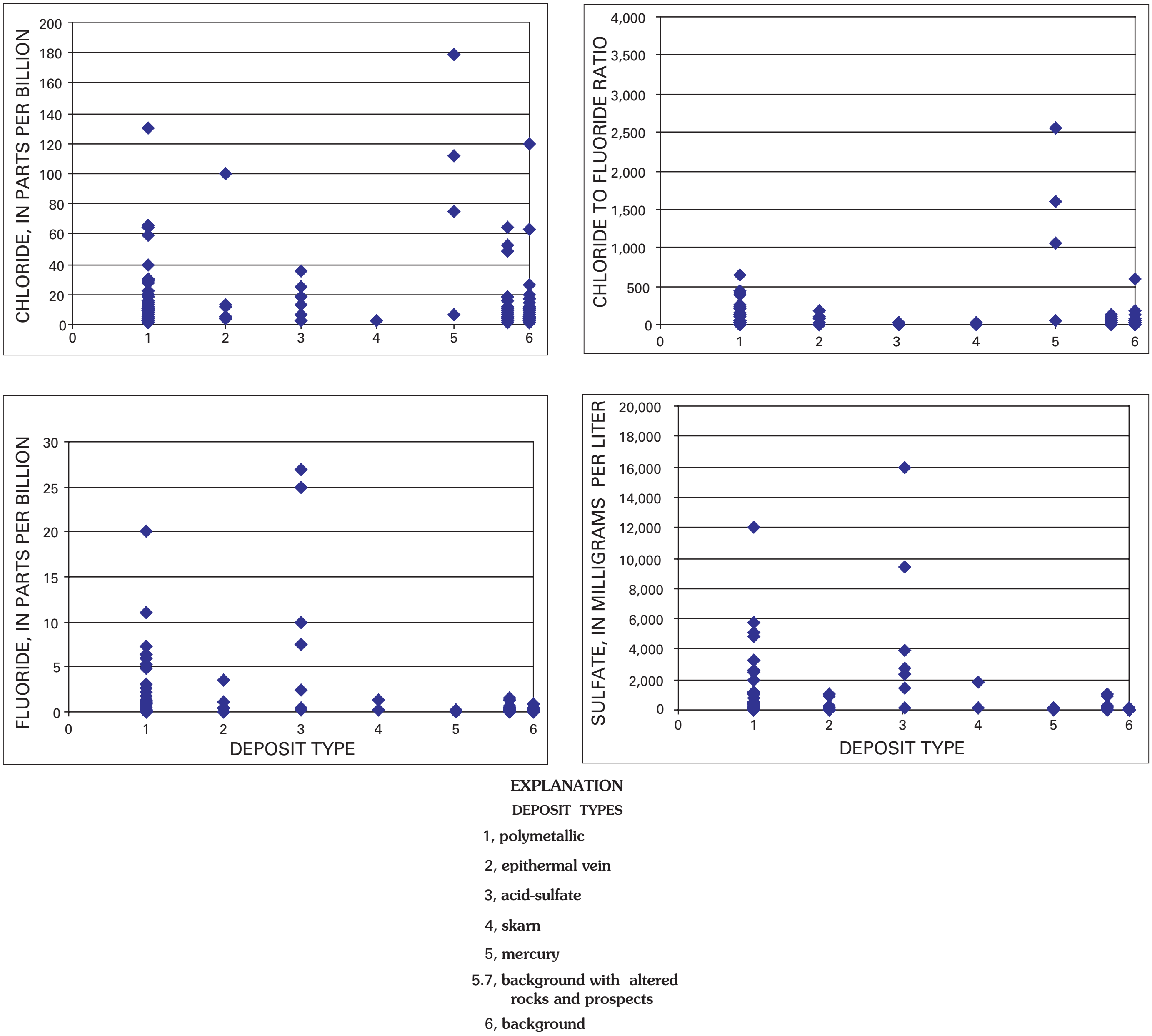


**Figure 39.** Anion chemistry of surface water in relation to deposit types.

metals can be observed up to the point at which water infiltrates alluvium and cannot be sampled. Reactions continue in shallow ground water but are not considered here because wells generally are not available for sampling. In most situations water compositions change over a distance of 100 or more yards downstream from a mine source; these waters are here termed "mixed" if there is evidence for addition of other surface water or springwater and reactions, all of which raise the pH and lower the conductivity (or dissolved solids). The mixed waters have pH values in the range of 3 to 8. These mixed waters are of interest for both their geochemistry and their implications for beneficial use—because they are much larger in volume than the mine-source water and have a more direct effect on wildlife habitat.

Improvements in water quality by natural processes involve reactions of several kinds that raise pH and decrease metal concentrations. Several processes can be involved: (1) oxidation and formation of Fe- and Mn-oxyhydroxide phases; (2) ion exchange, as on clays or organic materials; (3) adsorption, especially on fine-grained or amorphous Fe- and Mn-phases; (4) flocculation of colloids and sedimentation of particles; (5) sulfate reduction, generally mediated by bacteria; and (6) uptake by plants. In the study area, processes 1 and 3 seem to be most important, whereas 5 and 6 are rare.

**Table 9.** Composition of streams leaving six mining areas in northern Nevada.

[Analytical results are from ICP-MS analyses, in parts per billion (ppb); Cond., conductivity, in microsiemens per centimeter, (µS/cm); distance is measured to the major source inflow]

| Site | Number of samples | Distance (feet) | pH | Cond. (µS/cm) | Al (ppb) | As (ppb) | Cd (ppb) | Cu (ppb) | Fe (ppb) | Zn (ppb) |
|---|---|---|---|---|---|---|---|---|---|---|
| Pittsburg Creek | avg 2 | 6,700 | 7.6 | 440 | 66 | 3.0 | 2.9 | 2.9 | 355 | 48 |
| Hilltop Creek | avg 2 | 2,300 | 7.5 | 500 | 108 | 35 | 1.6 | 9.1 | 222 | 19 |
| Rock Creek | 1 | 7,800 | 7.6 | 290 | 32 | 7.8 | 0.2 | 2.0 | 49 | 8.0 |
| Galena Creek | 1 | 5,900 | 6.9 | 810 | 102 | 6.2 | 63 | 91 | 1,310 | 1,085 |
| Charleston Creek | 1 | 2,500 | 6.0 | 200 | 51 | 2.0 | 0.3 | 5.0 | 110 | 100 |
| Coon Creek | avg 3 | 4,000 | 8.1 | 420 | 36 | 24 | 3.7 | 13 | 320 | 265 |

Hydrous iron oxide phases of red, orange, and yellow hues and various compositions are typically involved and important for the removal of metals such as Cu, Pb, and As, consistent with the theory and observations of Smith (1999). The fact that Nevada acidic mine water starts with high iron concentrations makes these reactions possible. These adsorption reactions in nature, over the pH range of about 3 to 7, are the basis for the concept of "self-mitigating capacity" (Smith, 1999). Mixing and precipitation are evident in several of the larger mine drainages in the study area where several kinds of surface water and springwater mix with mine water over distances of hundreds of yards. The naturally mitigated compositions of streams leaving six mining areas are summarized in table 9. The natural attenuation and improvement of water quality in these waters are discussed next.

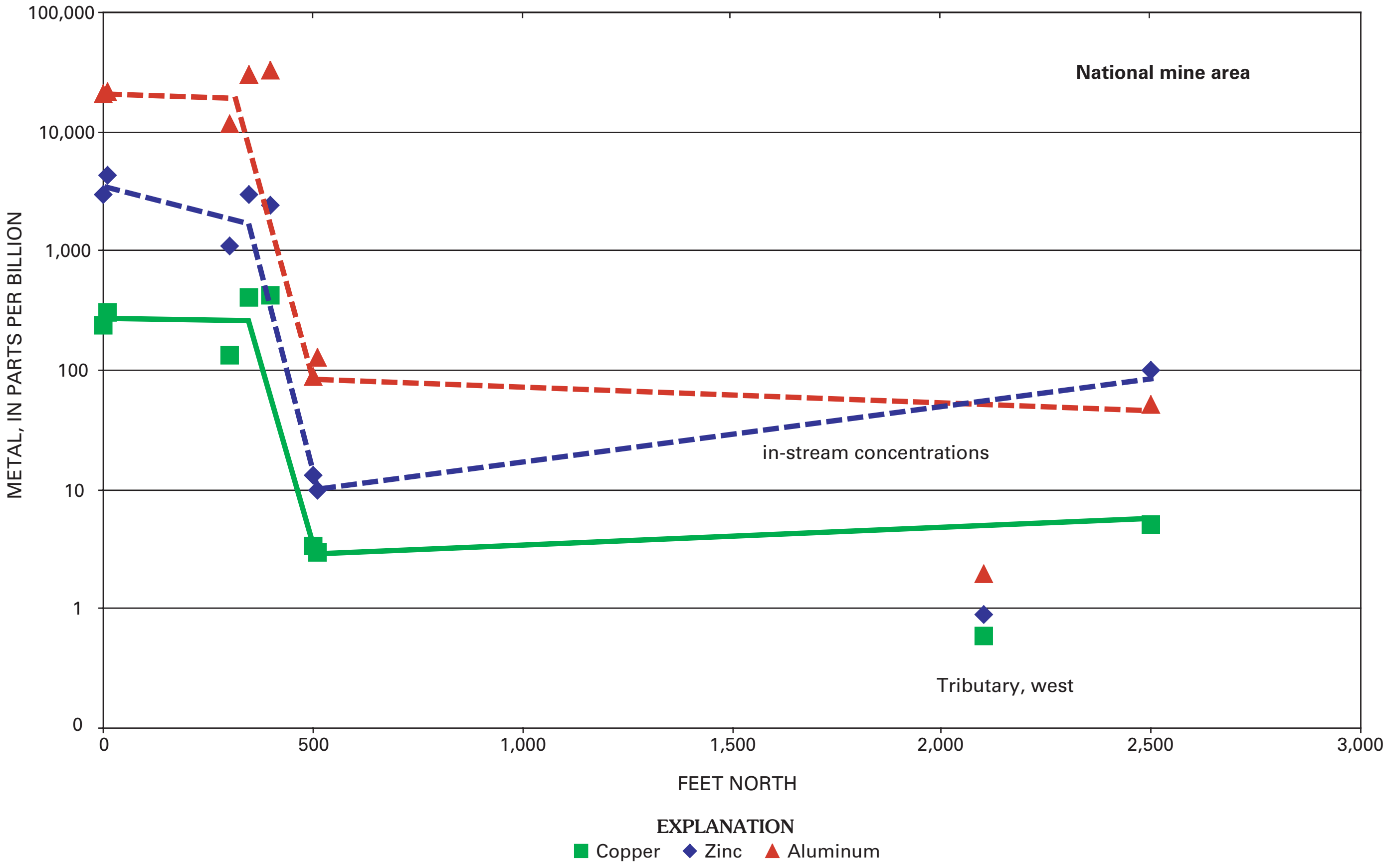


**Figure 40.** Evolution of mine drainage in the National mine area. Lines connect in-stream values.

**Photograph 99.** The collapsed tunnel of the National mine is not very impressive, but the acidic water is among the most acidic and metal-rich of the historical mines in northern Nevada. The flow of about 10–20 gallons per minute is low compared to some abandoned mines elsewhere in the Western United States, but the metal loads are high.

**Photograph 100.** Acidic drainage from the National mine (right center) evolves as it mixes with streams and ground waters in this headwater basin of Charleston Gulch. Streams flowing in tributary basins, to the right and left, are alkaline, and when they mix with the mine drainage the pH rises to above 6 within 3,000 feet of the tunnel.

### National Mine Area

A good example of natural attenuation is the case of the National mine complex and evolving water compositions in Charleston Gulch, shown graphically in figure 40. The collapsed mine adit releases a moderate flow (10–20 gpm) of pH 2.8–3.1 water (photo 99) that interacts with mine waste for about 400 ft (photo 100), at which point the main flow of mine water joins a stream from the southwest (a basin with small prospects). The mixed waters flow over the remains of a tailings pond and through several breached catchment ponds. Small streams from the east and west join the stream about 1,800 to 2,100 ft north of the adit. Probing of water in the area of the dump, stream inflow, and tailings (400 to 800 ft north, fig. 40) showed large local changes in conductivity and somewhat smaller variation in pH readings, both of which are considered to indicate mixing of several kinds of surface and shallow ground water. The chemical analyses (fig. 40) show that concentrations of Cu, Zn, and Al increase during reaction of the acid-mine drainage and the mine waste. North of the mill tailings pH values rise from less than 3 to 4.3, and conductivity values decrease, possibly from diffuse inflows (springs); relatively small amounts of hydrous iron oxides precipitate in this reach. The stream does not change much in

**Photograph 101.** This small creek in the center of the Hilltop district receives drainage from a mine tunnel and flows over mill tailings placed in the creek in the 1920's. The acidic waters are naturally attenuated when they mix with the higher flow from the East Fork of Rock Creek.

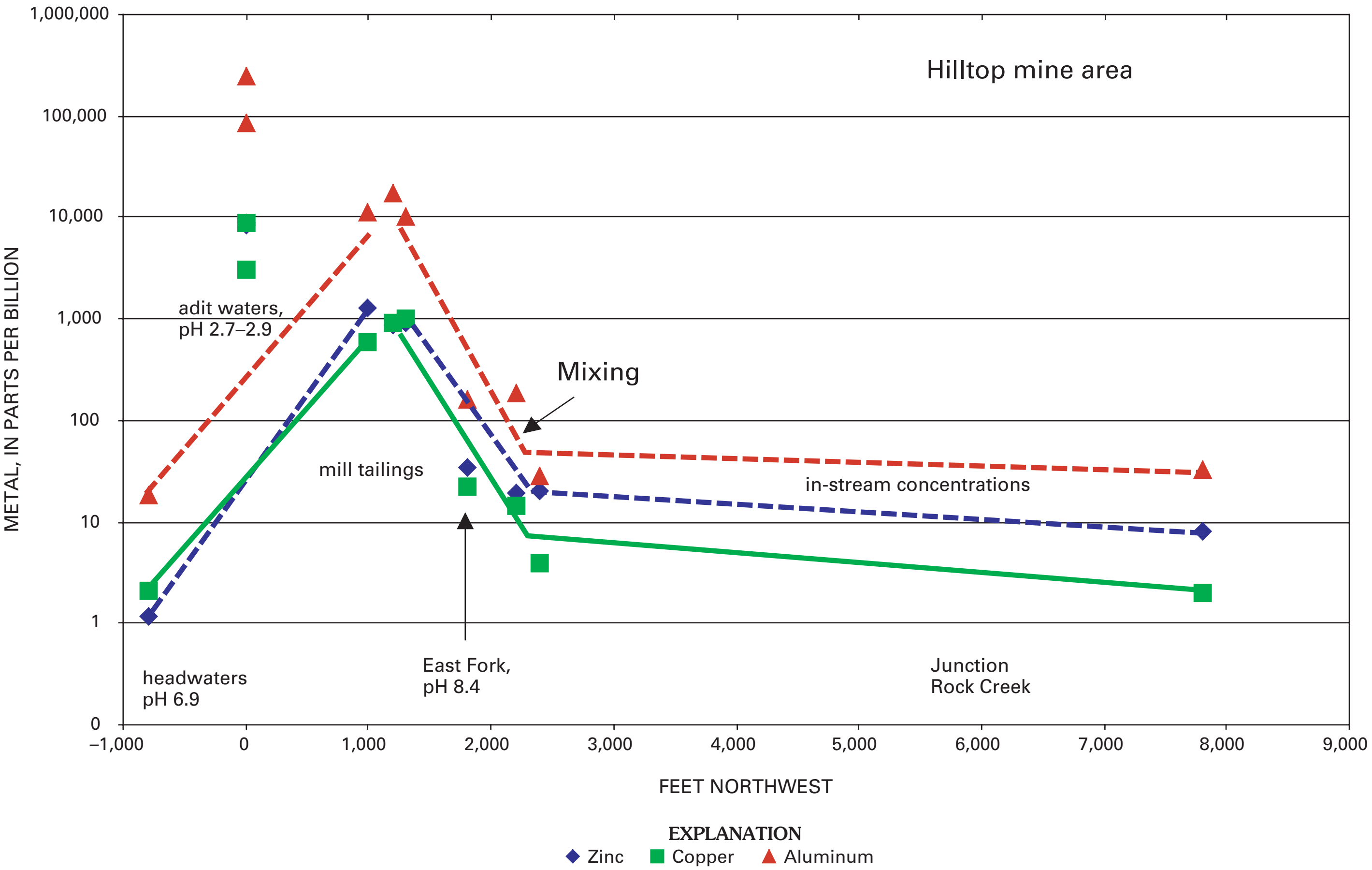


**Figure 41.** Evolution of mine drainage in the Hilltop mining area. Lines connect in-stream values. Some sites have two values, reflecting different sampling events.

appearance or pH values until two tributaries join, each larger than the stem from the mine, and quadruple the volume of the stream. The mixing raises the pH to 6.0 and the conductivity decreases by more than 60 percent. Metal concentrations are greatly reduced after these mixing reactions: Zn is down to 100 ppb and Cu is down to 5 ppb. The quality of the evolved water about one-half mile north of the adit has improved to approximately the aquatic-life standard.

### Hilltop Mine Area

Another example, from the central Hilltop district, involves acidic mine drainage from a mine adit that flows over mill tailings in Hilltop Creek (photo 101; fig. 41). The adit (in siliceous rocks with low neutralizing capacity) yields about 10 gpm of pH 2.7–2.9 water. The mine drainage flows into the creek, which then flows over eroded mill tailings for about 500 ft. About 1,800 ft north of the adit, Hilltop Creek joins the East Fork, a larger stream from a basin with only a few small mine prospects. The East Fork joins the West Fork about 6,000 ft north-northwest of the adit to become Rock Creek.

Metal concentrations vary greatly along the stream (fig. 41). The spring-fed headwaters in altered sedimentary rocks initially have low metal concentrations. Metal concentrations increase in Hilltop Creek from the adit inflow, but it is not clear if metals are released from the tailings. Relatively small amounts of iron oxides coat the stream channel, which could be explained by several kinds of mixing reactions, including seeps from the tailings. There is relatively little precipitation of iron oxides from these mixed waters compared to the examples described next. Hilltop Creek joins the larger East Fork, and for several hundred feet there are thin white films on the streambed, probably an Al-oxyhydroxide mineral. The pH rises from 4.2 to 7.1–7.8, and samples collected a few hundred feet north of the junction have much lower metal concentrations (better than quality standards for aquatic life).

### Dean Mine Area

Tunnels created during mining of sulfide-rich veins in the western part of the Hilltop district nearly 100 years ago were reopened for exploration in 1988–94. These mine workings, about 2 mi west of the Hilltop mine, created very acidic, metal-rich drainage (fig. 42) for about 6 years until the tunnels and mine dumps were reclaimed in 1998. The abandoned Dean adits created flows and pools of pH 2 to 3 water (photo 102) where the workings were in siliceous rocks, but a similar tunnel exploring the same vein system in limestone released pH 7 to 7.5 water. The pH values reported here varied by a

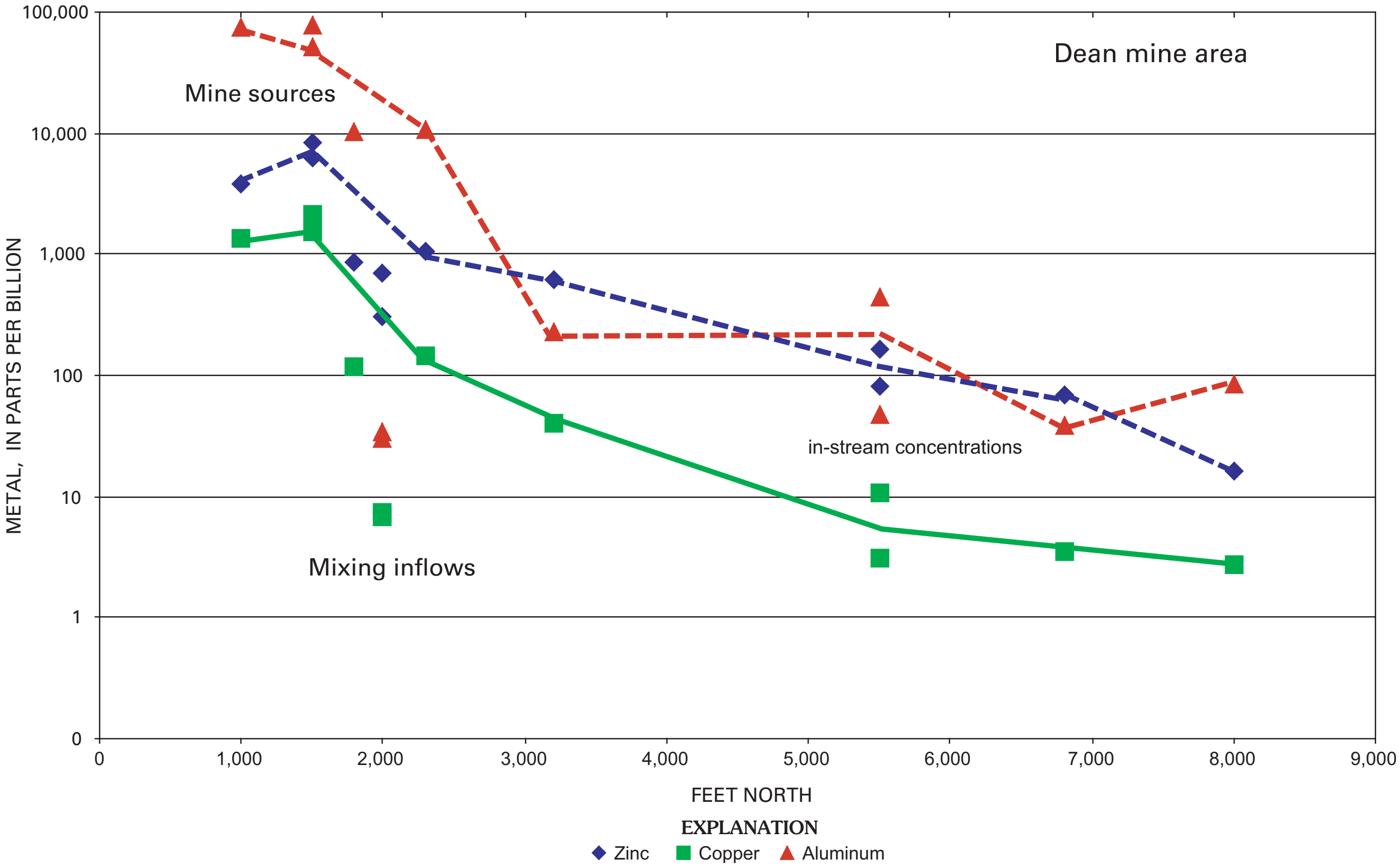


**Figure 42.** Evolution of mine drainage in the Dean mining area. Lines connect in-stream values. Some sites have two values, reflecting different sampling events.

**Photograph 102.** Mine drainage from several tunnels like this at the Dean mine contribute acid and metals to the headwaters of a small creek. The siliceous wall rocks offer no neutralization capacity for the waters with pH values of less than 3.

**Photograph 103.** Contaminated waters from the Dean mine complex mix with surface and ground water in this headwater basin. North of the gray dump (upper center) limestones and ground water from limestones raise the pH from 3–3.5 to 6.5, as described in the text.

few tenths of a standard pH unit in measurements during May or June of 1996, 1997, and 1998 (prior to reclamation). The mine drainage from several upper adits flowed less than 100 ft to the headwaters of Pittsburg Creek, and for about 2,000 ft the water precipitated large amounts of ocher iron-oxyhydroxide on the streambed. The mixing zone, from about 2,000 to 3,500 ft (photo 103; fig. 42) involved a combination of limestone strata and numerous spring inflows having conductivity values that varied by more than 100 percent at sites a few feet apart. Mixing of pH 3–4 stream water with pH 8.2 springwater caused immediate flocculation of iron and reduction of metal concentrations by more than an order of magnitude. Mixing in the vicinity of the lower adit flow and limestone-rich waste dump was equally complex: the mine drainage added meals, but it also added alkalinity and raised the pH. Reactions continued down the canyon, and at 7,000 ft (fig. 42) the metal concentrations were within aquatic-life standards. Mixing of Pittsburg Creek with the West Fork of Rock Creek further decreased metal concentrations. Two relatively large mill tailings piles (5,800 to 7,200 ft, fig. 42) produced no measurable inputs to Pittsburg and Rock Creeks, but sampling ground water (which would require wells) might yield different results. This small basin demonstrates the “self-mitigating” effects of high-iron water described by others (Drever, 1997; Langmuir, 1997; Smith, 1999). Brief study and sampling in June of 1999, after the mine adits were plugged and mine dumps were reclaimed by NDEP and BLM in 1998, suggested greatly improved water quality (described later).

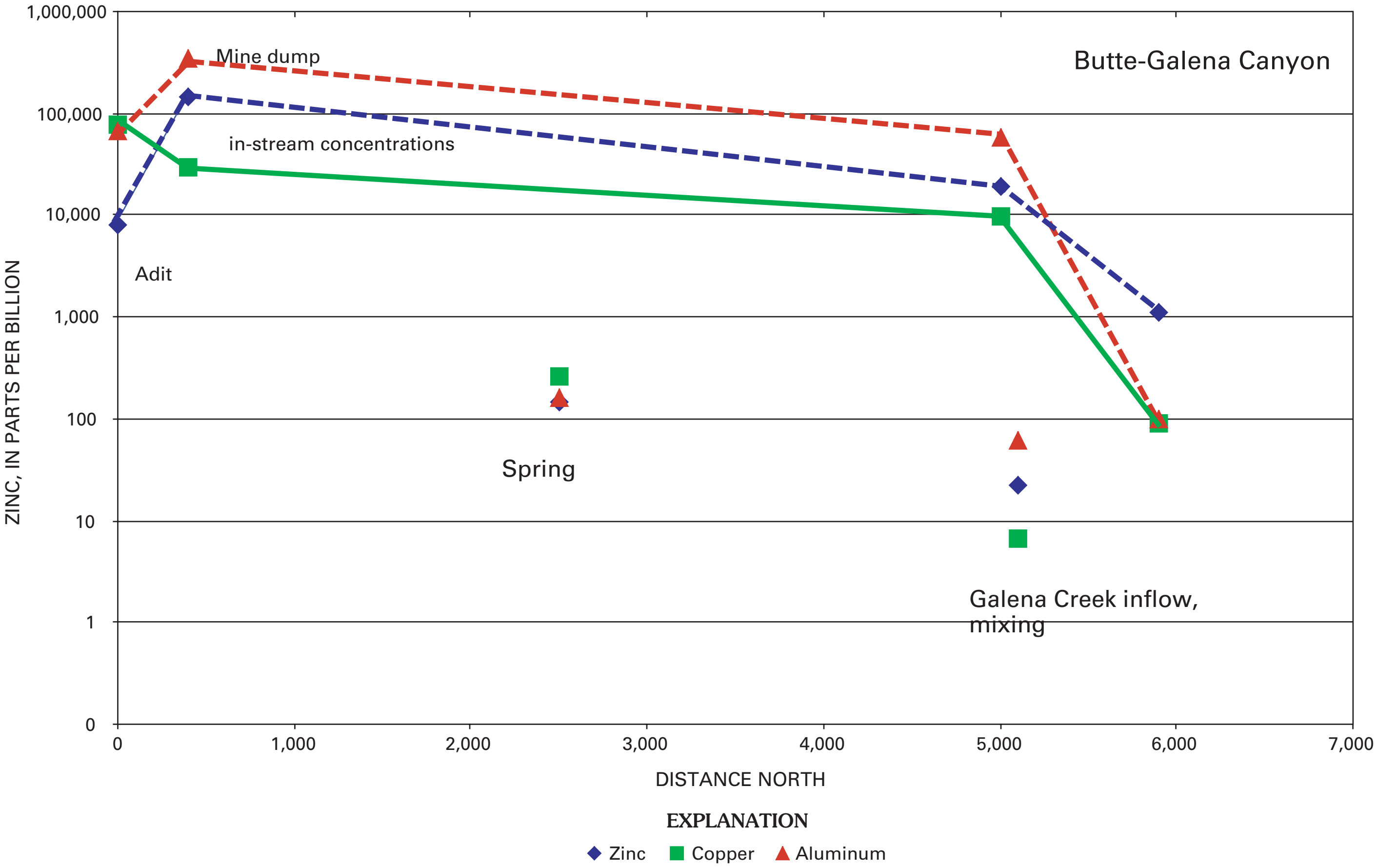


**Figure 43.** Evolution of mine drainage in the Galena mining area. Lines connect in-stream values.

**Photograph 104.** The acidic, metal-rich floodwaters of May 1998 deposited iron on the bed of Iron Canyon Creek as they were neutralized by natural processes. These ocher crusts on the channel were visible in June 1999. Although not identified by X-ray diffraction, these materials have the appearance and the reactivity in leach tests of schwertmannite.

**Photograph 105.** Acidic mine water from polymetallic vein deposits in Butte Canyon reacts with dumps to attain very high metal concentrations. The flow seen here (orange, center) was strong in June of 1998 and extended all the way to Galena Canyon Creek, where mixing reactions neutralized the pH.

**Photograph 106.** Unusually wet weather in May of 1997 and 1998 caused water from old mines and springs to flow into Butte and Iron Canyons, which normally are dry. Acidic surface waters (pH 3.3) mixed with alkaline surface waters (pH 8.2, right side), and were neutralized. The mixing process caused Fe-rich phases to precipitate (milky part of stream), and base metal concentrations decreased to 10 percent of the values prior to neutralization.

## Galena Canyon Area

A fourth example comes from a complex watershed on the northeast side of the Battle Mountain district in the area of Butte, Galena, and Iron Canyons (figs. 18, 20). High precipitation in the spring seasons of 1997 and 1998 created substantial flow from some historical mine adits and springs in this area of polymetallic deposits in sedimentary rocks (siltite and chert). The springs in this area are notable for their high conductivity, high sulfate content, and pH values from 3 to 4. Mixing of several kinds of surface water and springwater produced copious amounts of ocher iron-oxyhydroxide (photo 104) that resembled schwertmannite (Fe-hydroxy-sulfate; Desborough and others, 2000), which forms below pH 3.5. A traverse, shown schematically in figure 43, starts with extremely acid, metal-rich mine drainage that flows over a large sulfidic dump (photo 105) and mixes with surface water and spring water over a distance of about 4,000 ft. Mixing in this zone caused iron-oxyhydroxide deposition, but the pH stayed between 3.2 and 3.4, probably reflecting acid released during hydrolysis of iron. Another factor in this reach was a strong layer of ferricrete-cemented alluvium in the bed. At the 5,000-ft mark (fig. 43) this small flow (20–40 gpm) joined the much larger (400–700 gpm during flood stage) Galena Canyon Creek, resulting in a pH rise to 6.8. This mixing zone of milky and rusty water (photo 106) extended for several hundred feet.

**Photograph 107.** A series of mill tailings impoundments in the channel of Coon Creek, west of the Rip Van Winkle mine, is a potential source of acid and metals. Most water samples in this reach show surprisingly small amounts of contamination.

**Photograph 108.** The white and gray mineral crusts on the surface of the Rip Van Winkle dissolve in rainstorms, and the red-brown materials on the streambed reflect acidic seeps.

The evolved water had much lower metal concentrations, less than 1 percent compared to the source, but was still high in Al, Cd, Cu, Fe and Zn (table 9). The outflow of metals and acid in June of 1998 appears to have overwhelmed the capacity of the area to accomplish natural attenuation. During this unusual spring flood of 1998, similar acidic water from historical mine adits and springs were treated by Battle Mountain Gold using a temporary water-treatment plant in adjacent Iron Canyon. During normal spring runoff, the springs and adit discharges in these canyons flow on the surface for only a few hundred feet.

## Coon Creek—An Unusual Example

Coon Creek, flowing west from the Rip Van Winkle mine (photo 107), is an example of how physical conditions control the chemistry of mine water. The lower tunnel is dry, and no

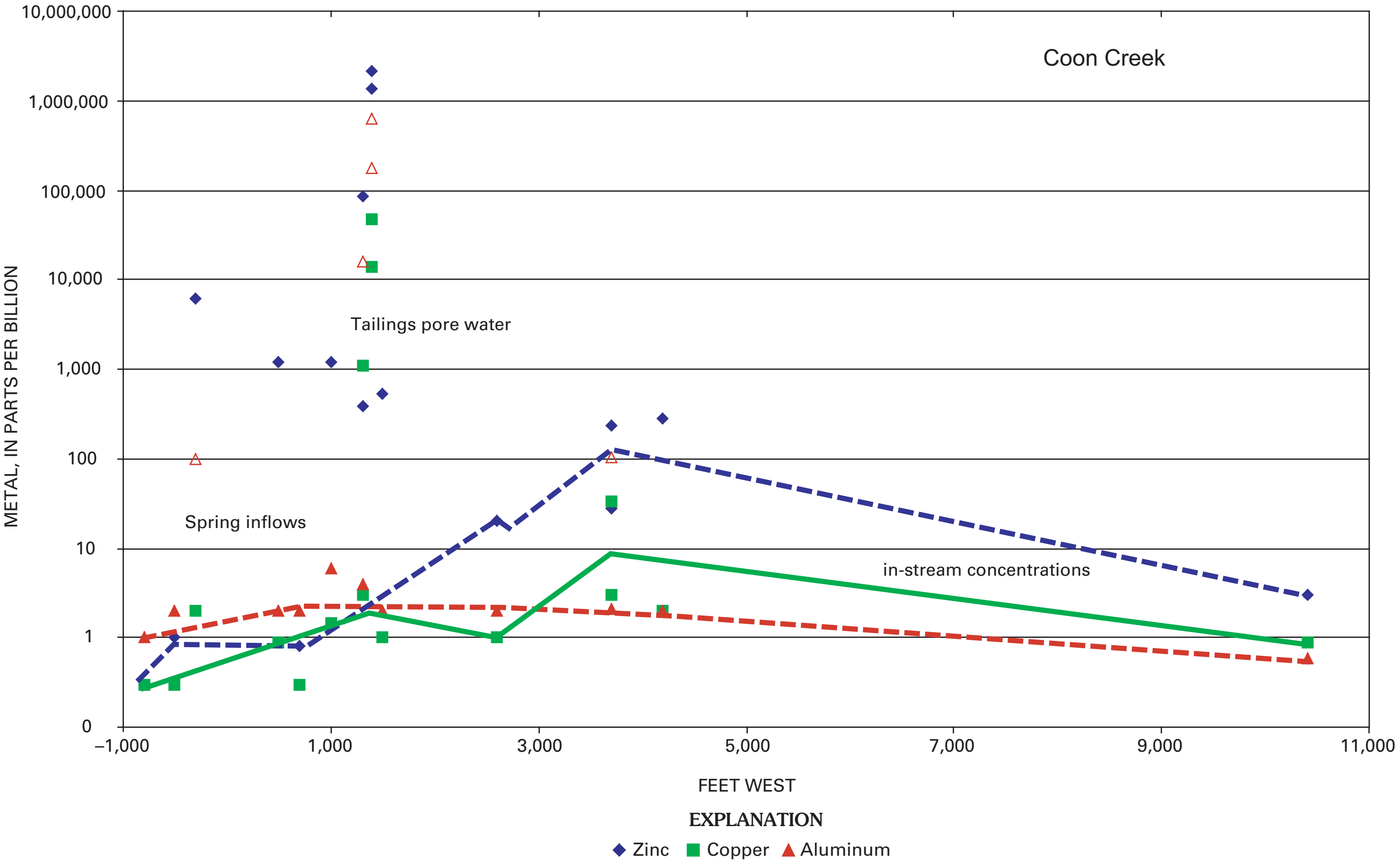


**Figure 44.** Evolution of mine drainage in the Coon Creek, Rip Van Winkle mine area. Lines connect in-stream values. Some sites have two values, reflecting different sampling events.

seeps come from the waste dumps. The concern here is for stream water flowing over and through mill tailings (photo 108). Geochemical results are summarized in figure 44. Four visits to this area provided results that seem paradoxical on first examination. Measurements of pH of stream water in contact with tailings showed values to be consistently in the range of 6.8 to 7.4, rising to about 8.4 west of the tailings. Laboratory leach tests (Nash, 2001) confirmed the expectation that the sulfidic tailings should create acidic, metal-rich water, but no such surface water was detected. Closer inspection on the third visit disclosed thin films of red iron-oxide precipitate along the edge of the creek next to the tailings, and depressions made by cattle hooves contained small pools of reddish water—which proved to have pH values of 1.7 to 2.1 and very high conductivity (2,000–4,000 $\mu$S/cm). Not surprisingly, chemical analyses of the acidic seeps showed extremely high metal concentrations, especially for Cu and Zn, which were more than 40,000 and 1 million ppb, respectively. Cadmium mimics Zn, reaching more than 8,000 ppb in tailings seeps. Repeated sampling of Coon Creek shows that relatively small concentrations of metals actually enter the stream (about 200–400 ppb Zn) despite the evidence in leach tests and in the seep water for thousands of parts per billion of Zn and other metals. The discrepancy appears to be explained by high clay content in the tailings that gives them very low permeability: only small amounts of water can infiltrate, react, and exit these tailings. The conclusions for this mining area: (1) despite moderate precipitation (about 15 in/year), little water from waste dumps and mine workings enters the nearby creek; and (2) although mill tailings are in contact with stream water, the potential for acid generation and metal release are limited by low permeability. Poor mining practices and potentially reactive waste materials at this mine ultimately produce only slightly degraded water. Natural attenuation further minimizes metal concentrations within about one-half mile of the last tailings impoundment.

## Quality of Streams Leaving Mining Areas

The quality of surface water flowing a mile or more from mining areas may be of greater significance than that present locally at mine adits or near mine waste because such water is used by wildlife, by ranches or farms, and by humans. However, few streams actually flow out of the historical mining districts in northern Nevada. The summary of surface water leaving 50 mining areas (table 10) shows that 19 mining areas have no streams flowing near the mines, or the streams

**Table 10.** Water quantity and quality for streams in mining areas, northern Nevada.

[Stream: Y, a stream is in vicinity of mines; N, no stream involved. Size: 0, arroyo that rarely flows; 1, very small, flows in wet season; 2, small, intermittent; 3, medium; 4, medium-large; 5 large (Humboldt River). Chemistry: results are from ICP-MS analyses of one to three samples, in parts per billion]

| Mining area | Stream | Size | As (ppb) | Cd (ppb) | Cu (ppb) | Zn (ppb) | Comment |
|---|---|---|---|---|---|---|---|
| Adelaide | Y | 3 | 29 | 0.1 | 0.8 | 0.5 | Gold Run Creek |
| Antelope Springs | N | 0 | | | | | |
| Austin | | | | | | | |
| Austin | N | 1 | | | | | Not typical of mining |
| Quito | Y | 2 | 3.9 | 0.1 | 2.0 | 13 | Birch Creek |
| Awakening | N | 0 | | | | | |
| Battle Mountain | | | | | | | |
| Iron Canyon | Y | 1 | | | | | Not properly sampled |
| Galena Canyon | Y | 1 | 5.6 | 0.8 | 6.6 | 22 | One atypical(?) sample |
| Long Canyon | Y | 1 | 37 | 0.7 | 5.2 | 30 | |
| Black Diablo | N | 0 | | | | | |
| Bottle Creek | Y | 1 | | | | | Not Bottle Creek |
| Buena Vista (Unionville) | Y | 1 | | | | | Not sampled |
| Buffalo Valley | N | 0 | | | | | |
| Burner | N | 0 | | | | | |
| Cortez | N | 0 | | | | | |
| Golconda | N | 0 | | | | | |
| Gold Circle | Y | 1 | | | | | Not sampled |
| Hilltop | Y | 3 | 7.6 | 0.1 | 1.0 | 22 | |
| Imlay | | | | | | | |
| Standard mine | N | 0 | | | | | |
| Iron Point | N | 0 | | | | | |
| Ivanhoe | N | 0 | | | | | |
| Lewis | Y | 3 | | | | | Not sampled |
| Majuba | Y | 3 | 22 | 0.5 | 3.6 | 43 | |
| Merrimac | Y | 2 | 31 | 1.2 | 1.7 | 83 | Coon Creek |
| Mill City | N | 0 | | | | | |
| Modarelli | N | 0 | | | | | |
| Mt. Hope | N | 0 | | | | | |
| National | | | | | | | |
| Charleston | Y | 3 | 2.0 | 0.3 | 5.0 | 100 | North of National mine |
| N. Fk. Little Humboldt | Y | 3 | | | | | Not sampled |
| North Battle Mountain | N | 0 | | | | | |
| Potosi | Y | 2 | | | | | Not sampled |
| Railroad | Y | 2 | | | | | East of mining |
| Rochester | Y | 3 | 19 | 0.7 | 9.6 | 17 | Lower Rochester Creek |
| Safford | Y | 3 | 5.0 | 0.1 | 0.6 | 2.9 | Safford Creek |
| Scraper Springs | N | 0 | | | | | |
| Seven Troughs | Y | 2 | 8.2 | 0.1 | 14 | 0.5 | Seven Troughs Creek |
| Star | Y | 3 | 31 | 0.1 | 13 | 17 | Star Creek |
| Swales Mountain | N | 0 | | | | | |
| Tenabo | Y | 3 | | | | | Indian Creek; not typical |
| Tenmile | N | 0 | | | | | |
| Tuscarora | Y | 1 | 4.8 | 0.1 | 0.9 | 21 | |
| Willard | N | 0 | | | | | |

flow only on rare occasions (that is, they were not flowing during the wet years of 1997 and 1998). Eight (20 percent) of the mining areas have ephemeral streams that flow after storms and five (12 percent) have intermittent streams that flow for several weeks of the wet season. Ten mining areas (25 percent) are drained by substantial streams that may flow most of the year, but the largest of these is less than 10 ft wide. Only one of the streams flows into a tributary of the Humboldt River: the North Fork of the Little Humboldt River (east of the Buckskin National mine). Several of the larger streams flow into internal drainages (such as Star Canyon Creek, outside of the Humboldt River watershed), and most flow out of canyons and infiltrate thick, caliche-bearing alluvial deposits at the range front (such as Galena and Iron Canyon Creeks).

Water was sampled from 13 streams downstream from where these streams interacted with mines, mine waste, or mill tailings to determine the amount of metal contamination leaving the mining area. Several streams flowing from areas of mining were not sampled because they did not interact with significant mines or mined materials. Analytical results are summarized for four of the most significant, potentially toxic metals (As, Cd, Cu, and Zn) in table 10. The sampling sites were as far from the mining areas as possible (close to the point of disappearance into alluvium) or about 1 to 2 mi downstream from mining. The metal concentrations are quite low at these sites, and all appear to be close to or lower than the concentration values stipulated for likely beneficial uses, chiefly aquatic life (table 6). Concentrations of As are high at six sites, but the measured values of 19 to 37 ppb are below the most demanding criterion, that for domestic drinking water. Zinc is elevated at several sites, but the highest values (in the range of 43 to 100 ppb) are close to the aquatic-life water quality standard. Copper is elevated at six or more sites, and these values may be high enough to have adverse effects on aquatic life. Some of these borderline compositions are discussed next for streams that have class designations.

**Photograph 109.** Seeps of acidic water from the Black Beauty mine dumps create these brown precipitates when they mix with alkaline stream waters. The high flow in this tributary of Gance Creek dilutes and attenuates the contamination.

## Mine-Related Contaminants in Nevada Class A Waters

The waters of Nevada are classified in a system of classes, A to D, based on the amount of human or industrial activity and also beneficial uses (Nevada Division of Environmental Protection, 2002). Some streams in or near mining areas have been designated as Class A water, the most pristine in the State and therefore having the most stringent quality standards. The NDEP quality standards for Class A water use phrases such as “None attributable to man’s activities” and “None” for toxic materials (Nevada Division of Environmental Protection, 2002). The chemical criteria for water quality are related to beneficial uses such as municipal or domestic water supply and aquatic life, and to the tabulated criteria (Nevada Division of Environmental Protection, 2002, code 445A.119 and elsewhere). They are generally based on the same scientific and technical information used by both the USEPA and State agencies. Where there are multiple beneficial uses, the most stringent criterion is used; for instance, the Cu criterion for aquatic life and the As criterion for drinking water (table 6). Many pages of Class A water are listed and are a bit confusing because of the “tributary rule”—rules for a stream apply to headwater tributaries.

Parts of eight historical mining districts studied here are in headwaters designated Class A water: (1) Star Creek, Pershing County; (2) Bottle Creek, Humboldt County; (3) Lewis Canyon Creek, Lander County; (4) Birch Creek, Lander County; (5) Quinn River, Humboldt County; (6) North Fork Little Humboldt River, Humboldt County; (7) Maggie Creek, Elko County; and (8) North Fork Humboldt River, Elko County. These streams are shown in figure 15. The Cu concentration in Star Creek and the Zn concentration in Coon Creek (tributary to Maggie Creek) appear to exceed the stringent standards in those Class A waters. Birch Creek near the Quito mine may be slightly contaminated by seeps from mine waste, but the main stem of Birch Creek seems to have good water quality. Bottle Creek in the Jackson Mountains does not appear to be influenced by the Bottle Creek mercury district, which is in a basin to the northeast. The contaminants from the National mine, described herein, influence Charleston Gulch, a tributary of the Quinn River that is designated a Class A water. Gance Creek, a tributary of the North Fork of the Humboldt River in the Independence Range, flows through the Black Beauty mine (LaPointe and others, 1991). Seeps from the mine-waste dumps contaminate Gance Creek (photo 109), but the inflows are small in comparison with the stream and the high neutralization capacity from the carbonate rocks of the area naturally attenuates the acidic seeps within 100 yards. The headwaters of Lewis Canyon Creek (Dean Canyon Creek) flow close to mine waste and mill tailings from the Morning Star mine, which discharge a few low-flow seeps with relatively high metal concentrations; no downstream sample was collected, but I presume that natural processes reduce the concentrations to acceptable levels within a few hundred yards. I did not sample the North Fork of Little Humboldt River east of the Buckskin mine.

Class B water, with less stringent quality standards than Class A, are downstream from the headwater reaches, often in the foothills regions bordering the National Forest lands, where there is minor to moderate influence by human activity (such as ranching). None of the areas studied were in Class B water, but many of the current mining operations such as the Carlin area (Lynn district, fig. 2) are near these waters.

Nevada also classifies some of its larger streams and rivers by a system of beneficial uses that differs from the Class system. Six segments of the Humboldt River are described in detail (Nevada Division of Environmental Protection, 2002, article 445A.202–445A-207), including quality standards based on beneficial uses. Tributaries are covered by the tributary rule but not specifically listed. Some of the headwater streams in historical mining districts described above under Class A water may be considered tributaries to the Humboldt River. As required by the Clean Water Act, the State of Nevada reports impaired water in periodic reports termed 303(d) lists. The report for 2002 (Nevada Bureau of Water Quality Planning, 2002) lists pollution of concern to Mill Creek, a tributary of the Owyhee River (fig. 36), near the Rio Tinto mill tailings, as having elevated concentrations of Cd, Cu, and Fe, acidic pH, and other concerns. In the Humboldt River Basin, there are concerns in many reaches for total iron, total phosphorus, and turbidity, and in a few reaches of the lower Humboldt west of Imlay for boron and molybdenum. These parameters were not investigated in these reaches during this study.

## Attenuation Mechanisms

Three stages in a related process appear to be involved in the attenuation of metals in the areas described previously: (1) mixing of water; (2) rise in pH; and (3) precipitation of iron-hydroxides and adsorption of trace metals. These stages are in part inferred from chemical compositions, as summarized in figure 45. The attenuation reactions start with mixing of water, seen clearly at the junction of tributary streams and inferred from measurements of locally variable and low conductivities that suggest ground-water inflow (springs) into the stream. Reactions of acidic mine water with rocks and alluvium also are likely but not evident in the spatial distribution of conductivity and pH values that do not change immediately at lithologic contacts. More specifically, the inflowing surface and ground water attain high alkalinity values by reaction with rocks and alluvium, and the high-alkalinity water neutralizes the acidity of the mine water. The high alkalinity of surface and ground water (median 170 ppm $CaCO_3$, many values greater than 200 ppm $CaCO_3$) is an important factor in the efficacy of this process.

As the pH of the mixed water rises from below 3 to more than 4, red to ocher iron-rich coatings precipitate in the channel. Some of this has the appearance of schwertmannite (iron-oxy-sulfate; Desborough and others, 2000) and is

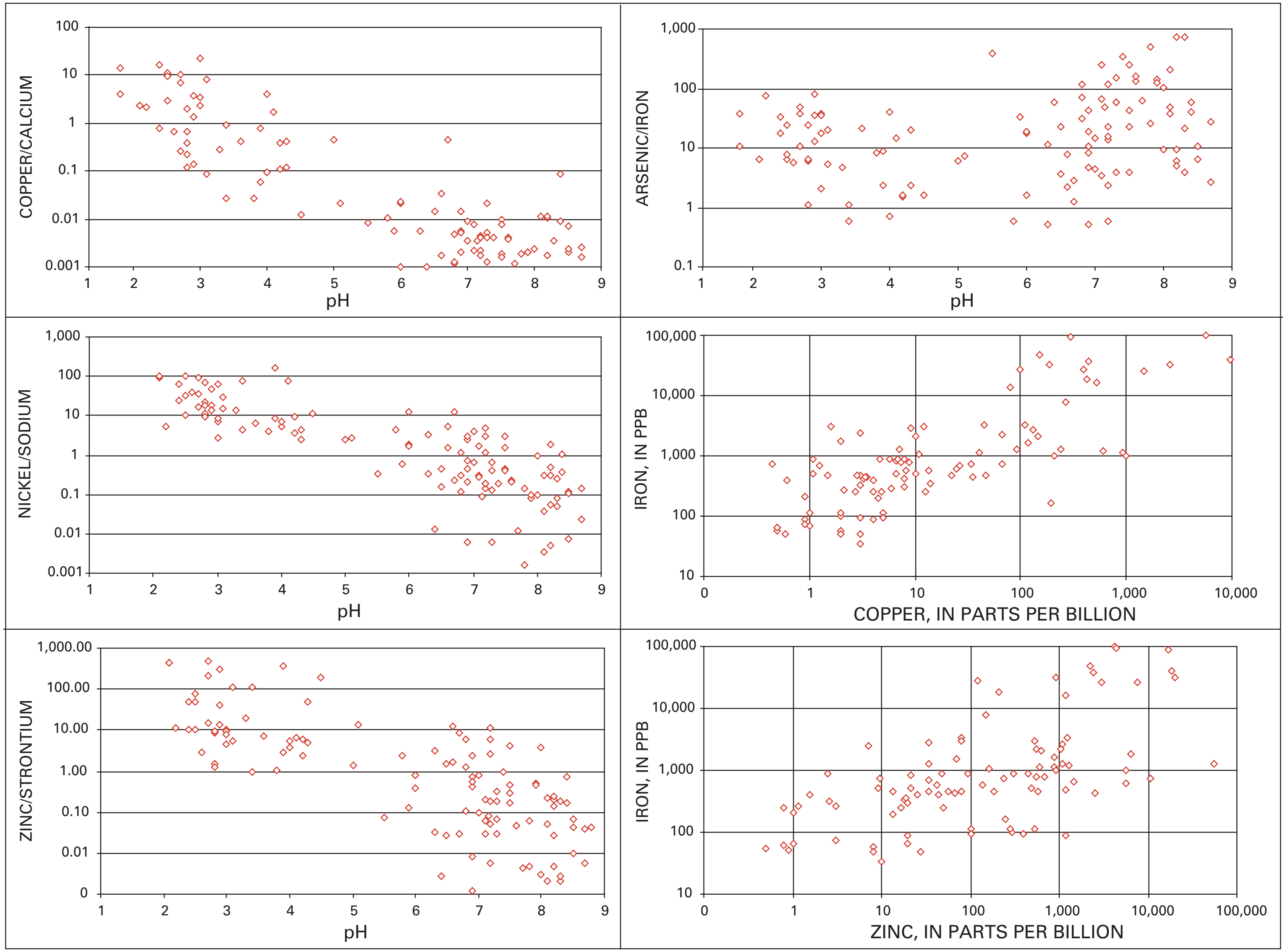


**Figure 45.** Evolution of mixed mine-related water as a function of pH, and concentration of iron and unreactive elements.

especially abundant in the Iron Canyon-Butte Canyon area (photo 31, 104). Coprecipitation of Cu with Fe as pH rises improves water quality (fig. 45). Concentrations of other trace metals in water, including Cd, Co, Ni, Pb, and Zn, generally behave like Cu (not shown in fig. 45) but differ in details of their behavior in the pH range of 4 to 7 (Smith, 1999). Concentrations of Zn and Cd also decrease, but less strikingly, and a higher fraction of these metals stay in solution at pH values of 4 to 7 (fig. 45); concentrations of Cd, Co, Cu, Ni, Pb, and Zn decrease with Fe over the pH range of about 4 to 7. The behavior of As, which is not a base metal, differs from those metals. The decrease in As concentration from pH 3 to 5 could be evidence for adsorption onto iron-oxyhydroxides as they flocculate. The general increase in As at pH values above 7 (fig. 45) suggests that the adsorption mechanism does not hold under alkaline conditions and low Fe concentrations where As is soluble or desorbs from iron-oxyhydroxide. If one plots the trace-metal concentrations against an unreactive element such as Na or Sr (which are called "conservative"), there is no correlation (fig. 45), which suggests that dilution is not a significant factor in the attenuation of metals. The compositional trends and metal associations strongly resemble the adsorption experiments of Smith (1999). More detailed, closer spaced sampling would clarify the attenuation mechanism(s).

As observed elsewhere (Nash, 2002a; Plumlee and others, 1999), Zn and Cd concentrations, and in places Cu concentrations, remain high after neutralization in these mixing reactions. This is predicted by adsorption reaction models (Smith, 1999). Once the water evolves through the pH 4–7 range and iron phases flocculate, there are few other natural reactions that can remove significant amounts of Zn and Cd. Carbonate and hydroxide phases of Zn-Cd can precipitate, but only at higher concentrations than observed here. Alkaline water can carry significant amounts of the oxyanions As, Mo, and Se above pH 7, regardless of whether there is acidic input to the water. Because alkaline waters predominate in Nevada, more attention is needed regarding the effect of metals (including oxyanions) in these waters and the possibility of long-distance transport to playas or sinks where evaporation will increase the metal concentrations.

### Conclusions on Effects of Mine Drainage

Reconnaissance hydrogeochemical studies of the Humboldt River Basin and adjacent areas of northern Nevada have identified local sources of acidic water generated by historical mine workings and mine waste. Where water attains pH values of less than about 3, the water mobilizes extremely high concentrations of many potentially toxic metals; these conditions generally occur where large amounts of pyrite are oxidizing but also can be created when sulfate mineral crusts on the surface of mine waste and mill tailings dissolve during brief storm events. Metals that are enriched and potentially toxic in these acidic mine waters include Al, As, Cd, Cu, Fe, Mn, Pb, Se, and Zn. Only in a few rare instances are some other elements, such as Mo, Sb, Te, Tl, and U, enriched sufficiently to pose a health threat to humans or wildlife. The processes that create these acidic, metal-rich waters in Nevada are the same as for other parts of the United States or the world, but the scale of transport and the fate of metals differ. In Nevada, acidic solutions do not migrate as far as in mining areas elsewhere because natural processes generally act to neutralize and attenuate metal concentrations within less than a mile of the source. The arid climate and associated soil-forming processes explain the reduced scale of metal mobility in Nevada. The same processes and the importance of caliche soils can be expected in similar climatic regimes of the Great Basin or other arid parts of the world.

Acid-mine drainage is rare in historical mining districts of northern Nevada, and the volume of drainage rarely exceeds about 20 gpm. My findings are in agreement with those of Price and others (1995) who estimated that less than 0.05 percent of inactive mines are likely to be a concern for acid-mine drainage. Most historical mining districts have no draining mines, and only a few have as many as three. Most drainage from mine workings appears to be related to melting snow plus spring rains; runoff from mine-waste dumps or mill tailings is generally limited to a few weeks of a year. Only in two districts (Hilltop and National) does mining-affected water flow into streams of significant size and length (more than 5 mi).

The results of these reconnaissance studies offer encouraging evidence that abandoned mines in northern Nevada create only rare and local water-quality concerns. In this semiarid climate, the high neutralization capacity of caliche soils and other natural processes are sufficient to compensate for these generally small sources of contaminants. A few of the headwater streams to Class A water may warrant more specific studies by specialists to determine in more detail the scale and magnitude of contamination. These results may provide useful analogs for future mining in the Humboldt River Basin, but care must be given to matters of scale. Larger volumes of waste and larger volumes of water could easily overwhelm the delicate balance of natural attenuation described here. One example of this may be the problems that developed in Iron Canyon of the Battle Mountain district in the unusually wet spring of 1998 that caused acidic drainage to flow 2 to 5 times farther than in normal seasons.

# Mill Tailings as Sources of Contaminants

## Abundance

Tailings piles are common features on the Nevada landscape. Most districts had at least one mill, and some had more than 10; but the majority of historical mills have burned or been dismantled. Many of the tailings piles remain today, although tailings from silver mines of the 1870–1910 era can be difficult to find because many have been reprocessed to recover silver and gold that were not recovered by the early, inefficient mills, and in some instances the tailings were hauled to smelters elsewhere. The 83 mills and associated tailings piles (data file NHMT.xls) are a partial estimate of the original total. In many districts there are unpublished reports of additional mills that I did not recognize. Additional work should be done to identify other tailings sites. Use of aerial photographs might be cost-effective, but in most cases there is no substitute for field inspection. The inventory (Appendix 5) may lack as much as 50 percent of tailings sites, but I believe that the larger historical sites have been identified.

**Photograph 110.** Ponds on tailings impoundments collect water with extremely high metal concentrations. If clay layers block infiltration, the water evaporates and the metals are further enriched.

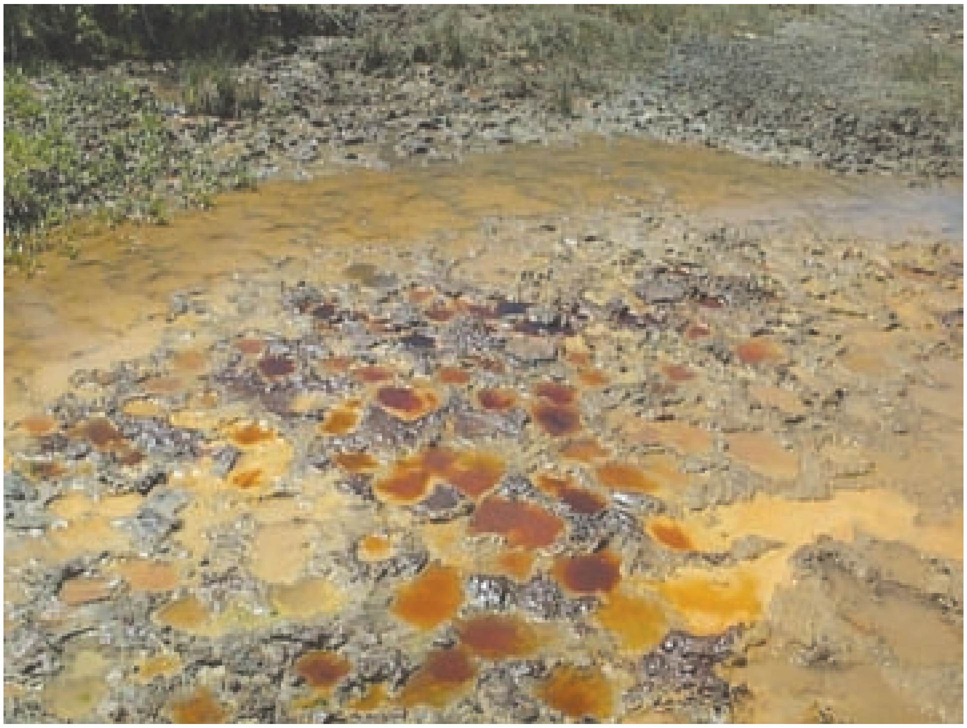
**Photograph 111.** Efflorescent crusts of sulfate minerals and native sulfur that form on the surface of mill tailings, as at Tybo, dissolve in minutes to create runoff water with pH values of 2 to 3 and very high metal concentrations.

## Environmental Concerns

Issues for mill tailings are similar to those for mine drainage and mine-waste dumps but can be more complex. Curiously, mill tailings generally are ignored in mined-lands assessments. In-situ reactions at impoundments create runoff and seepage water that are similar to those at waste dumps but have more significant effects where the tailings are in or near flood plains and riparian zones because there are no spatial buffers to induce chemical or physical changes in the drainage water. Likewise, the setting in flood plains makes tailings susceptible to erosion or to mass failure during storms.

## Runoff and Seepage from Tailings

The composition of runoff and seepage from tailings is so similar to that from mines and mine-waste piles that it has been discussed with those waters in previous sections. Because tailings are spatially distinct from mine waste and mine drainage, they should be evaluated as distinct entities. Only in a few locations, such as at the Buckskin National and National mines, National district, are mill tailings so close to mine waste and mine drainage that the tailings sites are integral to the mine-site and reclamation considerations. Because tailings in Nevada are generally dry, runoff seems to



**Photograph 112.** Tailings in Coon Creek are saturated in the spring and numerous seeps develop. Depressions, caused by cattle hooves, fill with water of differing compositions, as shown by the range in colors. The red-tinted water is acidic and metal-rich.

**Photograph 113.** The Morning Star mine tunnel and mill at 7,100-foot elevation receive more snow and rain than most mining areas, which is indicated by aspen groves along the creek. In late spring, water seeps from the tailings (whiter materials) and flows into nearby Dean Creek. Fortunately, the volume of seepage is small compared to the flow in the creek and the contamination is naturally attenuated.

be a more significant issue than internal seepage. During long dry periods, crusts of efflorescent minerals commonly form at the surface of tailings piles. Runoff is difficult to monitor, but on some very rainy spring days I was able to sample it. Runoff from tailings in the Tybo district in June of 1999 had a pH of 1.7 and very high metal concentrations. Another record of runoff water is in puddles that form on clay-rich areas, and these invariably have pH values less than 3 and extreme metal concentrations. If there are trenches in tailings piles, as are common from bulk sampling studies, small ponds can form and retain high-acid water (photo 110). These small ephemeral ponds on tailings piles have some of the very highest metal concentrations of all the surface water sampled in this study, and some are acutely toxic to wildlife in short-term exposure. Passive leach tests are appropriate for judging runoff compositions in situations where it is not possible to be present during a storm and sample the first "flush" in runoff. Tailings samples that contain efflorescent minerals (photo 111) and native sulfur (or similar appearing yellow copiapite, $FeSO_4$) are highly reactive, producing leachate solutions with pH values of less than 3 and very high to extremely high metal concentrations.

Seepage rarely develops from Nevada tailings. If there is low relief, there is insufficient head to cause the flow. In examples that have more than about 5 ft of vertical exposure in dams or erosional gullies, only a few show signs of seepage. The lack of seeps at sites such as Cortez, Rochester, and Tybo, where there are ample opportunities for head to develop and cause flow, may indicate that permeability barriers such as clay (slime) layers or hardpan prevent significant internal flow. The Morning Star tailings, Hilltop District (photo 113), are wetter than most due to snowpack and produced very low flowage seeps (less than 1 gallon per minute) with pH values of 3.2 and 6.9. At the Rip Van Winkle tailings impoundments, which are wet from Coon Creek flowing over them, two seep compositions were observed: (1) near-neutral pH water with metal concentrations only slightly higher than the creek; and (2) high-acid water (pH less than 2), with extreme metal concentrations, which appears to be pore water that is virtually stagnant in the clay-rich tailings piles (photo 112). No other pore water was sampled in Nevada, but by coring into Colorado tailings I was able to find and sample similar water with pH values of less than 3 and very high metal concentrations (Nash, 2002a). The leach test results and the Rip Van Winkle pore-water compositions show that mill tailings have the potential to generate acidic, metal-rich water that could infiltrate shallow ground water because the impoundments are placed on permeable alluvium. Tests should be made by drilling shallow wells with an auger. Based on available information, seepage does not appear to be a significant contaminant pathway at Nevada tailings sites.

## Erosion and Failure of Tailings Impoundments during Extreme Storms

Erosion or failure of a tailings impoundment or waste dump during an extreme storm event (flash flood) is a concept that is rarely mentioned in mined-lands assessments, yet the dire consequences of such a failure are known in the past century, and the probabilities are high enough to demand consideration in land planning. A few tailings-impoundment failures are described in the literature, as for Anaconda, Mont. (Moore and Luoma, 1990). An unusually graphic report of a 1975 tailings dam failure (Stiller, 2000) provides many insights into weather, floodwater, and transport conditions. My observations in northern Nevada indicate that at least 23 tailings impoundments have experienced major amounts of erosion, and there is evidence that 11 tailings impoundments probably failed (Appendix 5; Nash, 2002b). I suspect that many of the breached impoundments that I observed may have

**Photograph 114.** The swath of transported gray mill tailings on the gently sloping valley floor east of the Getchell mine reflects a tailings dam failure. View is west toward the tailings pond. The contaminated floodwaters probably flowed for several more miles to the southeast down Kelly Creek.

failed during the active period of mining and milling. Fluvial tailings in small to large amounts have been identified below 16 of the tailings impoundments.

Erosion and mass failure of tailings are end members of a spectrum of transport conditions in stormwater (Nash, 2002b). All tailings piles show evidence for simple erosion. Normal storm events cause minor erosion that creates gullies a foot or more in width and depth and deposits thin layers of tailings less than a mile from the source. These fluvial tailings are generally interbedded with more abundant gravel beds. These storm processes are fairly predictable, and the resulting runoff water and entrained tailings are not likely to cause large damage to property or loss of life.

Failure of tailings impoundments has occurred elsewhere in the world over the last 30 years, inflicting much damage and loss of life (Jeyapalan and others, 1981; Wegener and others, 1998). In northern Nevada there probably were failures at more than 10 sites (Nash, 2002b). A flood and failure at Seven Troughs in 1912 destroyed the small community, took nine lives, and carried away cyanide and tailings from an active mill (Gibson, 2000). Massive deposits of nearly pure tailings 5 to 30 inches thick, having large volume and extending for 1 to

**Photograph 115.** These fluvial tailings fill Slime Gulch 3 miles west of the mill in Tonopah. The tailings are 30 inches thick and contain only a few thin beds of gravel. Erosion today causes the banks to crumble and reworks the tailings down the gulch.

**Photograph 116.** These gray tailings were transported more than a mile from the original impoundment at Tybo in a catastrophic flood. The deposit is nearly pure tailings, 3 feet thick and 425 feet wide. There was no channel for this flow.

10 mi down the canyon or arroyo, are thought to be caused by catastrophic failure of tailings impoundments. Transport is reasoned (Nash, 2002b) to have been similar to mudflows, termed hyperconcentrated flows (Costa, 1988), defined as having 40 to 70 percent sediment by weight and properties intermediate between normal water transport of fluvial sediment and debris flows. This style of tailings transport appears to be possible only in young, water-saturated tailings.

An example in the study area of this failure scenario is the swath of tailings east of the Getchell mill tailings impoundment in the Potosi district. I was impressed by the width of the deposits on a gentle slope with no discernible

**Photograph 117.** The face of the dam at the Tybo tailings impoundment is only slightly eroded, and the pond appears full of tailings. The dam appears to have been repaired after the failure that created the large volume of fluvial tailings to the east.

**Photograph 118.** The tailings impoundment close to the Garrison mill are highly eroded, but the dam is mostly intact. The quantity of tailings eroded is a small fraction of the amount down the canyon. The original dam appears to have failed, been repaired, and the pond filled with more tailings.

channel (photo 114). The tailings were transported 3 to 5 mi, extending to Rabbit Creek (normally dry) near its junction with Kelly Creek. The date of this failure is not known but could go back to about 1940. There are several dikes or catch dams within the fluvial tailings, suggesting that the mining company attempted to stabilize the tailings after the failure. The tailings are very rich in As (Leventhal and others, 1996).

Other fluvial tailings deposits in northern Nevada, thought to be related to dam failures, are similar to those at Getchell (Nash, 2002b). Among the notable examples that I have observed are (1) New Cortez silver mill, fluvial tailings extend more than 2 mi to the southwest of the impounded tailings; (2) Leadville silver-lead mill, northern Washoe County, fluvial tailings extend about 1 mi east of the original crude impoundment; (3) Manhattan district (White Caps mill), several dams are breached, but fluvial tailings could not be located on private property (possibly went into the village); (4) Mount Hope district, fluvial tailings extend about 2 mi to the southeast of the impoundments, and the fluvial tailings appear to have greater volume than in the relatively intact tailings ponds; (5) Seven Troughs district, flood-deposited mill tailings extend about 1.5 mi east of a former impoundment; (6) Tonopah district, crudely impounded tailings have been transported west down Slime Gulch for 10 to 12 mi (photo 115); (7) Tybo district, flood-deposited tailings (photo 116) were carried 4 to 6 mi east of the impoundment and are probably more abundant than in the nearly full tailings impoundment. In most of these cases, the tailings originally were impounded in a relatively narrow canyon, about 200 to 400 ft wide, and fluvial tailings were deposited where the gradient decreased and the channel widened on the alluvial fan about 1 to 5 mi from the range front.

Several of the tailings dams appear to have failed during the active period of mining and milling, as best illustrated by features at Getchell, Cortez, Mount Hope, and Tybo where the impoundments today are essentially full: the dams appear to have been repaired and additional tailings added to fill the pond (photos 117, 118). It is not uncommon for tailings dams to fail during their first years of use when operators are inexperienced with the techniques of separating tailings sands and slimes (Ritcey, 1989); this would have been especially true in the early years of tailings impoundments (1920–40) when construction of tailings impoundments was a new art. Further, because there were few or no regulations at the time, the operators may not have been concerned about a failure.

## Implications for Water Quality

Most of the tailings sites identified in northern Nevada are dry for most of the year. The few that are in or near streams with flow most of the year do not appear to be reacting much with those waters. As discussed earlier, physical factors such as clay layers and hardpan cement appear to limit permeability and release of metals to surface water. It is possible that wet tailings release a small, slow flow of metal-enriched water to underlying alluvium and ground water. The major effects of mill tailings may be (1) brief flushes of runoff during storms that carry acid and metals released from soluble mineral crusts; and (2) creation of small ephemeral ponds and puddles that tend to collect in trenches and low areas and can develop extreme metal concentrations, in part through cycles of evaporation. Runoff could affect wildlife or infiltrate alluvium and contaminate ground water, but in that process caliche in soils should mitigate extreme concentrations.

Catastrophic failure of a historical tailings impoundment is not likely, but even the slight possibility is enough to cause concern because such an event could devastate a watershed. Reports of tailings failures in the past 30 years include descriptions of turbid water for tens of miles below the failed dam (for example, Stiller, 2000). Suspended material and dissolved toxic metals in the turbid water killed fish and caused widespread damage to the flood plain. Many years after the flood, the tailings continued to react either with stream water or with precipitation, slowly releasing metals to vegetation, streams, or ground water. The effects of widespread fluvial tailings on a watershed are well documented for the upper Clark Fork in Montana, below the failed Anaconda tailings impoundment (Nimick, 1993; Nimick and Moore, 1991; Smith and others, 1998). The metal concentrations probably would be even higher than determined by passive leach tests because mechanical mixing and abrasion during flow would promote reactions. During transport, the fine tailings fraction (termed "slimes") would separate from the sandy fraction, as is known from the processing of mill tailings (Ritcey, 1989), and travel long distances.

## Conclusions on Effects of Mill Tailings

This reconnaissance of mills and tailings has identified more than 80 mills and associated tailings sites in northern Nevada. The amount of tailings is variable from site to site but is approximately equal to the amount of waste rock from the associated historical mines. Because the tailings were generally placed in lowlands, commonly within flood plains of streams and ephemeral creeks, these mine-related materials are more likely to interact with surface water than mine-dump waste. Episodic release of acid or metals to flushes of storm runoff water is likely but probably extends for distances of only hundreds of yards before the water is attenuated by reaction with caliche or infiltrates into alluvium. In a few districts surface water and mine drainage flow through mill tailings to create severely degraded water; mixing with other sources of water and reactions with caliche in alluvium neutralize the acidic water within a few hundred yards of the tailings, and water quality improves to levels acceptable to aquatic life. Rare extreme storms have the potential to cause catastrophic failure of tailings impoundments, carry away metals in stormwater, and transport tailings as debris flows for 1 to 10 mi. If catastrophic failure processes require young, water-saturated

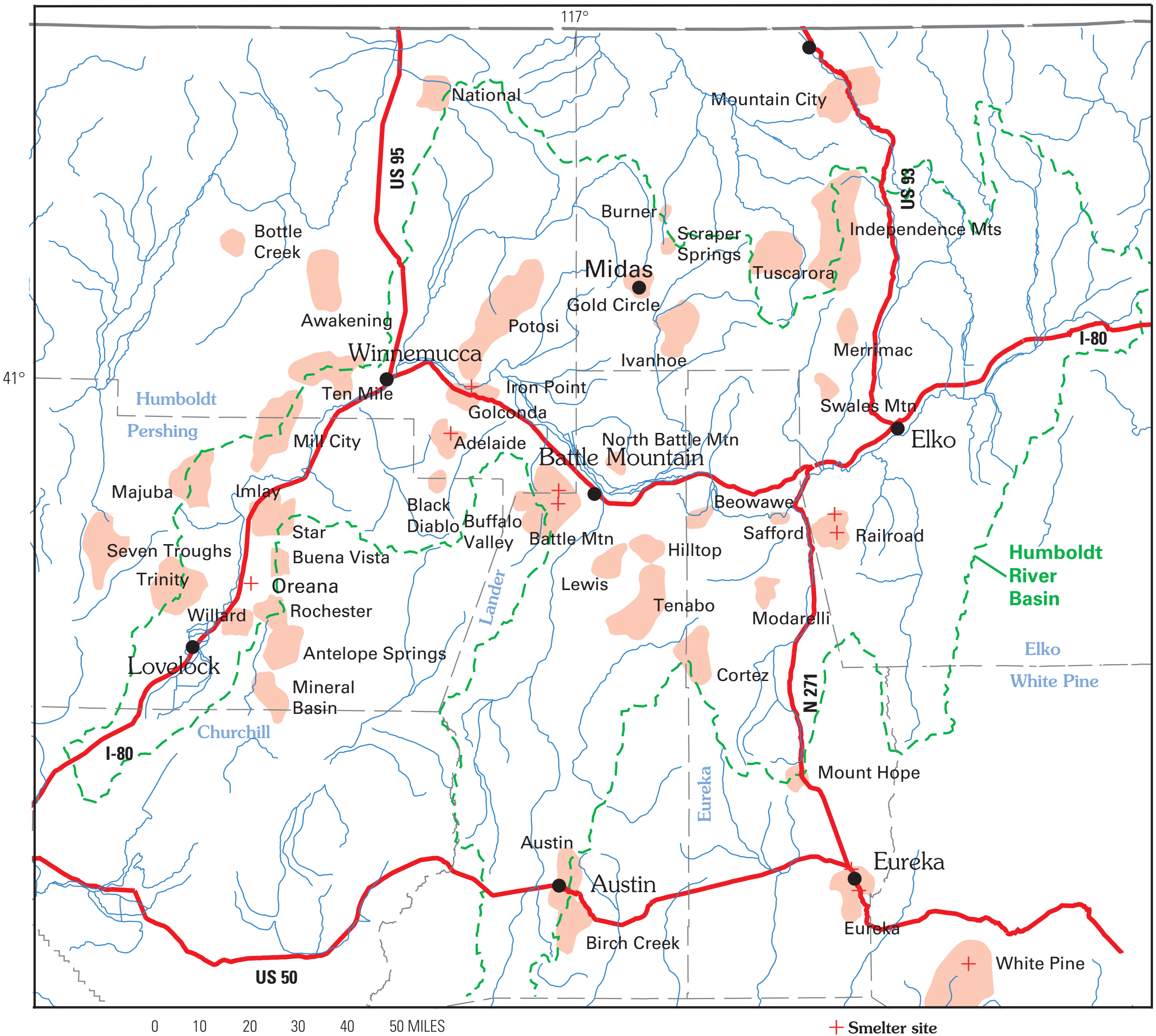


**Figure 46.** Location of smelter and slag sites in northern Nevada. District outlines are from Tingley (1998); only studied districts are shown.

tailings (Nash, 2002b), the risk of such failure in historical tailings is very low.

## Smelters and Smelter Slag as Sources of Contaminants

Smelters were used in northern Nevada for the first few decades of mining, but most were small, operated for only a few years, and seem to be causing little or no contamination today. Only in the Eurkea district were smelters large producers and likely to have been significant sources of pollution when operating. The slag piles today in Eureka may pose a threat locally. In Nevada, smelters were used in the early days of mining, when technology was crude and transportation facilities were meager, to recover silver from lead-rich ores. Prior to about 1880, some rich ores were hauled to San Francisco, then carried around the Horn to Wales for smelting; the shipping costs were not as high as we might imagine because the ore was used as ballast (Stager, 1977). Some smelters in Nevada were used before the completion of transcontinental railroads, and others were used prior to the development of milling methods such as flotation that were applied to the same ores after about 1900. Smelters were used in only eight districts in the study area: Adelaide, Battle Mountain, Eureka, Golconda, Oreana, Railroad (Bullion), White Pine (Hamilton), and probably Tuscarora (fig. 46).

**Photograph 119.** These slag piles at the Bullion townsite date to the 1870's. The spring-fed stream, used in the smelting process, does not show contamination from the refractory slag materials.

Smelter sites were identified in this study by finding piles of smelter slag (photo 119) at 11 sites, but there must have been more. Miscellaneous steel pipes and piles of bricks, suggestive of a smelter, were present at three sites. My findings corroborate the brief smelter descriptions by Lincoln (1923), Stager (1977), and LaPointe and others (1991). Large piles (thousands of tons) of slag can be seen at the north and south ends of Eureka, and small piles of slag (hundreds of tons) were identified at Galena townsite (Battle Mountain district, two sites), Adelaide, Bullion (Railroad district, two sites), Tybo, and White Pine. The smelter site at Golconda that processed Adelaide ores in the 1880's (Lincoln, 1923) was not located, nor was the smelter in Oreana (Lincoln, 1923). The stack at Tuscarora resembles that of an old smelter, but no slag was identified. Reduction plants are mentioned for some districts, such as Star, but none were recognized in field studies. Such plants heat ore and chemically reduce oxidized minerals to phases that are more amenable to recovery of metals; in some reduction plants the ore is heated to the point of melting, as in a smelter. The character and reactivity of waste material from the reduction plants are not known.

Several of the early mining districts appear to have used stamp mills rather than smelters, determined by the character of the ore. Several deposits discovered after 1930, such as Rio Tinto and Big Mike, did not use a smelter even though other similar massive sulfide deposits in the Western United States were served by smelters, because other technologies had been developed by the time of mining. Likewise, the time of mining and the character of ore explains the absence of smelters at the more important mining districts such as Rochester, National, and Gold Circle.

The dust and slag from smelters probably are not significant sources of contaminants at most of the small sites in northern Nevada. The slag piles may contain high concentrations of potentially toxic metals, but leach tests of slags generally show these materials to be unreactive (Nash and others, 1996; Nash, 2002a). The extent and composition of dust fallout has not been studied, except at Eureka (Chaffee, 1987), where it is substantial and in need of further study. However, there is anecdotal information that the dust contaminants may dissipate by natural processes over about 75–100 years. The pre-1900 smelters at Bullionville, Nev., that processed the early Pioche ores contaminated nearby soils, and livestock died after feeding on grasses in those fields. "Not until the middle of the twentieth century were cattle able to survive in the area of Bullionville. The density of lead on the ground caused lead poisoning in animals that grazed there" (Lee and Wadsworth, 1964, p. 17). Geochemical studies of soils, especially in the town of Eureka, would clarify the history of smelter smoke contamination and the health implications for residents.

## Comments on Methods and Suggestions for Future Studies

### Hydrogeochemical Methods

The field and analytical methods used in this study, described earlier, were selected after a project in central

Arizona (Nash, and others, 1996) showed them to be effective. Bill Miller, USGS, offered helpful advice, and his work over many years demonstrates the value of similar methods. The field method of using disposable syringe-type filters has proven to be effective for rapid sampling of water by one person, with minimal introduced contamination. The analytical methods were selected in the context of a modest budget for geochemical analysis (about $10,000 per year) and obviously influenced the kinds and quality of geochemical results. The ICP–MS method has proven to be very effective for water analysis (Crock and others, 1999). Although other analytical methods for cations may be superior for high precision and accuracy of water with metal concentrations at or below regulatory standards, the higher cost is not justified for reconnaissance work such as this, and those methods tend to have narrow calibration ranges that require dilution of the highly concentrated water encountered in mining areas. Although major elements in water, such as Ca and Mg, were not emphasized in this work, those cations are adequately reported by ICP–MS. If possible, within a project budget, ICP–AES analysis should be requested as it gives superior results for major elements in water.

Supplemental analyses for anions were not requested on all samples in this study, chiefly due to the added expense. If possible, those analyses should be made. However, in most of my anion analyses of mine water, sulfate is dominant, as expected of acidic water. Analytical data for F can be very informative for some types of systems associated with felsic intrusions (Richard Wanty and Dana Bove, USGS, oral commun., 2001) but was not very helpful in this reconnaissance.

Acid-neutralization capacity of rocks and water, mentioned frequently in this report, merits more analytical study than given here. Alkalinity determinations were not routinely made of my samples and are not possible on samples with pH values less than 4.5. More data on water alkalinity as a function of rock and soil type would be useful because the high alkalinity of many waters in Nevada clearly is important in natural neutralization of acidity. Likewise, more data on acid production and acid neutralization capacity of rocks would be beneficial, as shown by Fey and others (2000). The analytical work tends to be tedious in the laboratory (D.L. Fey, U.S. Geological Survey, oral commun., 2001) and thus expensive.

The passive leach method provides much useful information on acid generation and metal mobility at low cost. The passive leach tests require only simple equipment, and batches of samples can be run with only about 15 minutes per sample of operator time, followed by routine analysis by ICP–MS. These tests are especially effective in arid climates where water samples can be difficult or impossible to collect and where efflorescent mineral crusts develop and have the potential to create a toxic first flush in episodic storms. I think these tests are cost effective but suggest caution in the use of the data because many of the laboratory reactions do not occur in nature due to physical limitations such as permeability and grain coatings. Also, the analytical results are not readily used in a quantitative manner similar to metal loads for water analyses. Although not attempted here, derivative calculations using the amount of precipitation and the volume of waste piles can generate values that are roughly comparable to metal loads (Fey and others, 2000).

One perplexing sampling problem in mining-area studies is the number of water samples required to describe dispersion of metals. Although we know that some metals such as Zn are more mobile than others and continue to move as acidity is neutralized, it is not obvious what distance one should go in pH 5 to 7 water to collect samples to demonstrate natural attenuation to concentrations low enough to be healthy for wildlife. In this study, I commonly misjudged the mobility of Zn and had to return a year later to collect additional samples downstream. More samples 0.5 to 2 mi downstream from mine tunnels, or to the point at which the stream disappears into alluvium, would be helpful.

Another perplexing problem is the behavior of mercury in water samples and its strong tendency to adsorb on container walls, thereby invalidating conventional analyses if samples are not preserved properly. Much more work using special sample bottles and stabilizing reagents is needed on both mine water and leachate solutions, as discussed in the section on “Geochemistry of Mercury.”

The goal of this hydrogeochemical reconnaissance was to observe as many mining areas as possible and to collect as many representative samples as possible, in a limited amount of time and with no field assistance. The methods used allowed brief observations and sampling at about 15 to 20 sites per day. The cost of sample collection (field expenses) and analytical expenses was about $100–$125 for three media (water, waste leachate, and solid waste) per site; those costs do not include salary. These methods are easily employed by land management field scientists to characterize mining sites. Future analysis will determine whether they are cost effective for the stated goals of characterizing and ranking mine sites in reconnaissance mode.

## Stream-Sediment Geochemical Methods

Stream-sediment geochemistry has long been applied to mineral exploration and mineral resource assessment (Rose and others, 1979; McGuire and Peters, 1996; Yager and Folger, 2002), but the applications to the effects of mining on water quality are rare. Regional geochemical databases for stream sediments have been used to predict areas of water contamination (Tarvainen and Paukola, 1998; Coker, 1999), suggesting possible applications in Nevada. In the course of these district studies, 15 stream-sediment samples were collected and analyzed to provide information on active stream alluvium near known sources of mining contamination. The samples were collected to help understand regional geochemistry for mineral resource assessment and also provide information on the environmental signatures of mining areas. The samples were collected in the traditional USGS manner: multiple portions of alluvium were sieved to less than 2 mm in the field, dried, and the –80 mesh fraction was prepared in the laboratory and analyzed by ICP–AES (Nash, 2000b; Appendix 2).

The metal concentrations in these 15 samples are very anomalous for stream sediments in Nevada, as was expected, because the sample sites were chosen to be less than 2 mi from known mine dumps or tailings piles. Virtually any element from As to Zn is much more concentrated than in typical materials (see McGuire and Peters, 1996, for comparison). At the most basic level of descriptive geochemistry, these analyses and their high metal concentrations are useful for detecting sources of contamination. Some examples will be described and compared to corresponding water compositions.

Two samples of stream sediment were collected from the active channel of Licking Creek (Battle Mountain district), east (downstream) of the mill tailings pile. At one of the sites, a thin layer of fine sands with the color and size of tailings was interbedded with coarser gravels. The sediment sample contained very high concentrations of Ag, As, Au, and Pb and high concentrations of Cu and Zn. Water collected from Licking Creek after a rainy spell in 1997 had a pH of 7.5 and conductivity of 740 $\mu$S/cm (high); concentrations of As, Cu, and Mo were quite high for stream water, and Cd, Se, and Zn also were high. In this case, the water and sediment compositions were generally similar by anomalous element and concentration relative to background values. The notable exception is that Pb concentrations were high in the sediment but low in the water.

Coon Creek, west of the Rip Van Winkle mine and tailings impoundments (Merrimac district), was sampled on several occasions. A sediment sample was very high in Ag, As, Cd, and Zn, and high in Cu and Pb. Coon Creek water was sampled two times at two nearby sites (three samples). The pH values ranged from 7.5 to 8.1, and conductivity values ranged from 330 to 500 $\mu$S/cm. Many metals were present in water in high to very high concentrations: As, 11 to 27 ppb; Cd, 1.9 to 2.5 ppb; Cu, 2.3 to 8.2 ppb; Pb, 0.7 to 17 ppb; and Zn, 68 to 199 ppb; Ag was not determined. Metal anomalies were spatially similar in the two media, but of course the metal concentrations differed.

Mill Canyon (Cortez district) was sampled at the range front, about 0.7 to 1.5 mi west of the mines in this steep canyon. The sediment sample was high in Ag, As, Au, Hg, Pb, Sb, and Zn. The water sample had a pH of 8.4 and conductivity of 403 $\mu$S/cm; metals concentrations in water were low (similar to background values); only As was high (66 ppb). The Zn concentration of 6 ppb is very low for a water that probably evolved from acidic and metal-rich mine drainage. At this site the water and sediment compositions do not compare very closely.

In the Hilltop district two sites were examined to test for dispersion from mine dumps and mill tailings. A sediment sample from Pittsburg Creek below the Dean and Pittsburg mines and the mill tailings impoundment showed only slightly elevated metal concentrations. The companion water sample from this site had a pH of 7.2 and conductivity of 740 $\mu$S/cm (high value); all metal concentrations were very low and comparable to background values. Concentrations of 8 ppb As and 21 ppb Zn in water were only slightly elevated. The East Fork of Rock Creek was sampled about 0.5 mi below the mill tailings in Hilltop Creek. The sediment sample showed low metal concentrations, among the lowest of the 15 sediment analyses. The water sample had a pH of 7.1 and conductivity of 470 $\mu$S/cm; most metal concentrations were at background levels. The concentrations of As (23 ppb) and Cu (14 ppb) were elevated, but that of Zn (19 ppb) was not. At these two sites, the sediment and water compositions are comparable in their respective scales.

Sampling of stream sediments downstream from mercury mines in northern Nevada (Gray, 2003) shows that mercury is not dispersed in high concentrations more than a mile from the mines. Values fall off rapidly, within a few hundred yards of sources, as unmineralized alluvium dilutes the mine-related material. A few Hg concentrations exceeded 10 ppm, but most were less than 1 ppm. Methylmercury, the most toxic form of Hg, is present in concentrations below 1 ppb and likewise is diluted downstream. Gray's studies show that stream-sediment sampling is a reasonable proxy for water sampling in the arid environment.

These few examples show that stream-sediment geochemistry provides useful mineral-environmental information. These sediment samples are easy to collect by using simple methods, can be collected at nearly any time of year, and the analytical costs are low. This geochemical method may be especially useful for reconnaissance studies in arid regions when it is not possible to obtain surface-water samples or to time field studies to coincide with brief periods of flow. More of this sampling would have been helpful in this study.

The stream-sediment sample results raise more questions than they provide answers. What is the source of the metals—mine dump, mill tailings, mine drainage, or unmined mineralized rocks? Was the sediment deposited in a rare flood event from the past, or is it an ongoing depositional process? How do the metals move, in the aqueous phase or as clastic grains? At a regional scale, how do stream-sediment anomalies—such as for As or Zn (Yager and Folger, 2002)—compare with surface-water compositions in those areas? In most instances we do not know how much of the metal in a sediment sample is mobile in water. And we also do not know how much is bioavailable.

Specific answers to these and other questions require careful studies that are time consuming, expensive, and can be applied only to selected localities. For instance, more information can be extracted from sediment samples by doing electron beam analyses of grain coatings or by performing chemical analyses of weak-acid-soluble phases such as might coat clastic grains. A more effective approach may be integrated field samplings of bed material, colloids in water, and water as was done by Church and others (1997). Where there are biological concerns, such as fisheries, chemical studies of periphyton (biofilm or "slime") are appropriate (Besser, 2000).

## Geochemistry of Mercury

Information on the concentrations and distribution of mercury is sparse in this report. Numerous excellent methods exist (Gray and others, 1999; Crock, 1996; Lechler and others, 1997), but the additional special samples and analyses would have added about 40 percent to the analytical costs of this project. I recommend that followup studies be made, using appropriate methods at relevant sites.

Based on limited sampling and analysis of solids in this study, there are several indications of high Hg values in mill tailings from the Hilltop district and three other tailings samples from the National and Cortez districts. Mercury concentrations greater than about 5–10 ppm in solid samples seem to reflect contamination during milling because ore samples generally contain less than 5 ppm (not considering Hg ores). The list of Hg-contaminated tailings would be longer if more samples had been submitted for Hg analysis. Also, in my study the Hg values come from a selective digestion and ICP analysis that is not considered the most reliable or sensitive method for Hg geochemical studies (J.E. Gray, oral commun., 2001).

Mercury is surprisingly high in samples of tailings from the Hilltop district, with concentrations ranging from 14 to 1,690 ppm in five of six samples. Highest Hg concentrations in dump materials from this district are 5 to 8 ppm; thus, much of this Hg appears to be added during milling. This is not unexpected because amalgamation was commonly used to recover gold. The high values are associated with virtually all of the Hilltop tailings sites, not just one unusual mill and tailings site. The observed Hg values were in the range determined for calcine from mercury retorts, known to be rich in Hg (Gray, 2003). The observed high Hg values suggest that additional studies are warranted to monitor possible mobilization into surface water. Regrettably, my water samples were not analyzed for Hg.

## Monitoring Results of Reclamation

Documentation of changes in mine drainage following reclamation requires special protocols that are beyond the scope of this project. Some of my samples and observations may be pertinent, but more systematic studies are needed. Based on limited discussions with BLM field scientists, it is apparent that the land-management agencies do not normally undertake pre- and post-reclamation studies to document the results of the reclamation. Such studies are not expensive, relative to costs of reclamation work, and are recommended to better understand reclamation methods and recovery processes.

The Forest Service has identified, characterized, and made engineering plans for reclamation at three sites that I encountered in my reconnaissance: (1) the Bell Tunnel and Buckskin National mine, National District; (2) the Black

**Photograph 120.** The Black Beauty mine on the east flank of the Independence Mountains was worked for several metals but never was an economic success. The mine dumps were reclaimed by the U.S. Forest Service in 1998 to minimize reactions with stream water of a tributary to Gance Creek.

**Photograph 121.** Several mine workings and dumps in the upper part of the Dean mine complex were sources of acid and metals to this small stream prior to reclamation. The ocher coating on the bed, which resembles schwertmannite, precipitates during mixing reactions that raise the pH to 3 and higher.

**Photograph 122.** The creek below the Dean mines was nearly clear in 1999, following reclamation. The milky suspension in the water is probably an aluminum colloid that forms at a pH of about 5.5. Some ocher iron deposits remain on the streambed.

**Photograph 123.** This is a Dean mine tunnel after reclamation in 1998 that included plugging the tunnel with concrete and covering the waste dump with unmineralized rock. Only a small amount of seepage from the tunnel could be detected in June of 1999.

Beauty mine, eastern side of Independence Mountains mining district; and (3) the Apex uranium mine south of Austin. The major action at the Buckskin mine was control and diversion of mine drainage in about 1997 to minimize reaction with mine waste and mill tailings; this appears to be quite effective, but I did not see the drainage prior to reclamation. The action at Black Beauty (photo 120) was chiefly grading of sulfidic mine waste away from the stream and revegetation. This may be an example of pragmatic compromise required by limited FLMA funds for reclamation; placing the sulfidic waste in an engineered repository would have been much more expensive and would require special permits. The radioactive waste piles at Apex were investigated for reclamation, to supplement information given by the author to the Forest Service; no remedial work had been initiated as of June 2000. Similar prioritization studies by the BLM are underway.

Major reclamation in part of the Hilltop district merits nontechnical description here because that project has received little or no publicity. The BLM and Nevada Division of Environmental Protection worked together to direct reclamation of draining mine adits and sulfidic mine waste that resulted from exploration work from 1988 to the mid-1990's in the Dean mine area of the Hilltop district. Bankruptcy of the mining company required that BLM and Nevada Division of Environmental Protection take the bond and direct the work of a third-party contractor. The most significant action was the plugging of six tunnels that released acidic drainage, which further reacted with sulfidic waste dumps as described earlier in this report. In late 1997, the tunnels were inspected and cleaned of loose rock prior to emplacement of acid-resistant concrete bulkheads 7 to 13 feet thick inside the tunnels. The tunnels were pressure grouted to seal any leaks (William Brown, BLM, written commun., 2001). My brief observations in June 1998 and June 1999 suggested that there was very little leakage. I am impressed at how effective the plugging and other reclamation work has been at these sites. The dumps were covered with barren rock, including limestone, and that action should minimize reactions and runoff from precipitation. The water quality in the nearby creek was markedly improved. Where the water had been precipitating a thick coating of iron-oxyhydroxides and schwertmannite in 1996 and 1997 (photo 121), the water appeared clear and water quality was much improved (photo 122). The in-stream pH improved from 3.3–3.6 to 6.3 after reclamation. Regrettably, there was no systematic monitoring by any agency of the streams in this area to document the benefits of this well-executed reclamation work (photo 123).

*Final Remarks.*—The results of these reconnaissance studies offer encouraging evidence that abandoned mines create only rare and localized water-quality problems in northern Nevada. Natural processes are sufficient to compensate for these relatively small sources of contamination. These results may provide useful analogs for future mining in the Humboldt River Basin, but care must be given to matters of scale. Larger volumes of waste and larger volumes of water could easily overwhelm the delicate balance of natural attenuation described here. One example of this may be the problems that developed in the Battle Mountain district in the unusually wet late spring of 1998 that caused contaminated surface water to flow about 5 times farther than in normal seasons. Rare extreme storms also can cause catastrophic failure of tailings impoundments and other mining structures that have been stable for 50 or more years. Further dialog between the public and FLMA's is needed to define acceptable environmental risks to wildlife and human health and to set biological and chemical goals for reclamation.

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