

Hydrogeochemical Investigations of Some Historic Mining Areas in the Western Humboldt River Basin, Nevada

By J. Thomas Nash



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Contents

- Abstract 1
- Introduction 1
- Data Files 2
- Methods 2
 - Rock Chemistry 4
 - Leachate Chemistry 4
 - Water Chemistry 4
- Geologic and Geographic Setting 5
- Introduction to Ore-Deposit Types and their Environmental Signatures 6
 - Polymetallic Deposits 6
 - Skarn Deposits 6
 - Epithermal Vein Deposits 6
 - Mercury Deposits 7
 - Sediment-Hosted Gold Deposits 7
 - Porphyry Cu-Mo Deposits 8
- Introduction to Chemical Composition of Dumps, Tailings, and Mineralized Rocks 8
- Passive Leach Tests of Dump and Tailings Samples 9
- Introduction to Mine-Related Waters 11
- Mining District Investigations 15
 - Rochester District 16
 - Tenmile District 22
 - Majuba District 24
 - Mill City District 26
 - Mineral Basin District 27
 - Seven Troughs District 29
 - Awakening District 33
 - Willard District 36
 - Antelope Springs District 38
 - Bottle Creek District 42
 - Buena Vista (Unionville) and Star Districts 44
 - Imlay District (Standard Mine Area) 47
- Discussion 51
 - Environmental Standards and Use of This Report 51
 - Risk of Tailings Erosion in a Major Storm 51
- Conclusions 54
- References Cited 54
- Appendix I—Water Sampling and Analysis 57

Figures

1. Map of the western Humboldt Basin study area showing location of mining districts investigated.....	3
2. Trends for rock geochemistry by deposit type	10
3. Geochemical trends for leachate compositions by deposit type.....	12
4. Ficklin plot of surface water compositions	13
5. Geochemical trends for waters associated with mines	14
6. Features of the Rochester district, showing sample localities.....	16
7. Features of the Tenmile district, showing sample localities	23
8. Features of the Majuba district, showing sample localities	25
9. Features of the Seven Troughs district, showing sample localities.....	30
10. Features of the Awakening district on west side of Slumbering Hills	34
11. Features of the Antelope Springs district, showing sample localities	39
12. Features of the Bottle Creek district, showing sample localities.....	43
13. Features of the Buena Vista and Star districts, showing sample localities	45
14. Features of the Standard mine area, Imlay district, showing sample localities.....	48
15. Analytical error diagram showing the magnitude of error at various concentration levels.....	59

Photographs

1. View to the southwest of the Nevada-Packard mine workings showing the mill site at the base of the hill, the 20 acres of mill tailings, and the piles of crushed rocks from the 1980's bulk mining–heap leach operation	17
2. The stamp mill at the Looney mine is a well-preserved example of the small mills that were typical of gold mines in the 1880's–90's.....	18
3. Trenches and pits were excavated in these tan-colored rocks above the former underground workings of the Nevada-Packard mine in an attempt to bulk mine silver	19
4. This view of the Lower Rochester tailings impoundment shows their location in the flood plain of the creek	20
5. Tailings in the Lower Rochester impoundment are severely eroded by the creek	20
6. These are fluvial mill tailings in the flood plain of Rochester Creek, carried 2 miles west from the Lower Rochester tailings impoundment.....	21
7. Fluvial tailings are present in the arroyo and in overbank deposits for at least a mile west of the Nevada-Packard tailings impoundment	21
8. The Packard mill operated for only a short time in 1917 and left these tailings in the arroyo to the west, just north of the Packard townsite.....	22
9. The lower adit for the Majuba Mountain mine releases a small amount of water.....	26

10.	Tailings from the Pacific Tungsten Corp. mill were placed on the alluvial fan south of the mine-mill complex, which later became the Springer mine.....	28
11.	This view of the central part of the Seven Troughs mining district shows the dumps from the Kindergarten and nearby mines and the mill on the south side of the creek	29
12.	This old mill in the center of the Seven Troughs district probably treated ore from the Kindergarten mine	32
13.	Mill tailings were carried into arroyos east of the Seven Troughs district when a flash flood breached a tailings impoundment	32
14.	Fluvial tailings deposited on the alluvial fan east of the Seven Troughs Range cover tens of acres	33
15.	The Sleeper pit exposes rusty- and pink-colored volcanic host rocks	35
16.	This photograph of the Sleeper mine shows the large area involved in the open-pit operation	36
17.	The Willard mine exploited silver-gold ore in oxidized siltstones	37
18.	This mercury retort at the south end of the Antelope Springs district is more complex than most and probably was operational in the 1950's or 60's	40
19.	A heap-leach operation in the 1980's attempted to recover gold from calcine, Pershing mine, Antelope Springs district.....	40
20.	Bulldozer trenches cut to explore for mercury collect water from rare rain storms in the Antelope Springs district	41
21.	View of the central part of the Bottle Creek mercury district and the many small workings in this area	44
22.	The Sheba mill created a few thousand tons of tailings in the 1880's	46
23.	The Arizona mill south of Unionville was a major silver mine.....	47
24.	The Standard mine was one of the first open-pit gold mines in Nevada	49
25.	Tailings from the Standard mill, placed on the alluvial fan west of the mine, have been eroded and dissected by surface waters	50
26.	Unconfined tailings southeast of Castleton, Pioche district, that are subject to erosion and reactions with surface waters	52
27.	This large tailings impound northwest of Goldfield shows significant erosion	52
28.	These tailings have been transported more than a mile east from the Leadville mill	53
29.	Tailings placed in Slime Gulch on the west side of Tonopah have been swept away in flash floods	53

Tables

1.	Summary of chemical composition of dump, tailings, and mineralized rock samples	9
2.	Summary of chemical compositions of leachates	11
3.	Summary of surface water compositions	13
4.	Aquatic life and domestic drinking water quality standards for Nevada	15
5.	Analytical results for mercury in water samples from Humboldt Basin	41
A1.	Elements determined in water and leachate samples by ICP-MS.....	57

Data Files

[Data files are stored in the "Data" folder at the root directory of this CD-ROM. There are six data files, and each is provided in Excel and CSV (comma-separated value) format. Brief descriptions of the files are shown below and are also included in the ReadMe file in the "Data" folder]

1. Location.xls Excel file, locations and descriptions of sample sites, western Humboldt Basin, Nevada
2. Location.csv CSV file, locations and descriptions of sample sites, western Humboldt Basin, Nevada
3. Mineral.xls Excel file, chemical analyses of mineralized samples (solids), western Humboldt Basin, Nevada
4. Mineral.csv CSV file, chemical analyses of mineralized samples (solids), western Humboldt Basin, Nevada
5. Leach1.xls Excel file, analytical results for ICP-MS analyses of leachate solutions, Humboldt Basin, Nevada (reporting all analytical values for all elements determined)
6. Leach1.csv CSV file, analytical results for ICP-MS analyses of leachate solutions, Humboldt Basin, Nevada (reporting all analytical values for all elements determined)
7. Leach2.xls Excel file, analytical results for ICP-MS analyses of leachate solutions, Humboldt Basin, Nevada (not all elements determined are reported here)
8. Leach2.csv CSV file, analytical results for ICP-MS analyses of leachate solutions, Humboldt Basin, Nevada (not all elements determined are reported here)
9. Water1.xls Excel file, analytical results for ICP-MS analyses of water samples, Humboldt Basin, Nevada (reporting all analytical values for all elements determined)
10. Water1.csv CSV file, analytical results for ICP-MS analyses of water samples, Humboldt Basin, Nevada (reporting all analytical values for all elements determined)
11. Water2.xls Excel file, analytical results for ICP-MS analyses of water samples, Humboldt Basin, Nevada (not all elements determined are reported here)
12. Water2.csv CSV file, analytical results for ICP-MS analyses of water samples, Humboldt Basin, Nevada (not all elements determined are reported here)

Hydrogeochemical Investigations of Some Historic Mining Areas in the Western Humboldt River Basin, Nevada

By J. Thomas Nash

Abstract

Reconnaissance field observations were made and samples of mine dumps, mine drainage waters, and mill tailings have been collected to characterize the geochemical signature of these materials and to determine their actual or potential contamination of surface or ground waters. Although there are thousands of very small prospects, small mines, and some large mines in the area west of Winnemucca, Nev., the approach in this investigation was to identify the largest accessible historic mine in a district for observation and sampling in order 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 waters) 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's (6.5–8.4) and water compositions attesting to significant amounts of carbonate derived from rocks, alluvium, and caliche-bearing soils. The alkalinity of surface waters is sufficient to naturally mitigate local sources of acidic waters.

Productive historic mines in 13 mining districts, of many geochemical types, were investigated in May of 1998, an unusually wet spring season that should have produced more than normal amounts of mine drainage. Only a small fraction of the mines produced mine drainage, and of those only a few were acidic. Leach tests of mine dump and tailings materials showed most sites have low potential to generate acid, probably because sulfide minerals in most of the mines were destroyed by oxidation prior to mining. Chemical analyses of mining-related materials and laboratory leach tests suggest that few of the sites release high metal concentrations relative to regulatory standards such as for aquatic life or drinking water. There are, however, indications of elevated amounts of As, Mo, and Se that are mobile in weakly alkaline waters. There is some risk for these elements to be cumulatively enriched in closed basins over many years, but the evaluation of that risk is beyond the scope of this investigation.

Mill tailings represent one of the potentially significant sources of contamination, in part because they typically were placed in canyons and arroyos where they are vulnerable to storm events. All tailings in the study area show evidence for episodes of erosion, and, at five sites, major erosion during flash floods has carried thousands of tons of tailings for several miles. Catastrophic failure of a tailings impoundment in a major flash flood—which has a low likelihood of occurrence—could produce a major release of metals and also spread metal-rich materials over a large area that would be prohibitively expensive to clean up.

The generally dry climate of this region minimizes potential water-quality problems compared to wetter regions of the Western United States. Reactions with water in dumps and tailings are less likely to release metals into surface or ground water than in wetter regions. One example of this is at mercury mines that produced large dumps, disturbance, and calcine from retorts, but at which there are few signs of significant mercury mobility. However, there is high potential for contaminated runoff from several kinds of mine waste and tailings during storm events. In this dry climate, efflorescent salts tend to accumulate on dumps and tailings, and these very soluble salts dissolve to create a “first flush” of runoff that can carry high concentrations of many toxic metals. In this region of alkaline waters and high evaporation, there is high potential for As, Mo, and Se to accumulate in local transient puddles, playas, and ultimately in the Humboldt Sink. The gradual accumulation of metals in closed basins of western Nevada merits further study.

Introduction

Mining for more than 140 years in Nevada has produced numerous changes to the surface of the Earth, including an estimated 225,000–310,000 inactive and abandoned mine sites having a wide range in size and chemical composition (Price and others, 1995). Many say that the abandoned and inactive mine lands (AML) are the source of much contamination,

2 Hydrogeochemical Investigations of Some Historic Mining Areas in the Western Humboldt River Basin, Nevada

but field investigations suggest that a very small percentage (possibly 0.05 percent—Price and others, 1995) are sources of significant acid-mine drainage and related contaminants. These investigations are part of ongoing studies by the U.S. Geological Survey (USGS), Mineral Resources Program of the Geologic Division, designed 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. This report is the first from a program that is investigating the geology, geochemistry, mineral resources, and mineral-environmental characteristics of the Humboldt River Basin, in cooperation with the U.S. Bureau of Land Management (BLM) and U.S. Forest Service but funded as part of the Mineral Resources Program. The goal of this investigation is to use knowledge of mineral resources to predict where geochemical problems may be caused by historic mining (Plumlee and Nash, 1995; Plumlee and others, 1999), observe and sample those predicted sites, evaluate the new information and chemical results to understand processes that do or do not mobilize metals in the surficial environment, and identify problem sources of contamination. This report is restricted geographically to the western part of the Humboldt River Basin (that portion within the Winnemucca District of the BLM), but similar studies are underway by the author and colleagues to the east, in the central part of the Humboldt River Basin. Some mining districts described here are northwest of Winnemucca, Nev., and are not technically in the Humboldt Basin because they are in closed internal drainages.

The study area comprises the western part of the Humboldt River Basin and adjacent areas (fig. 1), with emphasis on mining areas relatively close to the Humboldt River. The mineral resources of the Humboldt Basin have been investigated by many scientists throughout 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 impacts on water and environmental quality. The mineral resources of the Winnemucca BLM District were described and assessed recently (Peters and others, 1996), but those investigations did not include the parallel component of mineral-environmental assessment. The investigations reported here apply some of the techniques and perspectives developed in the Abandoned Mine Lands Initiative of the USGS, a program of integrated geological-hydrological-biological-chemical studies underway in the Upper Animas River watershed, Colorado, and Boulder River watershed, 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, follow-up work should be done using trace-

metal sampling protocols and more precise analytical methods. Additional studies, such as biological populations, may also be warranted by my reconnaissance studies.

Acknowledgments.—Discussions with BLM staff in District offices of northern Nevada provided helpful guidance regarding priorities on public lands. Steve Brooks of BLM's Winnemucca District Office provided very helpful suggestions and technical information on priority sites. Bill Miller, Lisa Stillings, and Alan Wallace of the USGS offered helpful guidance on this project; and Stillings and Terry Klein, USGS, provided 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.

Data Files

Data files accompanying this report are located in the "Data" folder at the root directory of this CD-ROM. There are six data files, and each is provided in Excel and CSV (comma-separated value) format. Files "Location.xls (.csv)" show locations and descriptions of sample sites in the western Humboldt Basin, and files "Mineral.xls (.csv)" show results of chemical analyses of mineralized samples (solids).

Files "Leach1.xls (.csv)" contain analytical results for ICP-MS analyses of leachate solutions from the Humboldt Basin and show all analytical values for all elements determined. Files "Leach2.xls (.csv)" contain partial listings of analytical results for ICP-MS analyses of the leachate solutions.

Files "Water1.xls (.csv)" contain analytical results for ICP-MS analyses of water samples from the Humboldt Basin and show all analytical values for all elements determined. These files include results for samples collected in the central part of the Humboldt Basin, near Battle Mountain, that are not discussed in this report; however, some geochemists may find the results useful for comparison with results for the western part of the Humboldt Basin discussed in this report. Files "Water2.xls (.csv)" contain partial listings of analytical results for ICP-MS analyses of the water samples.

Analytical results for all analyses of dump, leachate, and water samples collected by the author for the entire Humboldt River Basin study area from 1995 to 2000 are available elsewhere (Nash, 2000a).

Methods

Fieldwork for this study was conducted in May 1998, but I 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, U.S. Geological Survey records in the Mineral Resources

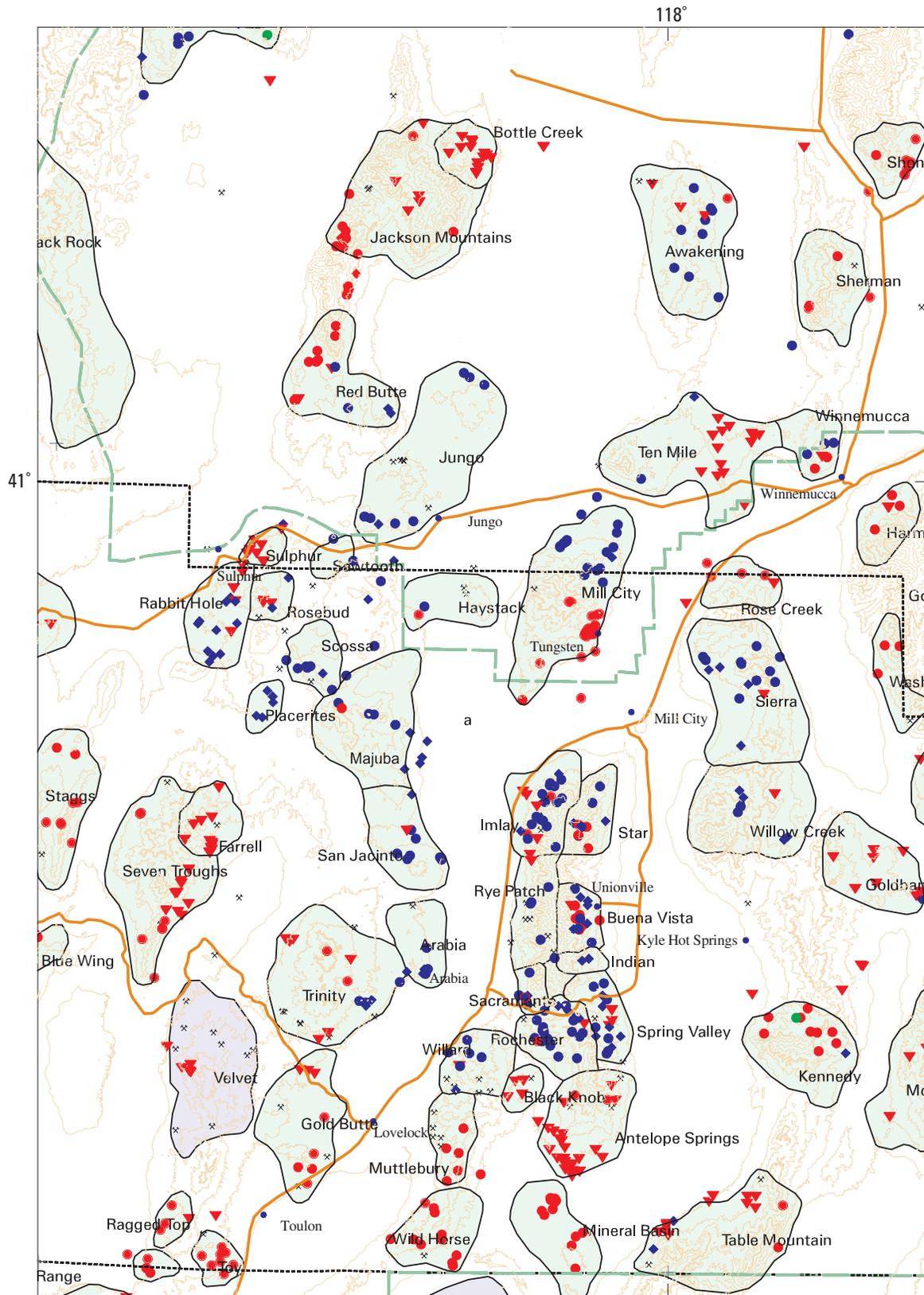


Figure 1. Map of the western Humboldt Basin study area showing location of mining districts investigated and mineral occurrences. For complete explanation of map symbols, see Peters and others (1996). Modified from Peters and others (1996, plate 1).

4 Hydrogeochemical Investigations of Some Historic Mining Areas in the Western Humboldt River Basin, Nevada

Data System (MRDS), information on U.S. Geological Survey 1:24,000-scale topographic maps, and by accessibility. Sample localities were recorded on topographic maps and measured with a conventional GPS instrument having an accuracy of about ± 100 to 150 ft based on tests at known sites.

Rock Chemistry

Rock 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 the collection of numerous small portions at 20 to 30 subsites and sieving the materials through a 2-mm stainless steel sieve to derive a composite sample weighing about 2 to 4 pounds; this is the standard protocol developed for USGS-AML investigations (Nash, 1999).

Rock samples were prepared for analysis under the direction of Paul Lechler, Nevada Bureau of Mines and Geology, Reno, Nev., and analyzed by two commercial laboratories. In one method, the rocks are dissolved in a mixture of four acids, then the concentrations of 35 major and trace elements are determined using inductively coupled plasma (ICP); 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 (1990), although slight variations in method may exist between laboratories. Rock samples were also analyzed by a method that employs weaker acids to dissolve most minerals, and then employs 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; 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), 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 reported concentrations from correct ones) is less than 5 percent for most elements.

Leachate Chemistry

The chemical analyses just described 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 utilized. Solid

materials from dumps, mill tailings, and outcrops have been processed in the lab by a leach method that provides a measure of reactions in nature, such as during weathering or storm events. Quite simply, 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 beaker is agitated slightly, chiefly to mix the leachate solution. At 24 hours the acidity (pH) and conductivity of the leachate is measured, and a 60-mL portion (aliquot) is taken with a syringe and passed through a 0.45- μ m 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 an ICP-MS (inductively coupled plasma–mass spectrometry) method that provides results for 60 elements to detection levels well below 1 ppb (part per billion, equivalent to microgram per liter). This analytical method, identical to that used for natural water samples that is described next, is well suited for this work because the leachates are highly varied in composition and this method provides results for elemental concentrations that span the range from 0.1 to 1,000,000 ppb. Anions are not determined by ICP-MS and no work has been done on them in this investigation because the dominant anion in acidic solutions is expected to be sulfate. The analytical results resemble those for surface waters degraded by mine waste. However, unlike the water analyses that show the results of real water-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.

For most rock samples no sample preparation was done for these tests. The majority of dump samples were sieved to pass 2 mm while in the field. Mill tailings are, by their nature, ground to fine sand size and were not sieved. In a few instances, efflorescent crusts on dump or tailing materials were hand picked in the field or lab to provide material for leaching that is more than 50 percent crust. The samples were dry and friable when weighed and placed in the reaction vessel.

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 $\mu\text{S}/\text{cm}$ (often termed “microsiemens”), 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 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 units. 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- μm cellulose filter. The syringe and the 60- or 120-mL polyethylene bottle were rinsed twice in the sampled water prior to collection. The filtered sample was acidified to a pH of about 2 at the site with 5 drops of ultrapure 1:1 HNO_3 per 60 mL. The acid stabilizes most metals but is not effective for mercury—regrettably no reliable Hg determinations can be made with this sampling method because it becomes adsorbed on the container (J. Gray, oral commun., 1997). At selected localities where results for Hg were needed, a special aliquot was collected and filtered into a glass bottle to which had been added an appropriate amount of dichromate solution to stabilize Hg prior to analysis (Crock, 1996). At appropriate localities (with pH >4) an unfiltered sample was collected for determination of alkalinity. Lab and field blank tests using deionized water indicated that contamination introduced by the sampling procedure and equipment is in the low parts per billion level (1–10 ppb), which is considered adequate in the search for metal concentrations orders of magnitude greater than the sampling error. Stated in other words, because the known goals of this reconnaissance were to determine which metals are significantly enriched in surface waters—far above so-called “trace levels”—costly and time-consuming trace-metal protocols of the USGS or EPA 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 below 1 ppb, but in this report only 10 to 15 elements of prime environmental concern will be discussed. Quality assurance is described in Appendix 1. This analytical method is appropriate for determination of many metals of potential concern that are expected to have a wide range in concentrations; it is especially good for trace metals in water such as As, Cu, Pb, and Zn. (Crock and others, 1999). If water compositions reported here are a concern, follow-up work should be done using trace-metal sampling protocols and more precise analytical methods.

Geologic and Geographic Setting

Geology of the Winnemucca District is well known from numerous studies of regional and mining district geology (e.g., Knopf, 1924; Wallace and others, 1969; Johnson, 1977; Peters and others, 1996) and need not be reviewed here. Details can be found in maps and reports elsewhere, but a few points of geology should be emphasized here to set the framework for the mineral-environmental investigations:

1. The composition of many geologic units has important ramifications. Carbonate-bearing units (limestone, dolomite, calcareous shale) are fairly common in the region, especially in the Humboldt Range; these rocks provide excellent acid-neutralizing capacity (ANC) themselves, and clasts of these lithologies in stream deposits (alluvium) extend those properties to near-surface materials in contact with surface waters. 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 ANC.
2. 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 to the north and east, and possibly at the Wildcat mine and prospects at the north end of the Seven Troughs district.
3. 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 waters are caused by man and mining.

Climate has a major role in near-surface geochemical processes (Plumlee and Nash, 1995). The arid climate of the region minimizes potential reactions and transport of metals (metals broadly defined to include metaloids such as As, Sb, and Se, including both cationic and anionic forms (i.e., Cu^{++} and MoO_4). In detail, precipitation varies appreciably as a function of elevation. The higher elevations, such as in the Humboldt Range, receive more than twice as much moisture a year than the lower parts, chiefly in the form of snow. Most of the mining areas receive about 4–8 inches of precipitation a year (Houghton and others, 1975), whereas the mountain crests may receive more than 16 inches. Evaporation exceeds precipitation in most of the area, which reduces the magnitude of some hydrogeochemical effects in surface waters, but it enhances others. There are two especially noteworthy problems. Evaporation can concentrate some toxic metals to hazardous levels—in this area the elements most prone to this are As, Mo, and Se. Local ponds and playas can potentially accumulate these metals. At regional scale, the Humboldt River basin is a closed internal basin and the river water eventually evaporates in Humboldt Sink. There is the potential for metals such as As, Mo, and Se—released in daily amounts that exceed no regulations—to accumulate in both concentration and total mass.

Introduction to Ore-Deposit Types and Their Environmental Signatures

Many types of ore deposits have been located or mined in the Humboldt Basin throughout the past 125 years. Economic geologists utilize numerous classification systems to compare and summarize geologic and economic attributes of deposits (Lindgren, 1933; Cox and Singer, 1986; Guilbert and Park, 1986). If one were to utilize one of these classifications, 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 non-geologists and include much detail that is not necessary for a general understanding of mine-related geochemical impact on the environment. A much simpler system will be used here that emphasizes host-rock type (lithology) and ore composition, both of which play major roles in the generation and dispersion of acidic waters and chemical pollutants.

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 galena (PbS), sphalerite (ZnS), and chalcopyrite (CuFeS₂)), 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 high 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 later. Some are relatively large vein and replacement zones in limestone, as at the original Cortez silver mine or the Arizona mine near Unionville, Nev., also described later. 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, Montour,

and others, 1995). Because mining-related degradation commonly is proportional to the magnitude of disturbance (workings, mine dumps, tailings), it should be noted that these deposits tend to be relatively small in size (commonly less than 1 million tons, but some can be much larger) (Cox and Singer, 1986). Also, the global tendency to form in calcareous sedimentary rocks means that materials with high acid-neutralizing capacity are commonly present in mines and mine dumps, or nearby, and this can provide important natural mitigation for initially acidic and metal-rich waters.

Skarn Deposits

These deposits have been important sources of tungsten, copper, and molybdenum in Nevada, and recent technologic changes in bulk mining and bulk processing have allowed some deposits to be mined for gold that were considered uneconomic 20 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 historic 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 rocks (Hammarstrom, Elliott, 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 little sulfide in the mine and in waste dumps to create acid.

Only one mining area of skarn deposits was investigated in this study, the Mill City tungsten district.

Epithermal Vein Deposits

These deposits have been important sources of precious metals in many Nevada districts, including National, Tenmile, Midas, and Seven Troughs. 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 to 1990's (i.e., Sleeper, Florida Canyon, and Mule Canyon—an open-pit mine is also proposed for Goldbanks). These deposits are generally in Tertiary volcanic rocks, but the Florida Canyon example shows that 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 oxida-

tion. However, former underground mining and conventional milling of ores could accommodate sulfidic ores, as in the National and Seven Troughs districts. Sulfidic waste and tailings from the older mines pose substantially greater problems than those from the oxidized, low-sulfide, bulk-mined epithermal ores (Nash and Trudel, 1996). Character of wallrock alteration is an important factor in exacerbating or mitigating drainage signatures—green kinds of propylitic alteration provides added ANC, whereas most clay-rich (argillic) or acid-sulfate alteration adds acid and metals.

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, Colorado, very acidic, metal-rich mine drainage develops from examples that were rich in base-metal sulfide minerals and exposed to the moderately wet climate (Nash, 1999). Examples 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 waters develop and these carry high concentrations of many metals. In most other Nevada locales, these epithermal deposits create few problems, as will be described later.

Examples of epithermal deposits and districts described in this report include the Seven Troughs district, part of the Tenmile and Slumbering Hills districts, and the Willard mine.

Mercury Deposits

Deposits of cinnabar 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 above, but merit special treatment because of the problems associated with high mercury concentrations. The volcanic-rock-hosted mercury deposits of the Bottle Creek, Ivanhoe, and Goldbanks districts 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. Deposit of Hg in sedimentary rocks of the Antelope Springs district favor carbonate rocks and are controlled by major faults (Bailey and Phoenix, 1944). The genesis of these deposits is not well understood and has not been investigated by modern methods. The sulfide and alteration minerals at mercury deposits suggest that they may be related to polymetallic deposits in the Humboldt Range—both clearly are epithermal in character (low-temperature hydrothermal).

Environmental concerns at mercury deposits are numerous and complex (Rytuba and Kleinkopf, 1995). The major concerns at 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 (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 no mines are 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 methyl mercury is unlikely at these sites in Nevada (Rytuba and Kleinkopf, 1995)—such health concerns are beyond the scope of this study and specific investigations are recommended to address those questions.

Two classic Nevada mercury districts were investigated, the Antelope Springs and Bottle Creek districts, and results are described later in this report.

Sediment-Hosted Gold Deposits

Deposits of gold in sedimentary rocks, often called “Carlin-type” for the first major mine of this type, 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 Standard mine in the Humboldt Range is possibly in this class, although details of ore formation may differ from the deposits in the Carlin mine area. The environmental signature of the Standard mine and tailings are highly influenced by sedimentary host rocks. 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. Important geoenvironmental aspects (Hofstra and others, 1995) include:

1. Host rocks that have moderate to high acid-neutralizing capacity (ANC) from carbonate minerals,
2. Fine-grained pyrite in ore and alteration zones that commonly amounts to 5 percent by volume and locally—below the weathered zone—amounts to as much as 50 percent, and
3. A trace-element suite that includes substantial amounts of As, Sb, Hg, Se, and Tl, and locally Zn and Cd (but other base metals are low).

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 unweathered rocks contain appreciable amounts of fine-grained pyrite, most acid created during post-mining oxidation is neu-

tralized 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, Sb, Mo, Se, Tl, and Hg 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 As, 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 Standard mine, was investigated and is described later. It is much smaller than the major mining operations to the northeast, but may provide some useful insights to those mining areas.

Porphyry Cu-Mo Deposits

Porphyry deposits of copper and molybdenum, associated with shallow-level igneous stocks with 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, Utah) 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 waters and encourages acid-generating and metal-liberating reactions.

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. The Mo-rich variety (termed “Climax-type”) have the potential to produce acidic waters that are rich in F and U.

Porphyry deposits are not common in Nevada, but two have been mined in the Humboldt Basin at Copper Canyon and Copper Basin (Battle Mountain district), and a few prospects have been drilled. Significant Mo and Cu porphyry pros-

pects are known at Buckingham, near Battle Mountain, and at Majuba Mountain, Pershing Co., Nevada. The Cu mines and Mo prospect at Majuba Mountain were investigated here but are not typical of the large open-pit mines on porphyry deposits.

Introduction to Chemical Composition of Dumps, Tailings, and Mineralized Rocks

Metal concentrations in mined rocks vary greatly by deposit type and by style of mining. The previous section described general compositional trends by deposit type. In chemical terms, abundances of metals range 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 that wind up on waste piles. Geology determines the concentration of these metals, and their concentrations generally are predictable by geologic setting and deposit type (Plumlee and Nash, 1995; Plumlee, 1999).

Compositions of mined and waste rocks in mining districts reflect economic and technologic factors, 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 very low (background) concentrations of metals and generally low sulfide content, is removed while gaining access to ores by excavating shafts or cross-cut tunnels, or by stripping in an open-pit mine, and in most mines this variety of waste is stacked in piles that are spatially distinct from mineralized ones. Stockpiles of ore-grade material are generally rare, but not uncommon, in prospects and reopened mines that lack a nearby mill to treat the nominal ore.

There are substantial differences among tailings that reflect changes in economics and technology (Nash, 2000b). Stamp mills in the 1800’s, which utilized 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 is substantial variation in tailings mineralogy and composition

from a given mill, shown by visibly differing colors of layers in the impound—this reflects the (1) changing character of ore mined (such as oxidized near surface ore vs. sulfidic deeper zones), (2) changes in ore mined on a custom basis (same mill, but ore from different mines), or (3) changes in mill function. In a general way, 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. Sulfidic tailings are not common in the study area because most mills were designed to remove these minerals, but even a few percent 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 is the sulfide-rich tailings from the Rio Tinto massive sulfide mine near Mountain City, Nev., that is a Superfund-caliber site because of contamination it introduces into the Owyhee River.

Representative samples of dumps, tailings, and unmined altered rocks were collected and chemically analyzed to provide a generalized chemical description of the range in composition of these materials. Table 1 shows the median and maximum concentrations of elements of possible mineral-environmental interest, including summary statistics for both the central part of the Humboldt Basin (roughly centered on Battle Mountain) and the western part that was investigated in 1998. In this report the simple terms high and very high will be used to describe concentrations of elements relative to the database of 69 samples for the western area. 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 seven deposit types in the Humboldt Basin are shown on figure 2. Clearly there is a broad range in metal concentration for various samples of materials associated with these seven types of deposits. Although generalizations are risky, there are some general trends. Polymetallic vein, massive sulfide, and porphyry deposits tend to contain high concentrations of base metals, whereas mercury and volcanic-hosted vein deposits tend to be low in these metals. Concentrations of base metals in the Rochester samples is similar to that of polymetallic vein deposits.

Passive 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 below 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. Most of the samples created orange to pale-yellow colored water; a few were light gray and some produced very little color. Suspended material in the leachates tended to settle in 8–10 hours, and these clear solutions were easy to filter. A small percentage of samples created milky solutions that did

Table 1. Summary of chemical composition of dump, tailings, and mineralized rock samples, Humboldt Basin, Nevada.

Element	Central Humboldt Basin (n=226)			Western Humboldt Basin (n=69)	
	Minimum (ppm)	Median (ppm)	Maximum (ppm)	Median (ppm)	Maximum (ppm)
Ag	<0.02	8.1	2,890	23	279
As	0.03	165	15,700	466	5,110
Au	<0.001	0.12	25.8	0.25	4.3
Bi	<0.02	1.4	>9.8	0.36	273
Cd	<0.01	1.6	990	1.8	114
Cu	<2	94	91,400	57	10,150
Hg	<0.01	1.5	4,930	2.1	531
Mo	<0.1	5.0	1,580	8	2,085
Pb	<5	181	42,840	633	12,360
Sb	<0.2	26.9	8,860	132	3,330
Se	<1.0	3.0	>98	1.6	41.4
Te	<0.5	1.1	164	0.26	49.8
Tl	<0.5	1.9	19.9	0.71	28.2
Zn	<1.0	151	24,400	229	4,310

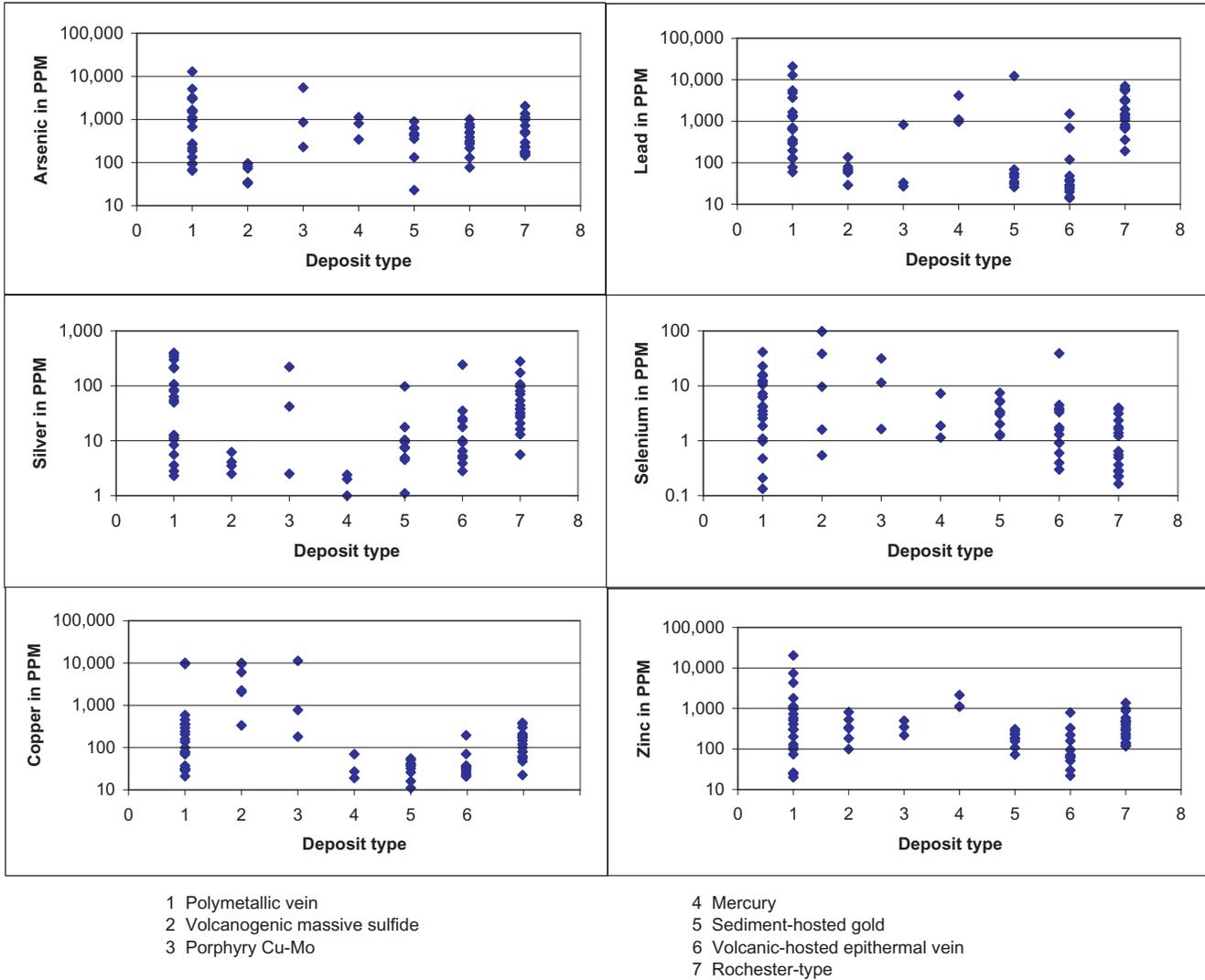


Figure 2. Trends for rock geochemistry by deposit type.

not clear overnight, and some of these (notably the Rochester tailings) were difficult to filter. A summary of the leach tests are in table 2.

Some general trends are evident in the leachate compositions. Comparing results for dump, tailings, and altered rock samples, leachate concentrations generally are highest in dump samples and lowest in altered rock samples. Likewise, there is wide variation in leachate concentration within the groups of dump samples, tailings, or altered rock samples. This wide variation is consistent with the wide range in dump compositions and differences in tailing composition from mill to mill or even from layer to layer within a tailings impoundment.

The following brief comments are for leach test results from dump, tailing, and altered rock samples from Humboldt Basin to give the reader a feeling for how the analyses are used to understand the behavior of certain metals in mined materials.

As Highest concentrations are from dump samples, but

some tailings yield similar high concentrations; many samples yield >50 ppb, and some are higher than 200 ppb. Arsenic is mobile under both acidic and neutral-alkaline pH conditions.

- Cd Highest concentrations are at acidic pH, but some are high at pH 6–8. Only a few samples exceed 5 ppb.
- Cu Highest concentrations come from acidic solutions (pH <4), but a few are high—pH 7–8 (which was not expected). Many dump samples yield concentrations far above 10 ppb, but most tailing and altered rock leachates are not this high.
- Mo This element is mobile in either acidic or alkaline leachates. Dump and tailings samples are similar, and only a few samples yield more than 15 ppb.
- Pb Highest concentrations are in acidic (<pH 5) leachates. Only a few samples exceed 50 ppb.
- Sb Concentrations do not correlate simply with leachate pH, but the highest concentrations are in alkaline leach-

Table 2. Summary of chemical compositions of leachates, Humboldt Basin, Nevada.

Element	Central Humboldt Basin area				Western Humboldt Basin area			
	Dump (42)		Tailings (17)		Dump (20)		Tailings (25)	
	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum
Leach pH	4.1	2.1	5.5	3.1	6.3	3.7	8.6	3.7
As (ppb)	1.8	47,300	3.6	314	10	137	17	203
Cd (ppb)	0.7	1,340	0.08	351	0.4	9	0.1	826
Cu (ppb)	9.7	83,200	2.8	238	7.5	4,390	1.1	73,700
Fe (ppb)	175	172,800	73	2,720	76	4,830	23	2,950
Mn (ppb)	150	11,100	4.7	2,900	6.3	1,580	0.7	21,560
Mo (ppb)	1.9	120	1.3	13.1	0.7	13	1.0	240
Pb (ppb)	0.8	1,500	0.3	2,160	1.2	716	0.7	1,560
Sb (ppb)	0.4	483	0.3	53.7	1.1	6.0	5.4	302
Se (ppb)	1.2	29.8	1.1	36.1	0.3	18	<0.2	83
Zn (ppb)	55	31,900	11.5	7,280	42	505	3.0	20,930

ates. Most leachate concentrations are low, and only a few samples exceed 100 ppb.

- Se Concentrations can be high in either highly acidic or alkaline leachates. Some of the highest concentrations come from tailings. Many leachates exceed 5 ppb, the maximum allowable concentration in the aquatic life standard.
- Te Observed concentrations were low and do not appear to indicate a problem for Te being mobilized into surface waters.
- Tl Samples from the western area yielded low concentrations of Tl in leach tests and suggest that, in these materials, thallium will not be released in sufficient amounts to be a concern.
- U Uranium is below concern levels in samples tested from the western Humboldt Basin, but at a few places in northern Nevada (near Austin) uranium-rich dump rocks release significant amounts of U into acidic leachates.
- Zn High concentrations are generally in acidic leachates (pH <4), but some are high—pH 7–8. High concentrations are above 100 ppb, and some very high concentrations exceed 1,000 ppb.

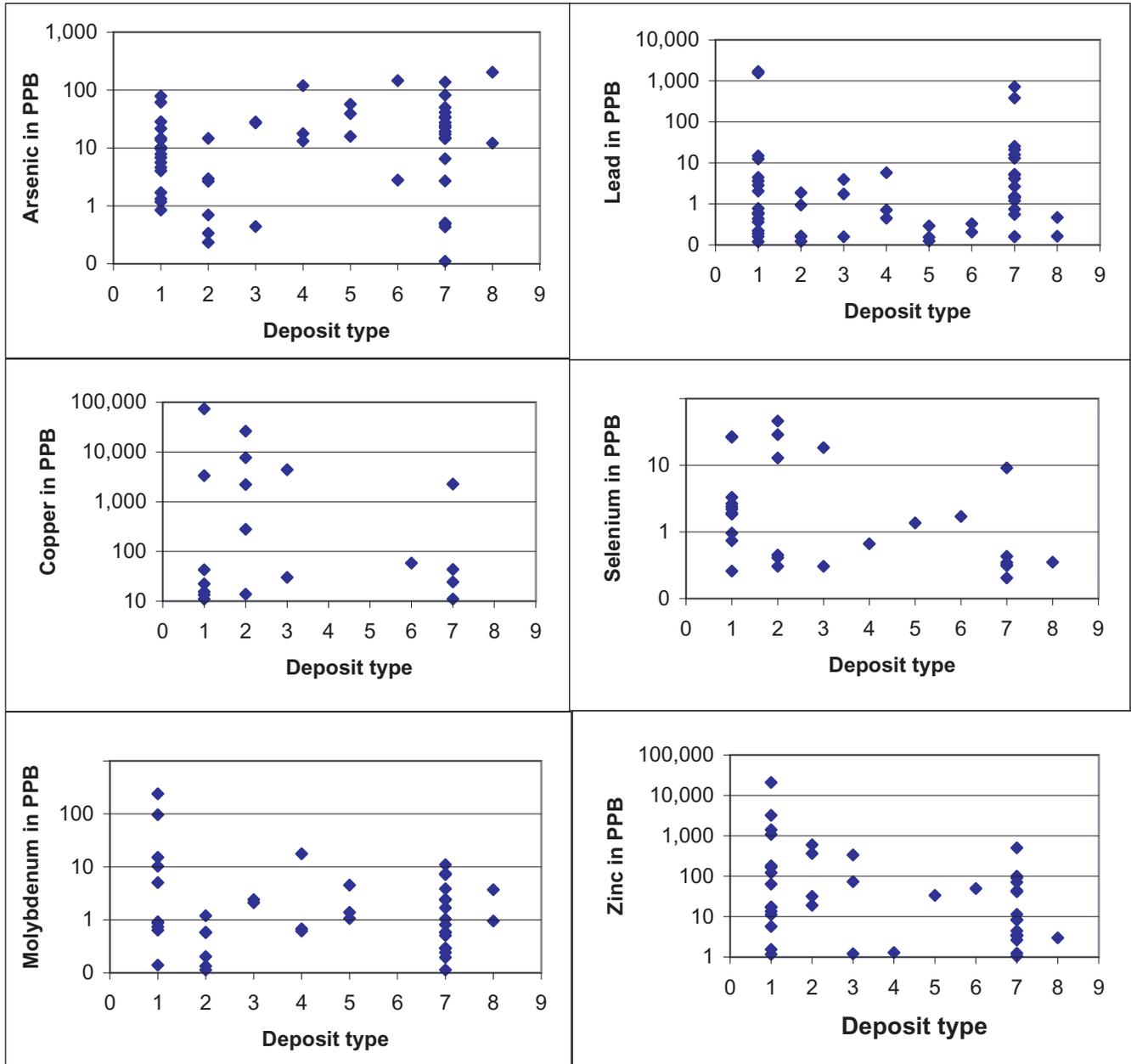
Trends for leachate compositions, grouped by deposit type, are shown in figure 3. Results include deposits in the Battle Mountain, Hilltop, and Black Diablo (Big Mike) mining districts—these districts are not discussed in this report but were sampled in 1998. The eight deposit types clearly do not produce a close cluster of leachate compositions—compositions for polymetallic, massive sulfide, and Rochester-type samples span several orders of magnitude. Base metals and arsenic tend to be highest in these three deposit types, but not uniquely so. As shown in figure 3, these results demonstrate the need to observe and sample mining-related materials to determine the mobility of metals.

Introduction to Mine-Related Waters

Surface waters 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 waters associated with coal mining, and in recent years the focus of much research and regulatory action has shifted to contamination associated with abandoned or active metal mines, mills, and smelters (Plumlee and others, 1999). The following is a highly simplified summary of some of the major principles, largely taken from reviews by Smith and others (1994) and Plumlee (1999), and Plumlee and others (1999).

Acid waters.—Why all the emphasis on acid mine drainage (AMD) and acid rock drainage (ARD)? 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 problems. Sulfuric acid is typically generated by weathering (oxidation) of pyrite or other sulfide minerals, often catalyzed by bacteria (Smith and others, 1994). Another source of acidity is reaction of water with jarosite-group minerals (K-Fe-Al-sulfate with significant Pb and other elements), according to research by G.A. Desborough (written commun., 1998). A third source of acidity in near-surface waters is the precipitation of Fe and Al oxy-hydroxide minerals in which protons (hydrogen ions) are produced by hydrolysis reactions.

Acidic waters have 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 (fig. 4) (Smith and others, 1994). In numerous districts, and across many deposit types, there is a predictable relation: the more acid (lower pH), the higher the metal concentration.



Leach tests

- 1 Polymetallic vein
- 2 Volcanogenic massive sulfide
- 3 Porphyry Cu-Mo
- 4 Mercury
- 5 Sediment-hosted gold
- 6 Volcanic-hosted epithermal veins
- 7 Rochester type
- 8 Gold veins

Figure 3. Geochemical trends for leachate compositions by deposit type.

The range of compositions for 53 water samples collected in the Humboldt Basin in May 1998 is summarized in table 3.

Correlations of water compositions with 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 vein deposits, and there are many exceptions to general “rules.” For the Humboldt Basin, the trends are summarized in figure 5. Highest concentrations of base metals tend to be from polymetallic and massive sulfide deposits (Big Mike is the example). Contrary to some

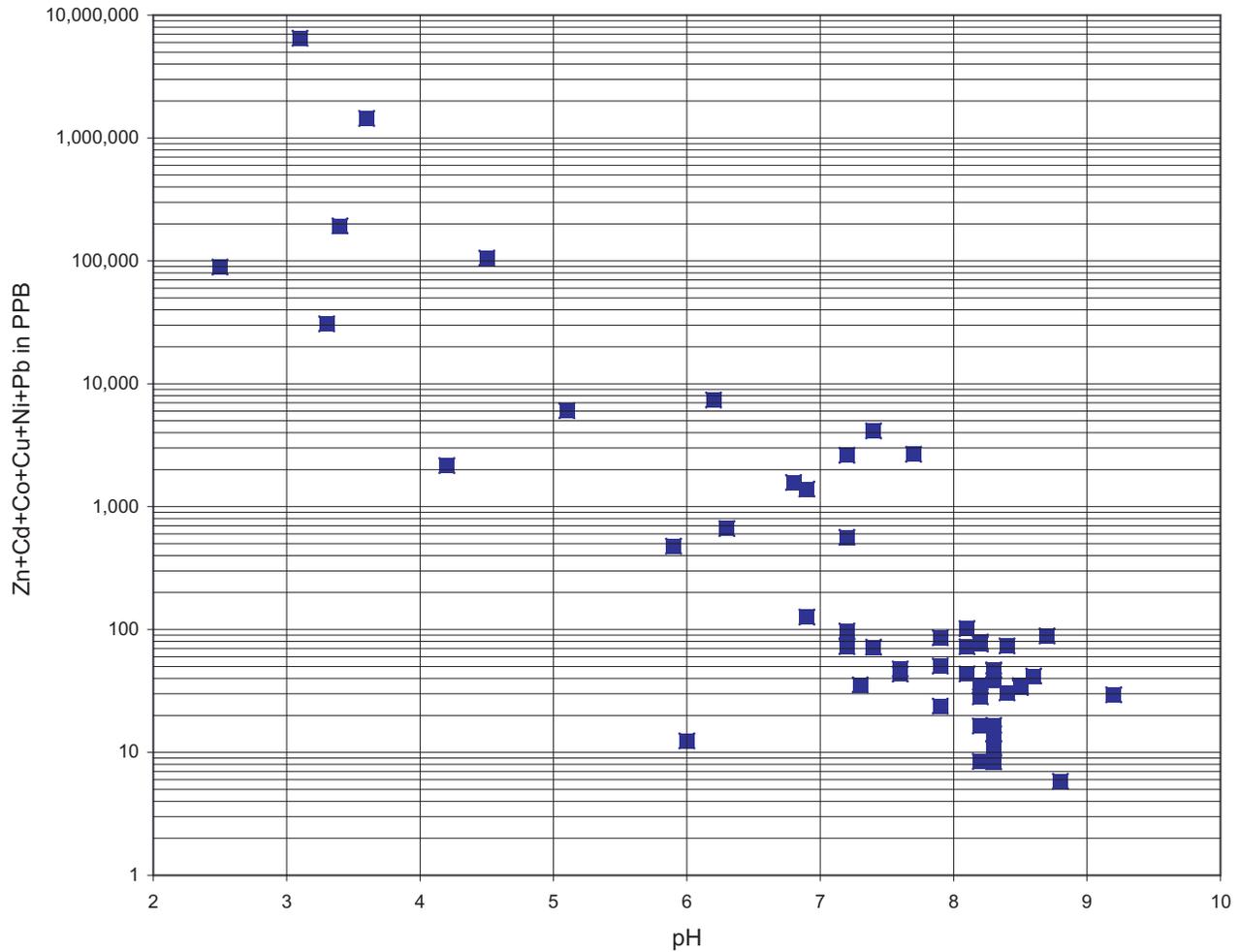


Figure 4. Ficklin plot of surface water compositions.

Table 3. Summary of surface water compositions, western Humboldt Basin, Nevada, May 1998.

[Analyses are by ICP-MS, reported in parts per billion; pH is in standard units, conductivity is in $\mu\text{S}/\text{cm}$, and alkalinity is in $\text{mg}/\text{L CaCO}_3$]

Component	Minimum	Median	Maximum
pH	2.5	7.2	8.7
Conductivity	206	690	>2,000
Alkalinity	0	222	390
Al (ppb)	2.4	88.2	351,640
As (ppb)	0.4	15.5	19,055
Cd (ppb)	0.04	1.4	5,113
Cu (ppb)	1.2	9.4	79,040
Fe (ppb)	289	892	772,140
Mn (ppb)	0.5	114	65,140
Mo (ppb)	0.5	2.6	181
Pb (ppb)	<0.1	0.2	611
Sb (ppb)	0.2	1.0	57.6
Se (ppb)	0.8	4.5	95.8
Te (ppb)	<0.2	<0.2	<0.2
Tl (ppb)	<0.01	0.01	1.0
U (ppb)	0.1	1.6	100.8
Zn (ppb)	<5	47.9	147,730

popular assumptions, concentrations of As and Se are variable and are in roughly the same range for many deposit types.

Alkalinity of surface waters.—One of the most striking characteristics of surface waters in arid regions of the Western United States is their high content of Ca-Mg-CO_3 —most obvious in measurements of conductivity and alkalinity. Waters in the Humboldt Basin and many parts of the Basin and Range Province generally have conductivities of $300 \mu\text{S}/\text{cm}$ or more and alkalinities of more than $200 \text{ mg}/\text{L CaCO}_3$. 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 normal waters 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/liter. Surface water samples from the study area have alkalinities in the range of 0 to 390 $\text{mg}/\text{L CaCO}_3$ 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.

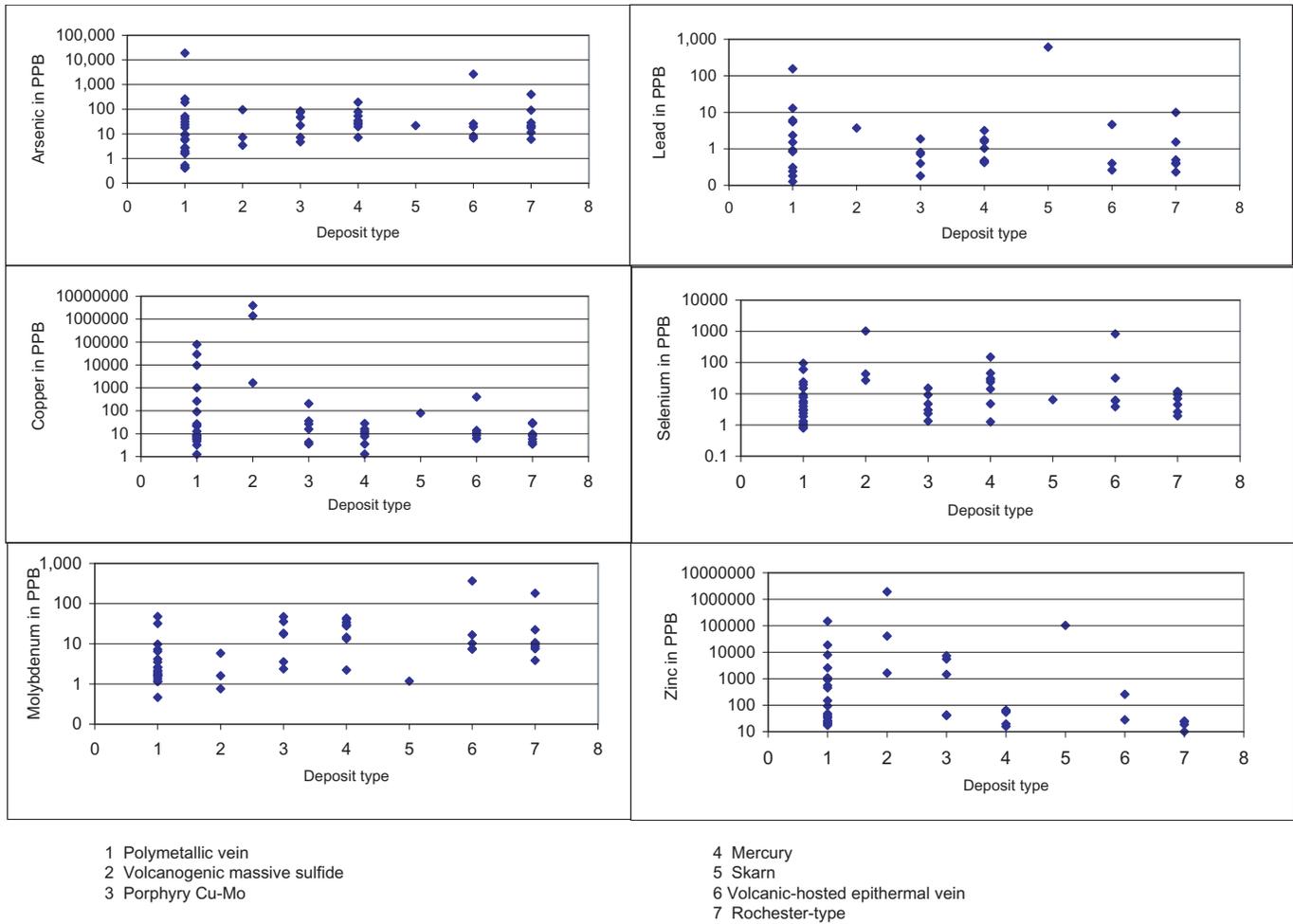


Figure 5. Geochemical trends for waters associated with mines.

The high alkalinities of most waters in the study area are potentially significant for natural processes of acid neutralization. These alkaline waters have high capacity to neutralize acidic waters 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 waters or subsurface springs. If the water is initially very acidic, with pH of about 3, the waters generally are clear (all metals are held in solution) but the waters become cloudy red-brown and precipitate iron oxy-hydroxide minerals (“iron floc”) a short distance after mixing as the rising pH causes iron and other base metals (Cu and Pb first) to precipitate. This is essentially titration, as done in the chemistry lab, of an acidic solution by an basic solution. This process is commonly seen in Nevada, in acidic drainages, and generally reflects mixing of solutions rather than reaction of an acidic solution with a rock such as limestone.

Buffering and acid neutralization by rocks.—Natural or engineered mitigation of acidic mine drainage involves raising the pH of waters by consumption of hydrogen ions. Limestone,

composed chiefly of the mineral calcite (CaCO_3), is most effective for consuming acid but reaction with other minerals also consumes acidity, albeit more slowly than for carbonate minerals. Ion-exchange reactions, as with clay minerals, also helps. Acid-neutralization capacity (ANC) 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 ANC 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 (e.g., Glass and others, 1982). Also, the estimates generally fail to acknowledge the large amount of calcite in alluvium

as caliche and 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 ANC is by measuring pH at springs—values in the range of 7 to 8.5 are caused by reactions with carbonate somewhere in the flowpath of the water. Waters with alkaline pH can neutralize acidic waters, as described above, 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), 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 stream beds and coatings on stream cobbles (Fe-oxy-hydroxides 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 and others, 1994). Arsenic can be 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 in zones where acidic waters mix with those of near-neutral pH or encounter 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 waters 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 exceeds 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 waters and reduce the concentrations of most metals below concern levels. However, concentrations of Zn, Cd, As, Mo, or Se remain high in some surface waters at pH 6–8.

Regulatory Standards.—Compositions of mine-related waters must be evaluated in the framework of regulatory standards set by the Clean Water Act and by regulatory agencies such as the Nevada Department of Environmental Protection. These standards generally are based on beneficial use and toxicity to humans or aquatic life. Beneficial use designations are assigned by Nevada Department of Environmental Protection (NDEP; see www.state.nv.us/ndep/bwqp) for the major streams and rivers. In the Humboldt River Basin only the main stem of the Humboldt River has use designations, and for it the water quality is evaluated every 2 years as required by the Clean Water Act, Section 303(d). The smaller streams in the basin do not have use designations by NDEP. Only in a few

places in the western Humboldt Basin are surface waters used locally for drinking water. In this report I will compare water composition to the aquatic life water quality standard (ALWS), shown in table 4. These ALWS concentrations are used here as a general guideline and to allow comparison among districts, but aquatic life may not be the regulatory standard for that surface water (for example, a few streams are designated for domestic drinking water).

Table 4. Aquatic life and domestic drinking water quality standards for Nevada.

[From Nevada Department of Environmental Protection, 1999; concentrations in parts per billion or micrograms per liter (µg/L)]

Element	Water quality standard for aquatic life	Water quality standard for drinking water
Ag	0.15*	
As	180	50
Cd	5*	
Cu	10*	
Fe	1,000	
Hg	0.05	2
Mn	1,000	
Mo	19	
Pb	50*	50
Se	5	50
Sb		146
Tl		13
Zn	100*	

Note: values shown with * should be adjusted for hardness; the values shown are for typical hardness of surface waters in the area, 200–300 µg/L.

Mining District Investigations

Investigations were made in 13 mining districts at sites that allowed access. The work focused on sites and impacts on public lands. Some sites visited may have been on private property (patented mining claims) that had no fences or signs posted. The approach was to examine and sample the mines that had relatively large production because my experience has been that the larger operations tend to have more impact than smaller prospects and mines because they disturb more ground, create large waste dumps, and most have associated mills and tailings. The district descriptions below include information on mineral production, to the extent that it is available, because that parameter helps the reader visualize the likely amount of disturbance and volume of dumps and mill tailings. Many of the districts contain more than one type of metallic deposit, and an effort was made to describe these separately while also making summary comments on impacts evident in the district. District geology is described in relatively nontechnical terms sufficient to provide a basic geologic framework for the geochemical results and interpreta-

tions; readers should consult other publications for more complete descriptions of geology.

The district descriptions that follow are organized in a sequence that emphasizes the dominant deposit type in the district. The descriptions attempt to give the reader a sense of the size of a mining operation and amount of disturbance, and field studies attempted to focus on larger mines in a district.

Rochester District

Location.—Western flank, central Humboldt Range, 15 mi northeast of Lovelock, Nev. (fig. 1). Precipitation about 4–8 inches per year in the mining area, somewhat more at the crest of the range. Features of the Rochester district are shown on figure 6 and on photos 1 to 8.

Principal commodities.—Ag, Au.

Brief mining history.—Gold and silver were first discovered in the area in the 1860’s, but the first real activity came in 1912 with the identification of high-grade ore on Nenzel Hill. Exploration and mining were active through about 1930, and there was little mining until 1980’s when Nenzel Hill was reevaluated for bulk mining—the large open-pit mine (fig. 6) started by Coeur Rochester continues to operate in 2000. The southern part of the district (fig. 6) was the site of the Nevada-Packard mine and nearby mines through 1930. The Nevada-Packard mine had a cyanide mill at the base of the hill (photo 1). A mile to the northwest, at Packard, Packard Mines Co. built a large mill in 1917 but operated it only a short time; the equipment was dismantled in 1922. The central part of the district (Nenzel Hill) was accessed from Rochester Canyon, with a town site in the canyon and several mills in the middle

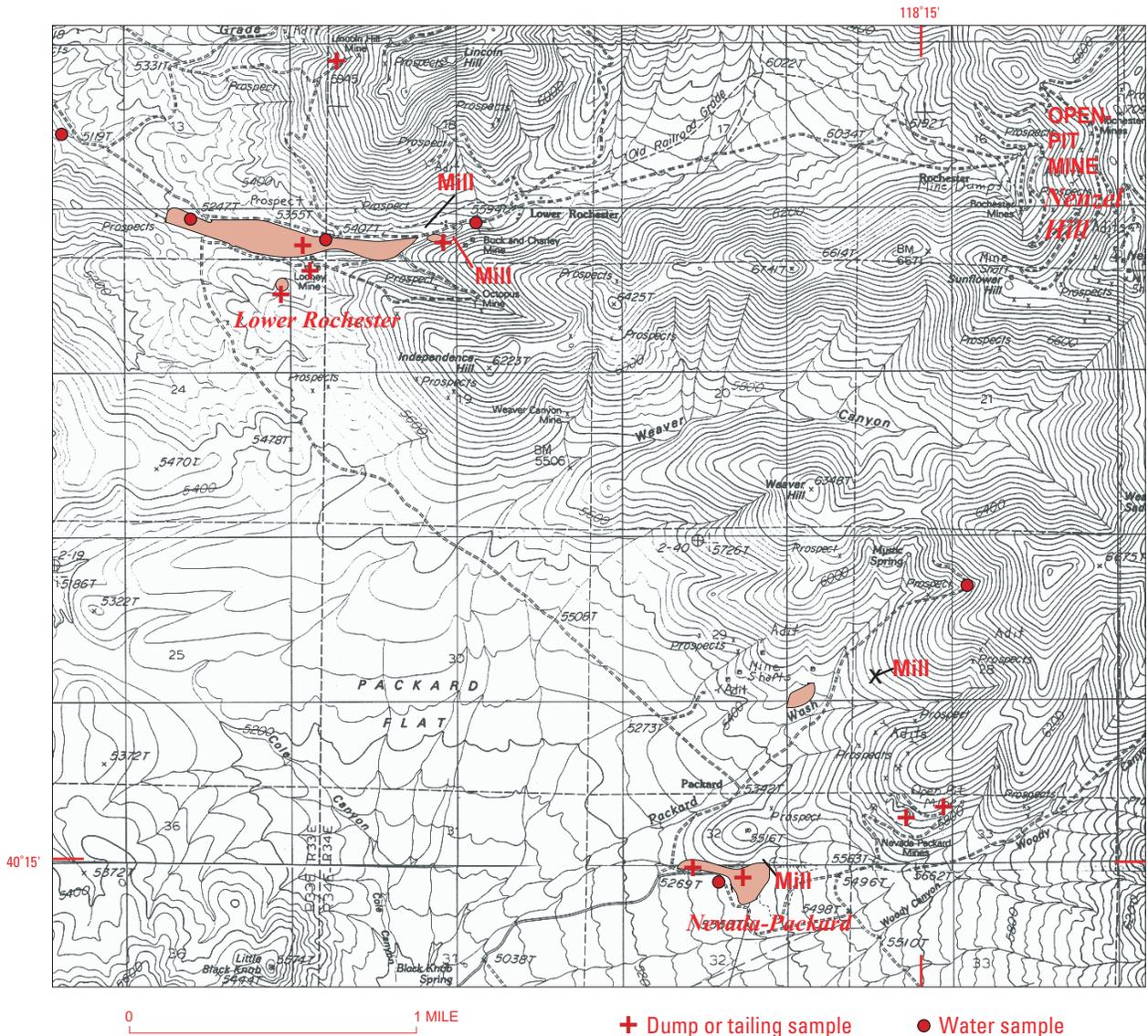


Figure 6. Features of the Rochester district, showing sample localities.



Photograph 1. This view to the southwest of the Nevada-Packard mine workings shows the mill site at the base of the hill, the 20 acres of mill tailings, and the piles of crushed rocks from the 1980's bulk mining–heap-leach operation. Flash floods erode tailings down the arroyo on the right side of the impoundment.

part of Rochester Canyon. The Rochester Mines Co. cyanide mill was a major producer through 1929 when the equipment was sold. The sulfide-rich ores of the Buck and Charley mine were treated by a 50 ton/day mill in lower Rochester Canyon, and the gold-quartz ores of the Looney mine were treated in a small stamp mill on the hill southwest of the canyon (photo 2).

Production.—Mining through 1951 produced more than 910,000 tons of ore containing more than 8.8 million oz Ag, more than 78,000 oz gold, and relatively minor values of copper, lead, and zinc. The resource in the newer Rochester open-pit mine is more than 94 million tons, and production has been about 6 million oz silver and 60,000 oz gold annually in the 1990's (Bonham and Hess, 1995).

Geology.—The key unit in the district is the meta rhyolite of the Triassic Koipato Group, which is host for the silver-gold deposits. On the west side of the district, sedimentary rocks of the Triassic Prida Formation are exposed, including beds of limestone and dolomite (Wallace and others, 1969). These rocks are intruded by large bodies of Cretaceous leucogranite, which locally metamorphoses the older rocks

and probably explains the apparently high-temperature tourmaline alteration in rhyolite. Funglomerate and older alluvial deposits on upland erosional surfaces carry important placer gold deposits.

Ore deposits.—Three kinds of metal deposits have been mined in addition to a rare variety of aluminum-silicate (dumortierite) that was formerly used to make ceramics such as spark plugs.

1. Silver-rich deposits in rhyolite that are unusually large and not like many other deposits in Nevada; the original ores contained pyrite-sphalerite-galena-chalcopyrite-tetrahedrite, but the only viable ore zones are those where supergene (weathering) enrichment of silver occurred in the formation of argentite. The fact that miners went after supergene enriched zones is important geochemically because most of the sulfide minerals in these rocks were oxidized prior to mining and milling, greatly reducing the likelihood of acid generation on mine dumps and tailings,
2. Silver-gold-quartz-tourmaline veins, as at Lincoln Hill and Looney mines, and



Photograph 2. The stamp mill at the Looney mine is a well-preserved example of the small mills that were typical of gold mines in the 1880's–90's. The stamps (vertical metal rods) crushed the quartz vein material so that gold could be recovered on jig tables.

3. Gold placer deposits in upland alluvial gravel in many of the canyons and flats. The placer deposits were not investigated here but could pose a problem if native mercury, commonly used to recover gold, was not handled carefully by the miners.

Mineral-Environmental Investigations

Two eras of major mining activity in this district have disturbed relatively large areas. The mining in the vicinity of the Nevada-Packard mine, by both underground and by a fairly recent attempt at bulk mining (photo 3), has created many dumps, trenches, and mill tailings in the southern part of the district. In the past 10 or so years there was a heap-leach operation, placed on top of earlier mill tailings. The historic mining on Nenzel Hill, in the center of the district, has been engulfed by the current open-pit mine and its waste dumps; that area was not visited, but the mill tailings produced from

the earlier Rochester Mine Company were examined in some detail.

Mine dumps in most places are tan to slightly rusty as a result of pre-mining weathering. Sulfide minerals are not abundant, and there are no signs of ARD in these rocks. Chemical analyses of five dump samples and two mineralized rock samples from trenches indicate more similarity in chemistry than one might surmise from color or mineralogy: samples tend to be moderately enriched in many base metals (Ag, As, Bi, Cu, Pb, Sb) whether sulfidic or oxidic. Some samples are enriched in Se, but most tend to be relatively low in Cd-Zn. These generalizations include samples from the Buck and Charley, and Lincoln mines of the sulfide type, and the Looney gold-quartz-tourmaline vein deposit, which are said to differ substantially from the Rochester and Nevada-Packard deposits (which are predominantly oxidized).

Tailings are a major concern because these materials were placed in or near canyons and arroyos, as in most districts, and all have been substantially eroded by storm events. Large



Photograph 3. Trenches and pits were excavated in these tan-colored rocks above the former underground workings of the Nevada-Packard mine in an attempt to bulk mine silver. The rusty color of the rocks is from iron-oxide minerals such as limonite and jarosite, derived from the weathering of pyrite that originally was in the rocks; the pre-mining oxidation minimized the tendency of these rocks to generate acid.

impoundments of mill tailings were made by the major mills at Nevada-Packard mine (photo 1) and by the Rochester Mine Co. mill in lower Rochester Canyon (photo 4). The lower Rochester impoundment is about 41 acres in area (Steve Brooks, BLM, written commun., 1998) and is deeply eroded on one side (photo 5). The Nevada-Packard tailings impoundment is smaller, about 20 acres in area. The tailings are 2 to 8 ft thick in eroded cuts. These major tailings piles are badly eroded by storm events in the canyons, and fluvial tailings are found for about a mile below the original impoundments (photo 6, photo 7). The volume of fluvial tailings is difficult to estimate, but appears to be substantial. The Buck and Charley mill has a nearby tailings pile of small size, less than an acre on the surface and perhaps a foot thick on average. The Packard Mine Co. mill, in service for only a short time, created only a small volume of tailings, which were placed in the valley to the west (photo 8). The Looney mine had a small stamp mill (photo 2) that created a very small volume of tailings in the canyon south of Rochester Canyon. Only the Buck and Charley ore and tailings contain visible sulfide minerals;

the Lincoln mine waste is sulfidic and the ore possibly was processed at the Buck and Charley mill.

Chemical analyses of 10 tailings samples show them to be enriched in many base metals, consistent with the composition of dump samples. The concentrations of Ag and Pb are surprisingly high (Ag ranges to 106 ppm), and Hg is 10–20 ppm in more than half of the tailings; Mo and Zn also are higher than in dump samples. The high Hg concentrations suggest the possibility of contamination during milling.

Passive leach tests were made on 15 samples, including 7 of tailings. Three leachate water samples were collected without filtration because most of the runs yielded murky solutions and the unfiltered solution provided information on metals that might be carried in the suspended very fine material (commonly called colloidal). Three samples of dump materials with visible sulfide minerals yielded pH's of 3.4 to 3.9; one of these from Buck and Charley mine carried high concentrations of Cu, Pb, and Zn. The oxidized dump and tailings samples yielded pH's of 5.6 to 9.7; the high pH from tailings (> pH 9) may reflect the addition of lime during the cyanide process.



Photograph 4. This view of the lower Rochester tailings impoundment shows their location in the flood plain of the creek. This view of the 41-acre impoundment shows the dump and mill of the Looney mine on the ridge to the south.



Photograph 5. Tailings in the lower Rochester impoundment are severely eroded by the creek. The pinkish tan tailings are about 5 ft thick in this cut; the lower materials are alluvial gravel.



Photograph 6. These are fluvial mill tailings in the flood plain of Rochester Creek, 2 miles west of the lower Rochester tailings impoundment. The fluvial tailings are about 18 inches thick at this locality.



Photograph 7. Fluvial tailings are present in the arroyo and in overbank deposits for at least a mile west of the Nevada-Packard tailings impoundment. This view is to the east, toward the mill; the tan pile with flat top, middle distance, is from the heap-leach operation placed on top of the tailings impound.



Photograph 8. The Packard mill operated for only a short time in 1917 and left these tailings in the arroyo to the west, just north of the Packard townsite.

The near-neutral and alkaline solutions carried very low metal concentrations. The three unfiltered solutions contained much higher concentrations of Al-Cu-Pb than the filtered equivalent, even at pH 9. The unfiltered leachate from the Looney tailings carried high As. In general, however, these leach tests suggest that Rochester district dump and tailings samples have low acid generation potential, and low content of mobile metals relative to most metal mines and to water quality standards.

Water is not abundant in the district, but in May 1998 water flowed in lower Rochester Canyon (through the area of tailings) and out of the heap-leach pile at the Nevada-Packard mill site; water also flowed from one spring northeast of the Packard town site (in altered rhyolite). The pH's were in the range 8.2 to 8.5, and the pH of the seep from the leach pad was 8.7 (possibly reflecting lime that commonly is added in cyanide milling processes). Curiously, the spring water (not influenced by mining) had the highest concentrations of As, Mo, and Se of any sample from the area. The seep of water from the leach pad contained low metal concentrations, but As was high. Waters in Rochester Creek contained low metal concentrations, but total dissolved solids increased downstream from the tailings. Concentrations of As, Mo, and Se are elevated in these neutral-alkaline waters, and Se exceeds aquatic life standards (5 ppb) at several sites. None of the waters is sufficiently degraded to suggest serious problems, but the possibility of bio-accumulation or evaporative concentration to significant levels should be considered for wildlife health.

The large amount of mining and milling of polymetallic ores in the Rochester district is not reflected in surface water quality. Leach tests suggest low potential for acid generation and metal mobility. The relatively good water quality of the district may largely be due to pre-mining oxidation. Seventy-five years ago miners reaped the benefits of supergene weathering and oxidation that enriched silver values and allowed easier milling of ores; surface waters today benefit from the

oxidation that destroyed sulfide minerals and precluded acidic mine and dump drainage.

References

- Johnson (1977)
Knopf (1924)
Vanderburg (1936)
Vikre (1981)

Tenmile District

Location.—Humboldt County, Krum Hills, about 10 mi west of Winnemucca, Nev. (fig. 1). Precipitation is about 4–8 inches per year. Features of the district are shown on figure 7.

Principal commodities.—Au, Ag; Cu, Pb, Zn.

Brief mining history.—Gold deposits were discovered in the northern part of the district in 1906, but the prospects near Barrett Springs were mined only briefly in 1910 before land-ownership problems forced closure. The Pansey Lee mine (polymetallic) was described by Vanderburg (1938) as being a small operation, thus the major activity at this mine (largest in the district) is presumed to have been in the late 1940's to early 1950's. The gold-quartz-adularia veins of the Tenmile Hills area were not mentioned by Vanderburg (1938); the major period of mining was the 1940's with intermittent attempts through the mid-1990's. Exploration in the 1990's focused on the gold deposits, with some success but not enough to warrant mining.

Production.—Uncertain because production tonnages and values have been aggregated with Blue Mountain and Winnemucca Mountain areas. Probably less than \$1 million.

Geology.—Basement rocks are dark-colored phyllites of the Triassic-Jurassic Auld Lang Syne Group, which is intruded by Cretaceous-Tertiary granodiorite stocks, as near the Pansey Lee mine. Tertiary tuff, lavas, and sedimentary rocks overlie these rocks.

Ore deposits.—Two types have been productive:

1. Polymetallic vein deposits, as at the Pansey Lee mine. These deposits are rich in pyrite-galena-sphalerite-chalcocopyrite and carry important amounts of silver and gold, and
2. Gold-quartz-adularia veins as at the Tenmile and Golden Amethyst mines in the Tenmile Hills. These are relatively narrow veins, with small amounts of pyrite, as at the Jumbo mine to the north in the Slumbering Hills (Awakening district).

Mineral-Environmental Investigations

The gold-quartz-adularia vein deposits, as at the Tenmile and Golden Amethyst mines, are dry and oxidized and appear to pose no problems. The ores contain low concentrations of

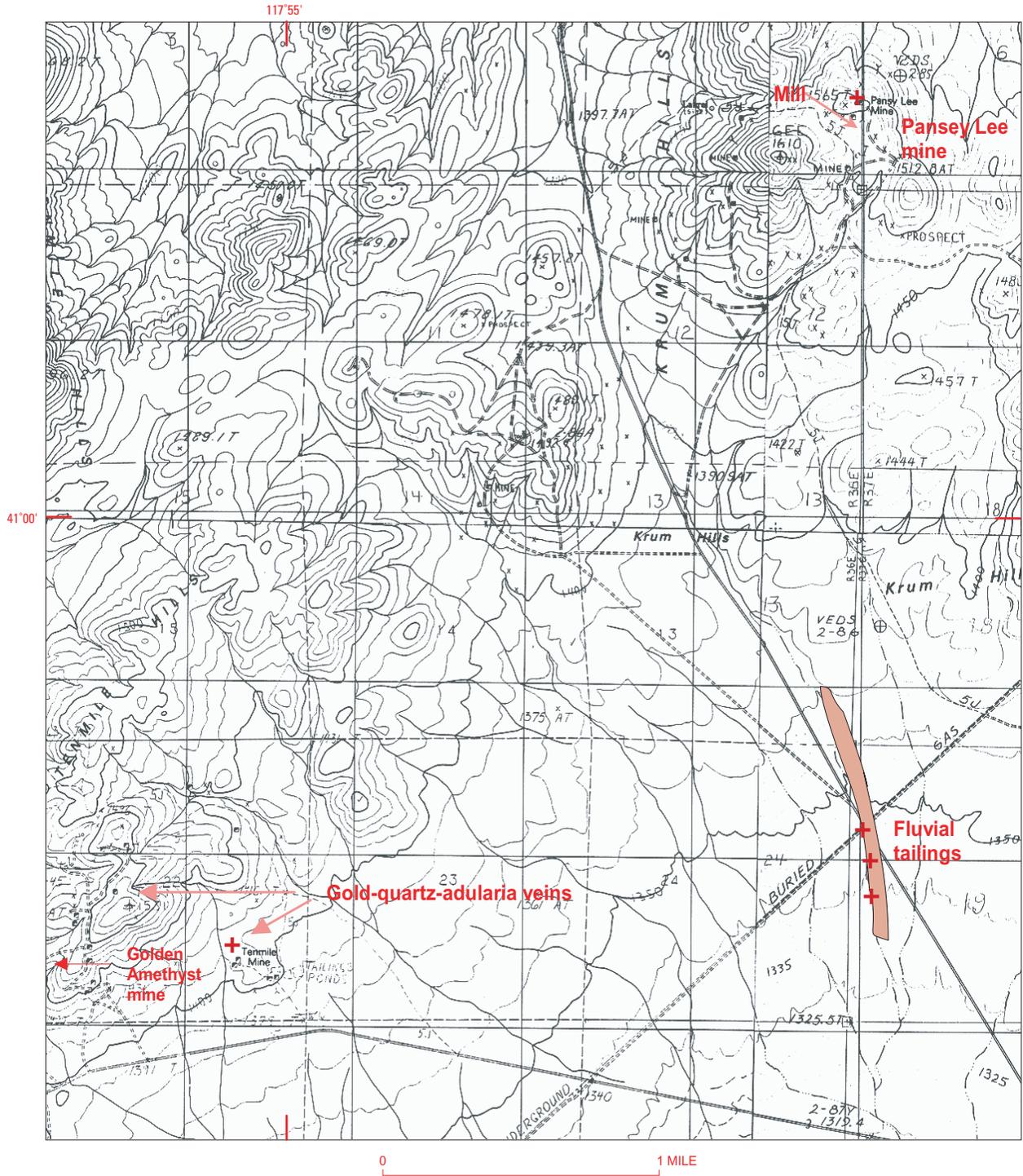


Figure 7. Features of the Tenmile district, showing sample localities.

base metals, modest amounts of arsenic, and, in the oxidized form, the metals are not mobile. There are no signs of acidic mine drainage (AMD) or acidic rock drainage (ARD) from dumps. A small area of mill tailings east of the Tenmile mine (fig. 7), observed in 1994, were covered during reclamation work in 1997.

The polymetallic deposit at the Pansey Lee mine is typi-

cal of this type of ore and is chemically distinct from the gold veins: the ores were rich in sulfide minerals that carried base metals, thus the dump rocks and mill tailings have the potential to generate acidic, metalliferous drainage. The unreclaimed dumps at the crest of the ridge (former shaft site) contain abundant sulfide minerals, but ARD is not evident. No water was noted at any of the mine openings in the area.

The Pansey mill tailings possibly are a source of acid and metals. The mill site, a short distance below the Pansey shaft, has very few tailings now. The small impoundment near the concrete mill foundation could not have been the primary holding place for the tailings, but no other likely spot has been identified. About 1.3 mi to the south (fig. 7) there is a long string of fluvial tailings that were transported down an arroyo in a storm event. The fluvial tailings are spread 5 to 50 ft wide, inches to several feet thick, for about 4,500 ft; the surface area of these tailings measures 7.5 acres (S. Brooks, BLM, written commun., 1998). The fluvial tailings, which extend nearly as far as the main road to Jungo, are similar in appearance and geometry to those described later at the Seven Troughs district (photo 14). Fragments of sulfidic dump rocks several inches in diameter are mixed with the tailings, another sign that this was a high-energy flash-flood regime.

Total chemical analyses of three tailings samples from the Pansey Lee fluvial tailings show that they have very uniform composition. Several metals of concern are present in rather high concentrations: Ag (median 12.6 ppm); As (1,588 ppm); and Pb (635 ppm); other metals such as Cd, Cu, Se, and Zn are higher than unmineralized rocks but are relatively low for mined rocks. Passive leach tests on the three tailings samples yielded solutions with pH of 4.4, high concentrations of Cd and Zn, and moderate concentrations of Cu. Concentrations of Cd, Zn, and Cu exceed standards for aquatic life, but not much As went into solution. Further studies would be required to determine if these tailings pose a threat to wildlife or to the Humboldt River.

No surface waters were observed, even during the very wet and rainy May of 1998. A small puddle on the fluvial tailings had a pH of 6.9, considerably higher than the pH of 4.4 generated in the 24-hr leach test. The paucity of water in this district suggests that any potential metal problems that may exist are unlikely to be mobilized in practice. Despite the large area of fluvial tailings and the relatively high metal concentrations, the metals of concern are not likely to be released into the environment. In a worst-case scenario of a flash flood, some metals (Cd, Cu, Zn) would be mobilized but would infiltrate the porous alluvium within a mile or so. It is highly unlikely that the metals would reach the Humboldt River, 4 mi to the south, because the metalliferous waters would react with carbonate-bearing alluvium and most of the metals would precipitate as the pH increased.

References

Willden (1964)
Vanderburg (1938)

Majuba District

Location.—Antelope Range, at Majuba Mountain, about 18 mi west of Imlay, Nev. (fig. 1). Precipitation is about 4–8 inches

per year. Features of the Majuba Mountain area are shown on figure 8.

Commodities.—Ag, Cu, Pb, Zn, Au, Sn, U.

Production.—This district contains some of the most diverse ore compositions in Nevada, but the total production over a hundred years has been quite small. This is one of the few locales in Nevada for tin and uranium minerals, but production of these rare metals was very small even at times of Government subsidies. Production of traditional base metals with silver amounted to less than 35,000 tons through 1951, and not much has been mined since then. The total value of the many kinds of ore is well under \$1 million.

Mining history.—Discovery of lead-silver ores was in 1875 with modest production through 1905 when more significant mining began at the Nevada Superior mine (Pb-Ag). The Majuba Hill copper deposit was located in 1907, and nearby deposits were found and brought into production. The Arsenic King mine on the northwest side of Majuba Mountain shipped silver-bearing ore that contained 20 percent As for a short time in the early 1920's. Tin was discovered in the Majuba Hill copper deposit in 1917, and a pocket of cassiterite was mined during WWII. Uranium in the form of metazeunerite (hexavalent U-Cu-As mineral) was identified in the supergene-enriched copper zone and studied in detail in the 1950's. The unusual ore compositions, especially the tin, has attracted exploration ventures in the last 40 years, including a thorough search for possible molybdenum resources (McKenzie and Bookstrom, 1976); results of the molybdenum exploration were never announced, but no molybdenum has been produced. The district has been inactive in the 1990's, with little or no evidence of exploration.

Geologic setting.—The major unit in the Antelope Range is a thick sequence of dark phyllite and slate of the Triassic-Jurassic Auld Lang Syne Formation, with local lenses of carbonate rocks. The rocks of greatest exploration interest are in the Tertiary rhyolite intrusive complex, which contains spectacular quartz-porphry dikes and breccias, and intense hydrothermal alteration that includes unusual amounts of tourmaline (McKenzie and Bookstrom, 1976). The complex sequence of breccias and intrusions on Majuba Mountain have been mapped in outstanding detail by McKenzie and Bookstrom.

Ore deposits.—Several unusual kinds of ore deposits are known in this district:

1. Tin as cassiterite in a small breccia zone within the Majuba Hill copper deposit,
2. Oxidized U-Cu ores in the supergene zone, postulated to be redeposited from primary uranium and copper zones. These have been drilled and studied in some detail, but no production appears to have been made from the small pocket of high-grade uranium (Garside, 1973),
3. Oxidized copper minerals along veins that were supergene enriched; primary chalcopyrite-pyrite-arsenopyrite is rarely seen as all mining was above the water table,
4. Polymetallic veins of galena and sphalerite, variably

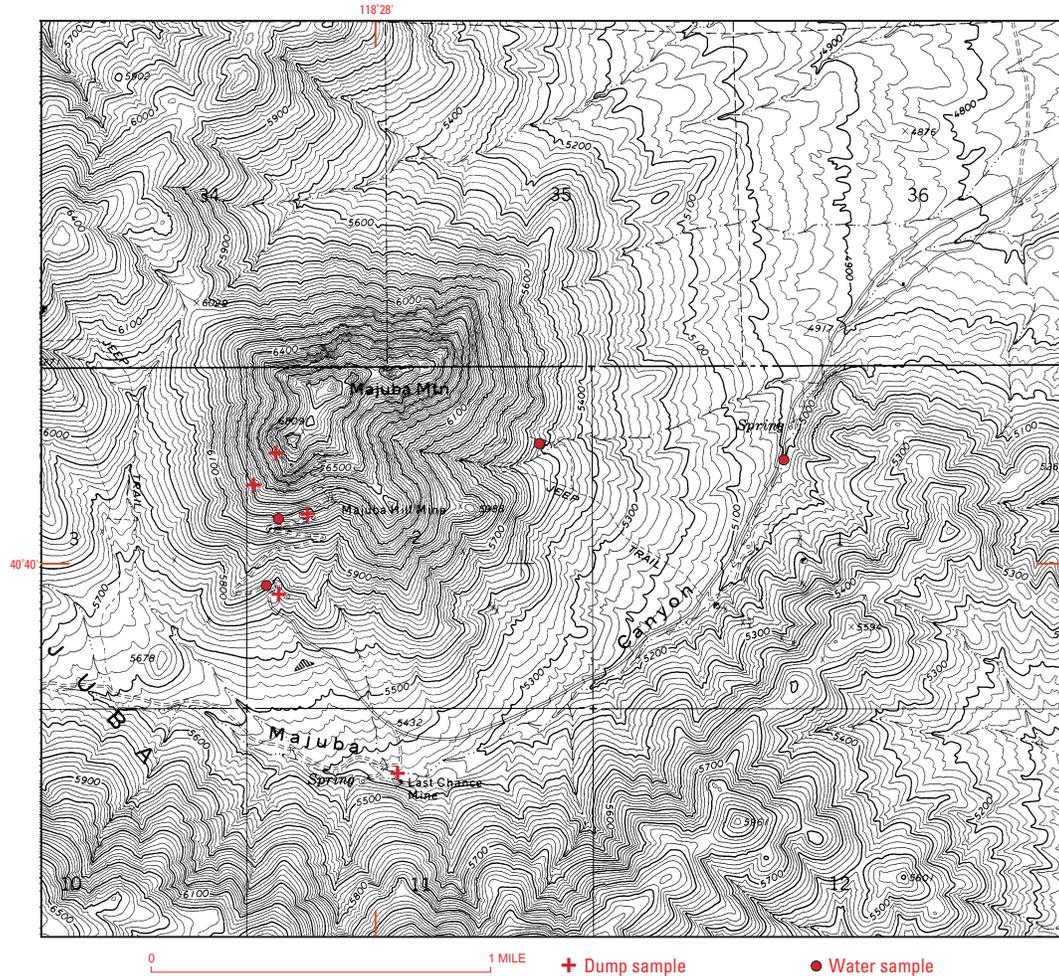


Figure 8. Features of the Majuba district, showing sample localities.

oxidized. As in other parts of Nevada, these were valuable chiefly for silver,

5. Porphyry molybdenum deposits: the multiple rhyolite intrusions show some similarities to the Climax deposit, and a team of geologists with experience at Climax (McKenzie and Bookstrom, 1976) tested Majuba Mountain in fair detail in the early 1970's with insufficient discovery to warrant mining. This is an excellent prospect, but the inferred drill results do not appear to match the grade and tonnage of a Climax system.

Mineral-Environmental investigations

The unusual kinds of mineralization described above suggest the potential for environmental problems related to arsenic, copper, uranium, or some unusual elements related to the tin-fluorite-bearing rhyolite intrusions. The Majuba Mountain part of the district was visited by the author in 1994 and 1998. The district was investigated by Lechler and others

(1995), who noted the presence of ferricrete deposits (goethite-cemented sediment and talus) and wrote of the information they provide on ancient acidic drainage unrelated to man and mining.

The central intrusive complex creates a conical peak that rises steeply from the low surrounding hills. The high relief of the peak above the surrounding area probably explains the deep and thorough oxidation of the vein deposits. A small amount of water was found at three of the adits in the wet May of 1998. The flow was a few gallons/minute at each site. The lower adit drainage (photo 9) had a pH of 7.4, high concentration of Se (15 ppm), and elevated concentrations of As and Mo. A small seep flowing over outcropping veins in the middle elevation of the mountain contained very high U (213 ppb) and high Se (9 ppb) concentrations, and elevated As and Mo concentrations. A small exploration adit at the eastern end of Majuba Mountain, with a dam and short length of plastic pipe for livestock watering, had very high Zn concentration (7,310 ppb). Surface water in Majuba Canyon Creek leaving the mining area had a pH of 7.9 and low metal concentrations, but elevated As (22 ppb) and Se (4.7 ppb).



Photograph 9. The lower adit for the Majuba Mountain mine releases a small amount of water. This mine tunnel and associated mine dump are relatively small compared to other mines in the Western United States.

Three dump samples were collected for chemical analysis, two from the major workings on Majuba Mountain and one from a polymetallic vein deposit to the southeast. A sample from the lower adit dump contained relatively low metal concentrations, whereas a sample from the larger dump halfway up the mountain contained abundant green copper oxide, and analysis showed very high As, Bi, Cu, Se, Sn, and U—the concentrations of Bi and Sn are uniquely high among the samples collected in this study. Molybdenum was not very high (29 and 47 ppm). Passive leach tests on the two Majuba Mountain mine dump samples yielded pH's of 8.7 (lower dump) and 5.2 (upper dump). The copper-rich upper dump sample yielded very high Cu, and high Se, Zn, and Cd concentrations and very low U. The lower dump sample leachate yielded low metal concentrations.

The adjacent polymetallic vein deposits have much different mineralogy and chemistry relative to the copper-tin-uranium veins on Majuba Mountain. The Last Chance mine, a typical example southwest of the peak, was sampled. The dark phyllitic rocks on the dump are stained dark gray by possible manganese-oxide coatings, and only a few sulfide minerals are evident. Chemical analysis showed very high Ag, As, Cd, Pb, and Zn, but low Cu and Mo. The passive leach test yielded a pH-7.9 solution with high Cd concentration.

In summary, the oxidized ores of this district have low potential to create acid, and most base metals are immobile in near-neutral waters. Arsenic and Se are mobile, but the

amounts probably are not so large as to pose threats to water quality. The Se could become concentrated by multiple stages of evaporation, forming Se salts that would be soluble in the first “flush” of water in a storm event. Bio-accumulation of Se is another possible result.

References

- Garside (1973)
- Johnson (1977)
- McKenzie and Bookstrom (1976)
- Vanderburg (1938)

Mill City District

Location.—Eugene Mountains of northern Pershing County, 10 mi north of Imlay, Nev. (fig. 1). Precipitation is about 8 inches and as high as 16 inches at the crest of the range.

Principal commodities.—W, minor Cu, Ag, Au.

Brief mining history.—The district is famous for being one of the largest tungsten (W) producers in North America (Stager and Tingley, 1988), but the first discovery was copper in 1856. Many small-scale mines worked copper and associated precious metal deposits for the next century, but with

modest production. The big event was discovery of scheelite in 1917, which led to the rapid development of tungsten mines for the WWI effort. Tungsten production was continuous through 1958 when all mines closed and the mill was dismantled. In the 1970's the price of tungsten improved, and new reserves at the Springer mine were defined and a new mill was built. The new Springer mine operated briefly in 1982, but was forced to close when prices fell as a result of competition from foreign sources. The tungsten mines have been idle for the past decade, and there has been only modest exploration and mining in the district.

Production.—The value of copper and associated metals was no more than a few thousand dollars a year. Production to 1900 was only 935 tons, worth about \$15,000. Production of tungsten through 1971 was about 1.5 million short-ton units of WO₃.

Geology.—The heart of the district is a cluster of three granodiorite stocks that intrude a sequence of Triassic-Jurassic sedimentary rocks including key beds of limestone and shale. The sedimentary rocks are metamorphosed adjacent to the stocks, and it is the metamorphic rocks that contain the valued tungsten deposits. The metamorphic rocks are termed “skarn” or “tactite” by miners for their content of calc-silicate minerals such as garnet, hornblende, and epidote. The chief ore mineral is the Ca-W-oxide mineral scheelite, which contains Mo.

Ore deposits.—The tungsten deposits are classic skarn-type that selectively replace specific sedimentary strata with the proper composition and permeability. Limestone and impure limestone beds are required to make ore. The host rocks are totally transformed to new mixtures of garnet, epidote, hornblende, other Ca-silicates, and quartz in and near ore, adjacent to intrusions. Small amounts of molybdenum and bismuth occur in the scheelite ores. The copper deposits are polymetallic veins and replacements in sedimentary rocks, and most are thoroughly oxidized near the surface.

Mineral-Environmental investigations

I made a very brief visit to the district in 1994 for a resource assessment (Peters and others, 1996) and was impressed by the small size and oxidized character of the copper-type ores and prospects. The hills were dry and I saw no signs of mine drainage. Based on the small size of deposits and dumps, and the paucity of water, I believe that these deposits are insignificant sources of contaminants.

The tungsten mines were not examined in this study. They are of a type that is known from studies elsewhere to produce few chemical problems (Hammarstrom, Elliott, and others, 1995). The abundant limestone in these deposits, and specifically at Mill City, mitigates acidic drainage before it can accumulate in quantity. Also, the sulfide mineral content of the ores is quite low. These deposits are known to be moderately enriched in As and Mo, two elements that are mobile in carbonate-buffered alkaline waters.

Mill tailings from the tungsten mines are a potential

subtle source of metals. The two impoundments of tailings south of the former tungsten mills each are among the largest in the Winnemucca BLM District and contain millions of tons of material. The older tailings (pre-1944) are on the alluvial fan about a quarter mile south of the Pacific Tungsten Corp. mill site (photo 10) (see photograph in Stager and Tingley, 1988), and the newer tailings are in a fenced impoundment a mile to the south and about 2 mi from the Humboldt River. From the mineralogy of the ores, the tailings are not expected to generate acidic drainage. One sample was collected from the unfenced old tailings area next to the paved road. A chemical analysis shows most metals and As are low, but Cu, Mo, and Zn are moderately high at 130, 68, and 200 ppm, respectively. In the passive leach test, the leachate evolved to a pH of 8.2, indicating buffering by calcite, and the solution contained very low metal concentrations. However, the concentration of Mo was 97 ppb. Considering the very large tonnage of the old tailings pile and the high permeability of these particular tailings (because of low clay content), there is potential for release of large total amounts of Mo to ground water. The new tailings possibly were placed on a liner, and, if so, the risk of release would be low.

In summary, the carbonate-bearing rocks and alluvium in this district mitigate acidic drainage. Most metals will not be mobile during storm events, but there is the potential for leaching and transport of molybdenum from tungsten mill tailings. Those waters are not likely to contain high concentrations of Mo, but there could be a large total amount of Mo released to ground water, and this ultimately could accumulate where waters evaporate in the Humboldt Sink.

References

- Hammarstrom, Elliott, and others (1995)
Johnson (1977)
Stager and Tingley (1988)

Mineral Basin District

Location.—Antelope Valley and Buena Vista Hills, south-central Pershing County and northern Churchill County, about 20 mi southeast of Lovelock, Nev. (fig. 1). Precipitation is about 4–8 inches per year.

Principal commodity.—Fe

Brief mining history.—Iron ore was discovered in the late 1880's, and small amounts shipped at that time. There was little activity until the demands of WWII called for new sources of rich iron ore. Production boomed in 1943, then declined, but revived during the Korean conflict years of the 1950's. Production declined and virtually ended in the late 1960's. There has been no mining in recent years.

Production.—This was one of the more productive iron districts in Nevada. Approximately 4 million tons of ore was mined with a value of about \$33 million.



Photograph 10. Tailings from the Pacific Tungsten Corp. mill were placed on the alluvial fan south of the mine-mill complex, which later became the Springer mine. View is to the southeast toward the Humboldt River, about 5 miles distant.

Geology.—The key geologic unit is a Jurassic gabbro complex that is the source and host for the many deposits of iron. The complex comprises several kinds of ultramafic intrusive and extrusive rocks, some of which are hydrothermally altered. The magnetite deposits are associated with areas of deuteritic hydrothermal alteration.

Ore deposits.—The magnetite deposits are associated with ultramafic intrusive rocks, a common global association. The iron deposits form during late magmatic stages from hydrothermal solutions. These ores are vein-like and podiform and contain relatively low amounts of titanium (in contrast to the magmatic type elsewhere).

Mineral-Environmental Investigations

Iron has been produced by many large mines in Nevada, but these mines are not prominent in geologic literature. Because the mines excavated more than a million tons of ore and waste rock, and some of the noneconomic zones are described as having abundant pyrite, questions exist regarding the mineral-environmental signature of the open pits and their waste dumps. In the mid-1980's I briefly examined the large Phelps Stokes open pit iron mine near Gabbs, Nev., and was

impressed by the abundant pyritic rock in the pit and on waste piles. In contrast, the Modarelli and Barth iron mines in the Cortez Range west of Elko, Nev., have large waste piles of magnetite- and hematite-rich rocks that seem totally unreactive in the surficial environment. On-site observation and sampling are obviously needed for iron ores and mine wastes, as for other types of ores. A similar type of Fe deposit of iron oxides in skarn has few environmental problems (Hammarstrom, Theodore, and others, 1995), but the skarn Fe deposits are in calcareous rocks.

Iron mining in the Mineral Basin district created large mesa-like dumps of waste rocks and large open pits. Most of the mines and dumps are behind locked gates, thus could not be examined. On brief reconnaissance tours it was evident that the pits do not drain water because of the low relief. No pit waters were sampled. The mine dumps do not appear to create acidic drainage. Inspection of one area of dumped waste showed only dark-colored mafic rocks and dark-colored magnetite. No bright-colored iron oxides, typical of weathered pyrite, were evident. Chemical analysis of typical waste rock showed 53 weight percent Fe, and very low concentrations of base metals such as Cu, Pb, and Zn. Concentrations of potentially toxic metals appear to be very low in this type of ore, just as analyses show for the Eureka County iron ore

samples. No passive leach test was made of the Mineral Basin sample, but tests on the Elko County magnetite and hematite waste showed no acid generation and very low concentrations of iron and other metals in the leachate.

These investigations were very cursory, but adequate to confirm the prediction that these magnetite and hematite ores seem to create no significant environmental problems. Iron deposits with pyrite zones are a different matter, and the pyritic waste rocks are likely sources of both acid and trace metals, just as in massive sulfide deposits (such as the Big Mike mine in Humboldt County).

References

Hammarstrom, Theodore, and others (1995)
 Johnson (1977)
 Reeves and Kral (1962)

Seven Troughs District

Location.—Seven Troughs Range, about 30 mi west of Lovelock, Nev. (fig. 1). Precipitation is about 4–8 inches per year. Features of the district and sample localities are shown on figure 9.

Principal commodities.—Ag, Au; minor Cu, Pb, Zn

Brief mining history.—Gold was discovered in 1863, but

the first significant discovery and mining was not until 1905. The rich bonanza ores attracted much attention for the next decade, but as the shafts went deeper water inflow became a problem and pumps were unable to keep up with the flow of water in 1916. The heart of the district, near the Kindergarten mine (photo 11), was flooded in 1917 and never returned to production, despite several attempts. In 1928, a bold effort was made to access the central high-grade veins and to dewater the old mines by the construction of a tunnel nearly 12,000 ft long. The Deep Tunnel headed northwest from Tunnel Camp on the east side of the range (fig. 9). This tunnel missed the intended target, but did intercept some veins about halfway to the high-grade destination. A 100-ton-per-day (tpd) cyanide mill at Tunnel Camp operated on these ores from 1931 to 1934 (Bruce Miller, unpub. company reports, 1994). Additional production after 1934 is not known but is presumed to be small. There has been no mining in recent years, but there have been several significant exploration and drilling programs in the 1990's in the area of Seven Troughs Canyon and to the north near Wildcat Canyon (north of fig. 9). The Rosebud mine, operating in 1998–2000 about 25 mi to the north, is similar in many ways to the gold-silver veins of this district.

Production.—Somewhat more than 152,000 tons of ore with a value of just under \$4 million (Johnson, 1977). Production from the Deep Tunnel and its mill was about 25,000 tons in the early 1930's. Precious metals were by far the most valuable, and the amount of gold was high relative to silver (158,000 oz Au to 996,000 oz Ag).



Photograph 11. This view of the central part of the Seven Troughs mining district shows the dumps from the Kindergarten and nearby mines and the mill (stone foundation) on the south side of the creek. An older, smaller mill was located even closer to Seven Troughs Creek; both mills placed tailings in the creek.

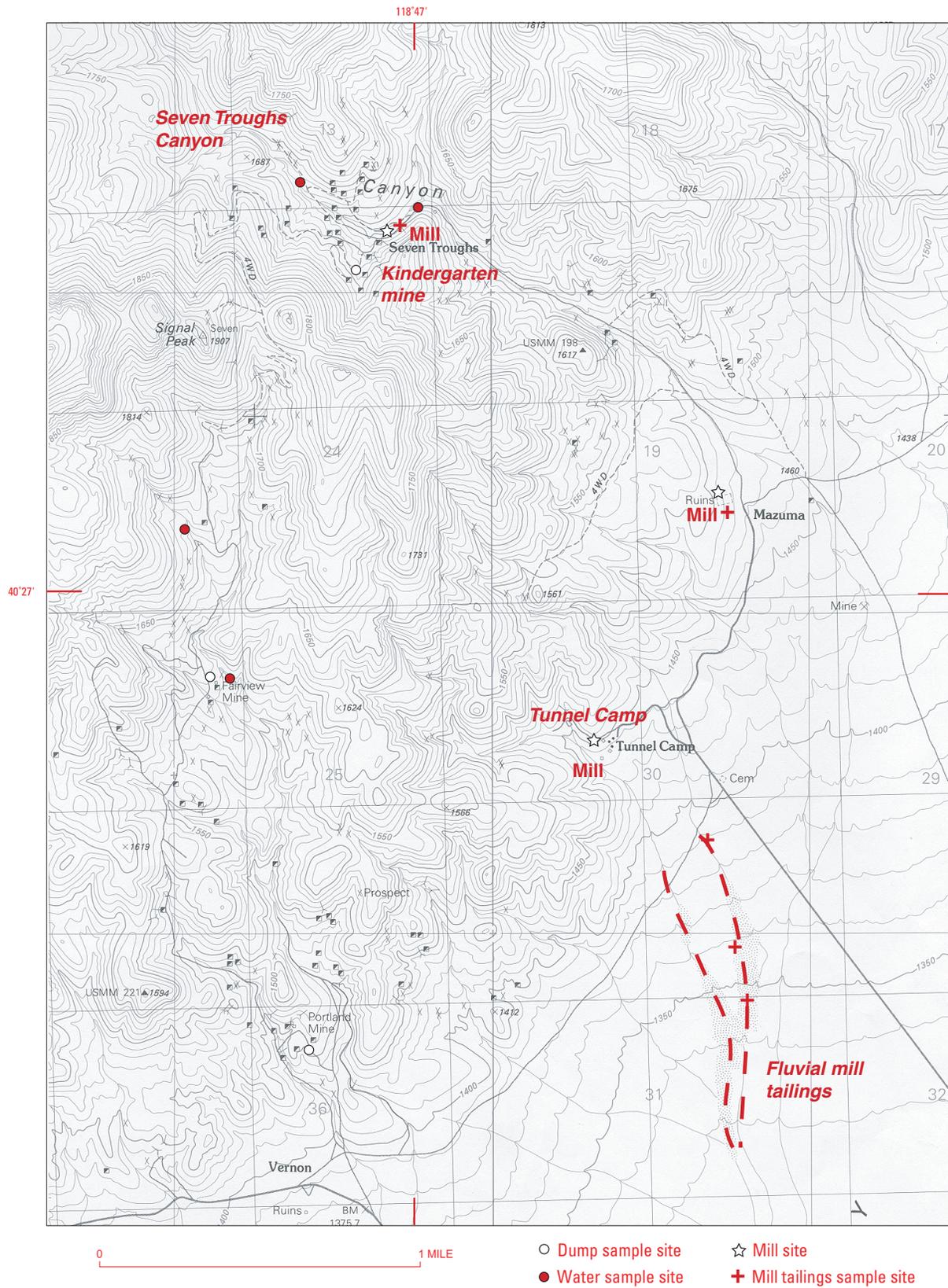


Figure 9. Features of the Seven Troughs district, showing sample localities.

Geology.—Basement rocks are phyllitic metasedimentary rocks of Triassic-Jurassic age, intruded by a Cretaceous granodiorite. The most conspicuous rocks are a thick sequence of mid-Tertiary andesitic to rhyolitic volcanic rocks (flows and ash flows). The volcanic rocks are altered in the vicinity of ore deposits to siliceous and argillic assemblages.

Ore deposits.—Veins and breccia zones containing quartz-adularia-electrum and complex silver minerals are economically most important. These deposits have low to very low base metal concentrations. Pyrite concentrations are moderate in some places, such as at the Wildcat prospect (minor past mining), to low in many areas. Tungsten-bearing skarn deposits occur in calcareous rocks adjacent to intrusive bodies in the southern part of the district but have had only minor production.

Mineral-Environmental Investigations

The precious metal mines in this district were examined briefly in 1994. The unusually wet May of 1998 was an optimum time to reexamine the district for metal mobility in waters and to characterize dumps and tailings by same methods used on other mining districts in the region.

Very little water is seen at mines in this district, even in May of 1998, yet water was a major problem for the miners and curtailed production in 1917 and in 1934. The shafts in the district do not create surface drainage, and only the Deep Tunnel at Tunnel Camp had a small flow of water in 1995, possibly 10–20 gpm. In 1998, the Deep Tunnel was dry; two local prospectors told me that the water “disappeared” after deep exploration holes were drilled in 1997. A few of the canyons have intermittent streams, the largest of which are in Seven Troughs Canyon and Stone House Canyon. Seven Troughs was named for the stock-watering troughs in place before mining started in 1907. The creek that fed those troughs is reported to have gone dry in about 1915 when the shafts were deepened to as much as 1,800 ft. Those deep shafts collected more water than could be pumped in 1916 and have been flooded since 1917. Seven Troughs Canyon now supports a modest creek for part of the year and is the site of some major storm events that raise the stream level several feet and cause severe erosion of banks, culverts, and roads.

Four water samples were collected near mines and near the mill tailings in Seven Troughs canyon (fig. 9). The pH's ranged from 7.2 to 8.3, and most metal concentrations were low. Concentrations of As, Se, and U were elevated relative to other waters analyzed in this study, and one sample of a very small flow near the Fairview mine contained 32 ppb Se. Aside from the potential Se problem, the metal concentrations are unusually low for an area of widespread alteration in unmined rocks and substantial amounts of disturbance and mill tailings associated with mining.

Mine dumps in this district tend to be small to moderate in size (probably less than 50,000 tons) because the veins were mined by local shafts and adits, and there was no consolidation

of claims by one mining company to make interconnected mine workings until late in the production history. The dumps generally have mixed sulfides and iron oxides, but in no place was ARD evident.

Total chemical analyses of two dump and five tailings samples showed them to contain elevated concentrations of Ag and As, and notable amounts of Hg and Se, but concentrations of base metals were below 100 ppm (relatively low). Passive leach tests yielded solutions with pH's of 3.8 to 7.0. The most acidic leachate, from the Kindergarten mill tailings, contained relatively high Al and Fe concentrations, and moderate Cu. Leachate from the Mazuma mill tailings contained high concentrations of As, Mo, and Se (consistent with the near-neutral pH). Leachate tests on two dump samples produced pH's of 4.8 and 6.3, indicating relatively little acid generation. The sample from the Fairview dump yielded high Cu and Fe concentrations and moderate Zn.

Mill tailings are a possible concern here because the tailings have been placed in or close to streams and arroyos. Ten mills were reported for the district by Shamberger (1972, *in* Johnson, 1977). Both cyanide and amalgamation concentration mills are mentioned by Vanderburg (1936). In my reconnaissance in 1998, I noted four mill structures and relatively small amounts of tailings remaining at each. As in hundreds of others tailings sites that I have examined in the Western States, it is difficult to determine the amount of tailings lost by inadequate containment practice or by storm events. The mill in Seven Troughs Canyon near the Kindergarten mine is close to that stream (photo 12), and some tailings are in the flood plain; tailings have been lost during storm events, but it is difficult to estimate what fraction was eroded. A leach test on the Kindergarten mill tailings indicated the potential to release Al, Fe, and Cu, but the small volume of these tailings (a few thousand tons remaining) may indicate that they are not a significant threat to the watershed.

A relatively large volume of fluvial tailings was discovered on the east side of the range (fig. 9; photo 13); these tailings probably are related to the Seven Troughs Mining Co. mill at Tunnel Camp. This mill reportedly processed about 25,000 tons of ore from 1931 to 1934, and an unknown amount after that. The mill and tailings impoundment could not be examined because they are behind a locked gate. The tailings impoundment was breached during a substantial storm event, at an unknown date, and the tailings were spread over the alluvial fan for about 6,000 ft to the southeast in two arroyos (photo 14). The fluvial tailings are few inches to a few feet thick, 5 ft to several hundred feet wide, as overbank deposits for more than a mile along the arroyos. Chemical analyses of five samples of the fluvial tailings show them to be high in As and enriched in Se and Hg, but low in Cu, Pb, Zn, and other base metals. No leach tests have been made to determine metal mobilities, but analyses of similar tailings materials suggests that the As and Se may be mobile in near-neutral waters, thus they could be mobile during storm events. Accumulation of mobile arsenate and selenate salts in desiccation crusts is probably the greatest concern as this could cause local



Photograph 12. This old mill in the center of the Seven Troughs district probably treated ore from the Kindergarten mine, in the background. Tailings were placed in Seven Troughs Creek.



Photograph 13. Mill tailings (ocher color) were carried into arroyos east of the Seven Troughs district when a flash flood breached a tailings impoundment.



Photograph 14. Fluvial tailings deposited on the alluvial fan east of the Seven Troughs Range cover tens of acres. Metals or acid released by the tailings kill sagebrush.

accumulations of very soluble materials or bio-accumulation in vegetation.

In summary, these observations and chemical analyses suggest that the dumps and tailings contain lower amounts of mobile base metals than at most metal mines. There is low potential for acid generation, but the near-neutral waters evolved from reacting with these mineralized rocks have the potential to carry notable amounts of As, Mo, and Se. Such waters could be problematic if they evaporated and became enriched in a pond or playa, but it appears that intermittent flows of water in this district tend to infiltrate alluvium. The volume of flow is so small as to pose only a minor threat to ground-water quality. Evaporative concentration of As, Mo, and Se in the vicinity of fluvial tailings is a small but potential threat to wildlife and livestock.

References

Johnson (1977)-
Miller, Bruce (1994, written commun. of unpub. company - reports)-
Vanderburg (1936)-

Awakening District

Location.—Slumbering Hills of Humboldt County, about 35 mi NW. of Winnemucca, Nev. (fig. 1). Early mining was on the east side of the range, but the larger, recently developed mines are on the west side (fig. 10). Precipitation is 4–8 inches per year for most of the district (a small area along the crests gets more as snow).

Principal commodities.—Au, Ag, minor W

Brief mining history.—Date of discovery is uncertain, but the first production was in 1914 when small-scale mining commenced. The original mines worked metamorphic gold-quartz veins and the small mill (5 stamp amalgamation mill) at Daveytown, Nev., on the east side of the range treated about 10,000 tons of ore prior to 1938. In 1936, the Jumbo mine was discovered and visited by former President Hoover, bringing much attention and a major increase in exploration and production in the district. The gold-quartz-adularia veins at the Jumbo mine were mined underground, chiefly from 1936 to 1941 and 1948 to 1951. A later period of bulk mining in small open cuts had mixed success. The mill, and a heap-leach operation for Jumbo ores, was located on the west side of the range to be close to a well (fig. 10). The Sleeper gold deposit was discovered in 1982 and mined by open-pit methods from 1986 through 1996 (photo 15). The spectacular high-grade ores at Sleeper inspired much exploration in the area, with a few discoveries but none sufficient for mining.

Production.—The gold production through 1963 was slightly under \$1 million, with modest production later at Jumbo. The production from high-grade veins and low-grade, bulk-mined zones at Sleeper dwarfed prior production at nearly 2 million oz gold and somewhat more silver.

Geologic setting.—Basement rocks in the Slumbering Hills are Triassic-Jurassic dark slate and phyllite of the Auld Lang Syne Group. These rocks were intruded and metamorphosed by a large granodiorite pluton. The overlying rocks are a moderately thick section of Tertiary volcanic flows and tuffs, and associated rhyolite domes and dikes. Basin-and-range normal faults cut the volcanic and older rocks and are the favored sites for epithermal gold ores and subsequent oxidation that is important for mineral economics by making originally sulfidic ores amenable to heap leaching.

Ore deposits.—Four types of ore have been prospected and mined:

1. Gold-quartz veins of the low-sulfide type in metasedimentary rocks (small production),
2. Skarn deposits of tungsten adjacent to the granodiorite plutons (minor production),

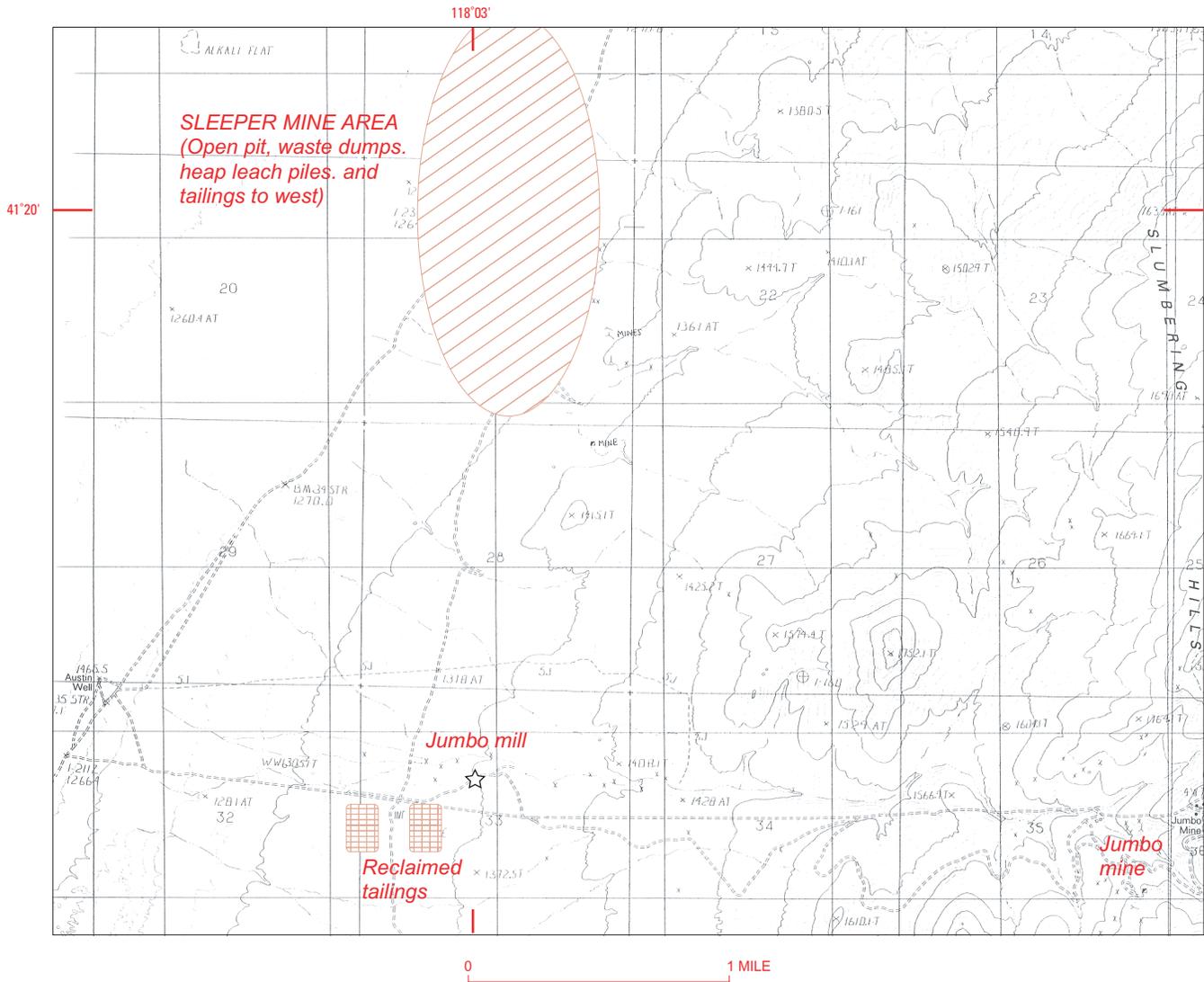


Figure 10. Features of the Awakening district on west side of Slumbering Hills.

3. High-grade bonanza gold-quartz-adularia epithermal veins at Sleeper, and similar but smaller veins at Jumbo mine (major production), and
4. Low-grade disseminated and breccia-filling gold-silver in oxidized sulfidic rocks adjacent to veins at Sleeper, amenable to bulk mining and heap leaching (major production).

Only type-4 ores were rich in primary sulfide minerals, and those were mostly destroyed by oxidation prior to mining; none of the ore types were rich in base metals.

Mineral-Environmental Investigations

The ores of the Sleeper mine were studied in detail by Nash and others (1995). Mineral-environmental work was not a major part of the project, but the research documented two

stages of weathering that destroyed acid-generating sulfide minerals. Geochemical studies of primary and secondary ores demonstrated low concentrations of base metals. The oxidized ores placed on the heap-leach piles (photo 16) have low potential to generate acid or to release toxic metals (Nash and Trudel, 1996). The waste dumps and heap-leach piles have been reclaimed. The pit at Sleeper filled with water in 1998 to within about 100 ft of the surface and is being treated with lime to control pH.

The mill site for the Jumbo mine, about 2 mi south of the Sleeper mine (fig. 10), was observed in the early 1990's while mapping geology, but neither the tailings impoundments nor the heap-leach piles were sampled. The tailings and leach piles were reclaimed in 1997 and could not be sampled. Judging from studies made at the Jumbo mine in 1992–1994 (Nash, unpub. data), the ores were thoroughly oxidized, thus contained no sulfide minerals, and the bulk composition of the



Photograph 15. The Sleeper pit exposes rusty- and pink-colored volcanic host rocks; these colors reflect clay minerals and iron oxides created during several stages of weathering several million years ago when the ore-bearing rocks were close to the surface. This oxidation makes the low-grade rocks amenable to heap leaching and minimizes the production of acid in mined materials. The open pit is about 300 ft deep and nearly a mile long.

ores was low in base metals. The tailings and the heap-leach materials should generate no significant amounts of acid or toxic metals.

The mill site at Daveytown, Nev., on the east side of the range, is dilapidated but recognizable as a very small mill. The tailings were placed to the east of the mill on a playa-like flat that generally is dry. The estimate of 10,000 tons made by Vanderburg (1938) seems appropriate and suggests that there was minor additional production after the 1930's. The unconfined tailings cover an area of 8 acres (S. Brooks, BLM, written commun., 1998). The tailings are light in color, contain no obvious sulfide minerals, and generate no colors suggestive of acidic drainage. Total chemical analyses of two tailings samples show low concentrations of base metals. Several

metals are somewhat enriched, notably As (466 and 564 ppm), Pb (147 and 69 ppm) and Hg (1.1 and 2.4 ppm). In passive leach tests on two tailings samples, the leachate attained pH's of 8.7 and 8.8 and contained very low metal concentrations. One leachate contained 203 ppb As, whereas the other contained only 12 ppb As. These reconnaissance studies suggest that most metals are present in low concentrations and are immobile; arsenic may be mobile locally and could infiltrate alluvium to enter ground water.

In summary, the geochemical problems related to historic mining on public lands of this district appear to be minor and local. This conclusion is supported by

1. The low sulfide content of mined rocks,
2. The low base-metal content of mined rocks,
3. The very low precipitation in the area, and
4. The observation that alkalinity from caliche and other forms of carbonate exceeds the potential to generate acid.

Closure of the Sleeper mine is being monitored by the BLM and State agencies.

References

- Nash and others (1995)
- Nash and Trudel (1996)
- Vanderburg (1938)
- Willden (1964)



Photograph 16. This oblique photograph of the Sleeper mine, taken in 1995, shows the large area involved in the open-pit operation. The pit is nearly a mile long, and the heap-leach pads extend for about 2 miles. Because the waste dumps and three of four heap-leach pads have low content of sulfide minerals, there is little or no acid rock drainage (but one heap with sulfidic rocks releases acidic drainage). The pit filled with water in 1998 and acids created by sulfidic rocks in the bottom of the pit are being treated with lime.

Willard District

Location.—West Humboldt Range of Pershing County, about 8 mi northeast of Lovelock, Nev. (fig. 1). Precipitation is 4–8 inches per year.

Principal commodities.—Au, Ag, Sb.

Brief mining history.—The first discovery was silver in 1905, and gold was discovered in 1915. A year later stibnite deposits were found adjacent to the gold deposit and mined on a small scale. Antimony was produced again during the WWII years. The largest mining development came in the late 1980's when a low-grade, bulk-minable silver-gold deposit was defined and mined from 1989 to 1993. The Willard operation is closed and the site reclaimed.

Production.—Production of antimony is of geologic interest, but was not of large tonnage or value. The Willard

mine had preproduction reserves of 3.6 million tons of ore at an unspecified grade; recovery was by heap-leach methods.

Geology.—Basement rocks in the district are shale, sandstone, and limestone of Triassic and Jurassic age, which are overlain by Tertiary tuffs and lavas. Hydrothermal alteration zones are common, some of which have created clay of sufficient purity to be mined.

Ore deposits.—Two types of ore deposits have been mined:

1. Hot-springs type silver-gold in altered siltstone at the Willard mine. The Willard deposit is inadequately described in the literature but appears to have features in common with those at Trinity, Florida Canyon, and Sleeper mines, although the nature of the host rocks differs among this group.
2. Polymetallic veins, rich in stibnite, probably similar to those to the north at Unionville and Star Canyon.

Mineral-Environmental Investigations

A review of the information on historic mines, and a very brief reconnaissance of the mines in 1994 suggested that the mines on polymetallic vein deposits were small and unlikely to create significant problems. The open pit and heap leach at the Willard mine was investigated briefly in May of 1998; the mine and leach pile are on public lands.

The open cuts at Willard have been only slightly modified since mining, chiefly to prevent vehicle access. Mining was in altered siltstones that resemble volcanic tuffs; the host rocks have been pervasively weathered and oxidized, with the final product being light-colored and friable (photo 17). Only a few rare pockets of preserved sulfidic rock were noted. There was no water in the pits, but there are signs of seasonal flows or puddles in a few places. Chemical analysis of one dump sample showed below-median concentrations of most metals, but somewhat higher-than-median amounts of As (1,000 ppm), Sb (99 ppm), and Se (3.7 ppm). Based on field observations and experience at the Sleeper mine, the appearance of these rocks suggest that there is very little potential for acid generation and very low content and mobility of base metals. The pit and mine dumps seem about as benign as any mined rocks in Nevada. The moderate amount of As in these rocks is probably is tied up in iron oxide minerals and, in that form, would not be reactive.

The heap-leach pile of crushed rocks is in place on a

plastic liner. The crushed ore resembles the rocks in the pit walls—light-colored and oxidized, with a few percent of iron oxides in place of former pyrite. A small amount of water had infiltrated the heap and was diverted by the liner to the peripheral gutter used to collect the leach solution. The liner is torn in a few places and some water leaks out and drains across the access road. The leachpad water had a pH of 7.7 and the conductivity was unexpectedly high ($>2,000 \mu\text{S}/\text{cm}$). The chemical analysis shows very high concentrations of As, Cd, Co, Mo, Ni, and Se, and high concentrations of Cu and Zn. Mercury concentration was 1.3 ppb. This water has some of the rare high concentrations of Co and Ni found in this study. The high base metal concentrations are not expected from this ore type. Possibly the metals have been concentrated by evaporation, which would also explain the exceptionally high value of 829 ppb Se. These high concentrations pose analytical problems and may reflect higher-than-normal analytical error. The heap-leach pads were reclaimed in 1999, and the water problems just mentioned were mitigated.

In summary, the historic mines of the Willard district do not appear to pose significant threats to water quality. The Willard mine open pits expose oxidized rocks with relatively low metal concentrations. Water remaining in the heap-leach pad had unusually high and unexpected concentrations of many base metals for several years after mining operations ceased, but final closure actions in 1999 appear to have mitigated those problems.



Photograph 17. The Willard mine exploited silver-gold ore in oxidized siltstones; the reddish hues indicate that sulfide minerals were present originally but converted to iron oxide minerals prior to mining. The dark colored rocks in right foreground are a rare pocket of sulfidic rocks.

References

Bonham and Hess (1995)
Johnson (1977)

Antelope Springs District

Location.—South end of Humboldt Range, 16 mi east of Lovelock, Nev. (fig. 1). Precipitation about 4 to 8 inches per year. Features of the district and sample localities are shown on figure 11.

Commodities.—Hg, Ag, Sb.

Production.—About \$3 million, as mercury and silver through 1969. Modest amounts of silver and gold in the 1980's. A well-preserved retort is shown in photo 18.

Mining history.—Stibnite was discovered in 1864, but attempts at recovery were not successful until improved milling methods were available during World War I. Silver ore was discovered at the Relief mine (to the northwest of fig. 11) in 1869, and much was mined in the 1870's—production continued at a lower scale through about 1910. Production estimates range widely, from \$200,000 to as much as \$2,500,000. Mercury was discovered in 1907, and major production occurred during wartime periods when prices were favorable. Total production from the district through 1969 was 12,517 flasks, and there has been only minor production since then. An attempt was made to recover silver and gold from siliceous rocks of the Pershing Quicksilver deposit in the last 10–15 years by heap-leach methods (photo 19), but the operation does not appear to have been very successful.

Geologic setting.—The favored units for ore deposits are Triassic and Jurassic sedimentary rocks containing carbonate beds. The sedimentary rocks are complexly folded and faulted, and these structures are important for the localization of ore. The volcanic rocks of the Koipato Group underlie the ore-bearing units and are exposed only in the northern part of the district, adjacent to the Rochester district. Younger basalt flows are not mineralized.

Ore deposits.—The known ore deposits are of two or three types mineralogically but may be genetically related hydrothermal systems. The mercury deposits are replacement bodies in carbonate rocks below shales on steep faults—very well described by Bailey and Phoenix (1944)—but questions of ore genesis relative to other kinds of mercury deposits and other commodity types remain. Cinnabar is the major mercury mineral, and the deposits contain calcite gangue and minor amounts of stibnite. The stibnite deposits occur in shale and sandstone. The silver deposit at the Relief mine was thought to be similar to those farther north in the Humboldt Range (polymetallic replacement bodies in carbonate rocks). However, in the 1980's, a new gold-rich deposit was identified at that site and mined as the new Relief open-pit mine; the deposit is in a complex breccia zone in sedimentary rocks (Wallace, 1989).

Mineral-Environmental Investigations

Numerous mercury mine dumps were accessible in 1998, but the Relief mine was not. The Relief mine was reclaimed in the late 1990's; two small pit lakes remain at the site, but there is no obvious surface discharge. The historic mercury mining areas were examined for mine drainage and to characterize the surficial geochemistry of the mine dumps and retort calcine piles. The roasted ore (calcine) is brick red (photo 19) and looks ideal for building roads, but is potentially hazardous because it still contains substantial amounts of Hg.

Total chemical analyses of three samples of calcine show them to be very rich in As, Pb, Sb, and Zn, and relatively rich in Se and Tl, as well as Hg. The high concentrations of Pb and Zn were not expected, but mercury ores are well known for their content of metalloids such as As and Sb. The bigger question is the mobility of these elements in water.

May of 1998 was unusually wet, and rain fell the day before I visited the district. With this unusual moisture there was some surface water flowing, and several trenches were filled with water (photo 20), but most of the recent rain had simply infiltrated the permeable dump materials and alluvium. Seven water samples were collected: three from mine trenches, two from surface flows (low volume), and two from springs; three of the water samples were from sources that did not appear to be influenced by mercury mining. The pH's were in the range of 8.1 to 9.3, and conductivities were all very high (1,300 to >2,000 $\mu\text{S}/\text{cm}$). Chemical analyses show concentrations of most base metals such as Cu, Pb, and Zn, are well below concern levels, but other metals are high to very high, including As (25–190 ppb), Mo (15–43 ppb), Sb (33–95ppb), Se (24–151 ppb), and U (15–49 ppb). The high concentrations of Mo, Se, and U were not expected from this environment, but these elements are known to be mobile in alkaline waters. Significantly, the samples from sources distant from mines had high concentrations of the same elements as the waters from mining areas.

Special water samples were collected for mercury analyses. Samples were taken at seven sites, three of which had no apparent relation to mercury mining but were in the same package of rocks. At three of the sites, both filtered and unfiltered samples were collected; analytical results are in table 5. The water samples from four mining areas were from a low-volume surface drainage and three puddle-like bodies in mine trenches; unfiltered samples contained 0.27, 0.28, 0.6, and 0.066 ppb Hg, and the filtered samples contained 0.013, 0.086, and 0.096 ppb Hg. These values exceed the Nevada standard for aquatic life, 0.01 ppb. The unfiltered samples of the muddy waters contain higher concentrations of Hg, probably adsorbed on clay particles—thus, this is not a truly dissolved form of Hg as is stipulated for other elemental analyses. The waters collected represent a worst-case scenario and was collected in an unusually wet spring.

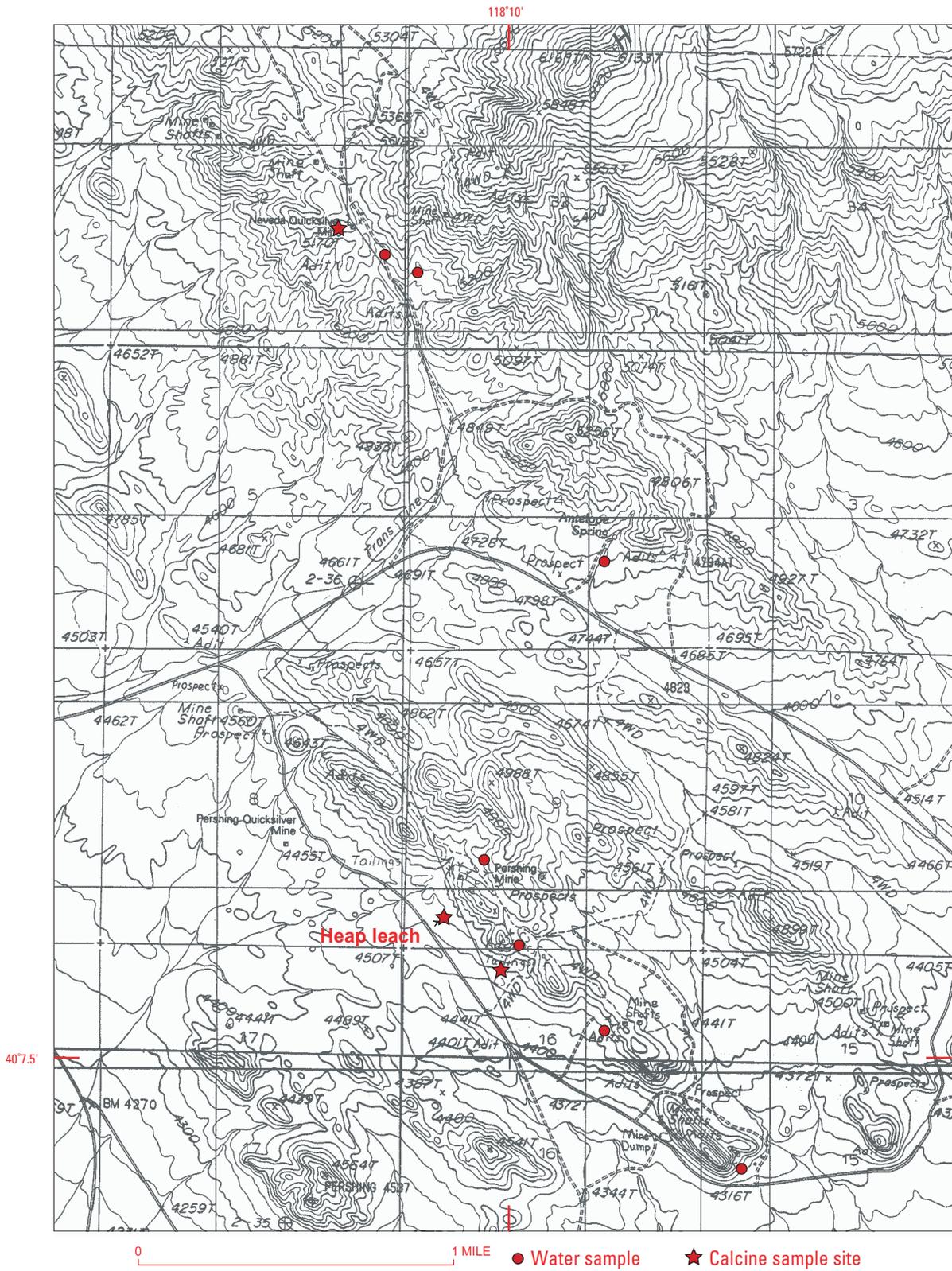


Figure 11. Features of the Antelope Springs mercury district, showing sample localities.



Photograph 18. Mercury retorts were made in many complex shapes to heat ore and collect mercury. This retort at the south end of the Antelope Springs district is more complex than most and probably was operational in the 1950's or 60's.



Photograph 19. In the 1980's, a heap-leach operation attempted to recover gold from calcine, red materials from a mercury retort at the Pershing mine, Antelope Springs district.



Photograph 20. Bulldozer trenches cut to explore for mercury collect water from rare rain storms in the Antelope Springs district. Mercury concentrations can be very high in these ephemeral puddles.

Table 5. Analytical results for mercury in water samples from Humboldt Basin, Nevada, 1998.

[CVAA, cold vapor-atomic absorption, results in parts per billion; Hg-fluor, fluorescence analysis, results in parts per trillion. Samples collected in glass bottles, preserved with nitric acid-dichromate solution (Crock, 1996). Filtration: f, filtered through 0.45-micrometer filter; u, unfiltered. Analyst: P.L. Hageman, September 1998]

Sample ID	N. latitude (degrees)	W. longitude (degrees)	Hg CVAA $\mu\text{g/L}$ (ppb)	Hg fluor ng/L (ppt)	Comment
NHW718f	41.3603	118.3161	0.38	na	Bottle Creek district, trench
NHW718u	41.3603	118.3161	2.5	na	Bottle Creek district, trench
NHW719f	41.3594	118.3056	na	34	Bottle Creek district, spring
NHW719u	41.3594	118.3056	na	24	Bottle Creek district, spring
NHW741f	40.1258	118.1625	na	86	Antelope Springs, seepage
NHW741u	40.1258	118.1625	na	66	Antelope Springs, seepage
NHW742f	40.1197	118.1522	0.13	na	Antelope Springs, puddle
NHW742u	40.1197	118.1522	0.27	na	Antelope Springs, puddle
NHW743u	40.1303	118.1672	0.6	na	Antelope Springs, puddle
NHW745f	40.1344	118.1711	na	96	Antelope Springs, trench
NHW745u	40.1344	118.1711	0.28	na	Antelope Springs, trench
NHW748f	40.1631	118.1767	0.2	na	Antelope Springs, spring
NHW749f	40.1619	118.1747	na	64	Antelope Springs, creek
NHW750f	40.1500	118.1619	na	34	Antelope Springs, spring
NHW753f	40.2472	118.3450	1.3	na	Willard, heap leach pad
NHW792f	40.2925	118.2408	na	42	Rochester Creek
NHW852f	40.4264	116.8564	na	25	Hilltop district, tails seep
NHW855f	40.4239	116.8378	na	21	Hilltop district, Dean Crk

Leach tests on three samples of calcine yielded pH's of 6.2 to 8.0 and generally low concentrations of metals. The leachate from one sample carried high concentrations of As, Sb, and Se, and Mo. None of the leachates was enriched in U. There are no analyses for Hg in the leachates.

In summary, mercury and a few other toxic metals are present in the mine wastes but probably are not mobile most of the time because there is very little precipitation in this district. For short periods after storms there may be high concentrations of As, Sb, Mo, U, Se, and Hg in waters, but these should not pose problems unless stock or wildlife consistently drink such waters. Especially high concentrations could develop where storm waters collect and evaporate. Most of the surface waters infiltrate alluvium and mix with ground water where it probably causes no problems for current uses.

References

- Bailey and Phoenix (1944)
 Johnson (1977)
 Vanderburg (1936)
 Wallace (1989)

Bottle Creek District

Location.—Humboldt County, east side of Jackson Range, 40 mi northwest of Winnemucca, Nev. (fig. 1). Precipitation is less than 8 inches per year. Features of the district are shown on figure 12 and photo 21.

Principal commodity.—Hg

Mining history.—Mercury was discovered in 1936. Mining in the late 1930's and 1940's exploited both lode deposits in bedrock and placer deposits in alluvium. Mining had ceased by 1943, but possibly was renewed in the 1950's when there was a mercury boom in Nevada. No mines have operated in the 1990's. There has been some exploration and drilling for gold in the past decade as a result of the discovery of the Sleeper gold deposit, a major producer, across the valley to the east.

Production.—About 4,500 flasks of mercury through 1944; production since then is not known but might be substantial from the open-cut mining in the 1950's(?).

Geology.—Basement rocks are weakly metamorphosed Triassic-Permian sedimentary and volcanic rock, overlain by Miocene tuffs and local rhyolite domes. The geology is generally similar to that of the Sleeper mine across the valley. Mercury veins are in both pre-Tertiary and Tertiary rocks. Structure is seemingly simple high-angle faults of basin-and-range style.

Ore deposits.—Two types have been mined: bedrock veins and disseminations of cinnabar, and placer accumulations of cinnabar-bearing clasts in alluvium (placers). The bedrock mercury deposits are of the opalite or hot-spring types (Bailey and Phoenix, 1944; Rytuba, 1986), in which cinnabar

is associated with abundant silicification, silica sinter, and argillization of volcanic host rocks. The placer deposits of mercury are derived from the bedrock deposits and transported short distances from their presumed sources. Exploration in recent years has attempted to locate gold-silver deposits related to the Hg-bearing hot springs, as at Goldbanks, southern Humboldt County (a former Hg producer and recently the site of a large gold discovery), and possible veins as at Sleeper.

Mineral-Environmental Investigations

The Bottle Creek district was visited by the author in 1994 while studying the Sleeper mine, and again in 1997 and 1998 in an attempt to characterize the mercury in the surficial environment. There is very little surface water here, even during unusually wet seasons. None of the mines shows evidence for drainage, and all are in thoroughly oxidized rocks. A spring on the eastern side of the district, and a small creek on the northwest side, have low, intermittent flows of water that are not obviously in contact with mercury deposits or mined rocks.

Silicified and argillized tuffs and rhyolite are widespread in this district, and much of the alluvium contains this material. The rocks are oxidized contain only a few percent iron oxides derived from pyrite. Chemical analyses show two samples contain very high concentrations of Hg, and high concentrations of Cu, Mo, Sb, Se, and Zn, which are not obvious to the eye. Leach tests on two samples (one dump and one retort calcine) produced pH's of 5.9 and 6.4; the leachates were high in As, Cu, Fe, Mo, and Sb. The leach tests suggest that these metals may be mobile in the rare storm events in this dry area.

A remarkably large area, thousands of acres (fig. 12), was disturbed by deep bulldozer cuts during exploration or placer mining at a time when bulldozers were strong and exploration regulations were weak (the 1950's?). These old diggings have not been reclaimed, although much smaller excavations for gold exploration in the 1990's have been reclaimed to modern standards. The disturbance, large for a district with moderate production, probably exacerbates the chances of mobilizing metals and mercury during rare storm events. Further studies, utilizing methods appropriate for mercury, are needed to properly characterize these disturbed materials.

There are no conventional mills in this district, but many of the more productive mines had retorts that created large piles of calcine. The siliceous rocks were crushed to less than one inch diameter, creating abundant fines, prior to processing through the retort. The calcine piles contain high concentrations of Hg, Mo, Sb, and Zn, some of which are mobile in near-neutral waters that are generated by these rocks according to leach tests. Thus they are a potential source of these elements in storm events.

No mine workings or dumps contained water in June 1997, but there was water at a spring on the east side of the mining area and in a small creek on the northwest side. Water from these two sources had pH's of 6.6 and 8.3 and moderate

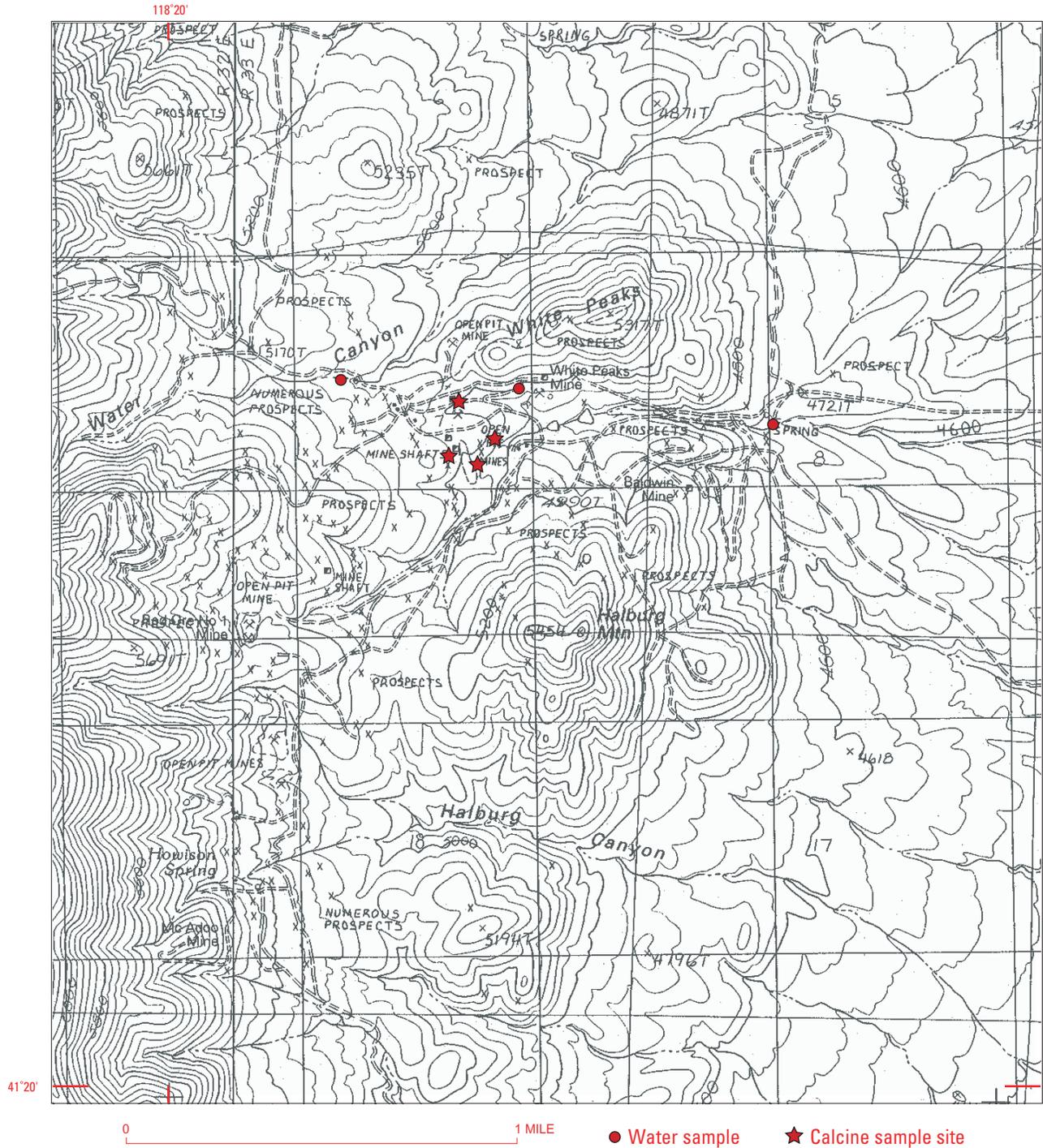


Figure 12. Features of the Bottle Creek district, showing sample localities.

conductivities. The waters contained high concentrations of As, Sb, and Se, but low total metal concentrations. Mercury was not determined on the 1997 samples. In May 1998 the district was visited during a rain storm that created much mud, a few puddles, but no surface discharge of water. The spring on the east side of the district had a pH of 7.9; metal concentrations were low. Concentrations of Sb and As were elevated, but below concern levels.

Two water samples from 1998 were collected and preserved using special glass bottles and dichromic acid to stabilize Hg. Puddle water in a trench through a mineralized zone had a pH of 8.1; the unfiltered, muddy sample contained 2.5 ppb Hg, and the filtered ($-0.45 \mu\text{m}$) sample contained 0.38 ppb. The spring water had a pH of 7.9; the unfiltered sample contained 0.24 ppb, and the filtered sample contained 0.34 ppb (the filtered sample should contain less than unfiltered, and



Photograph 21. View of the central part of the Bottle Creek mercury district and the many small workings in this area; larger open-cut excavations are to the southwest. The red piles in center are calcine from retorts.

this discrepancy is within the margin of sampling and analytical error). All of these concentrations exceed the standard for aquatic life (table 4).

In summary, large areas of hydrothermal alteration, many small mercury mines and calcine, and widespread bulldozing create conditions that are ripe for mobilizing Hg, As, Sb, and Se during storm events. The runoff probably would not be mitigated by carbonate or caliche because these elements are soluble in alkaline waters. The runoff is not likely to impact people or livestock but would probably join the internal drainage of Desert Valley and could become concentrated by evaporation in playas. Evaporative or botanical concentration of these elements could make them toxic to wildlife. Further specific studies are needed to define the cycling of these elements in a closed basin.

References

Bailey and Phoenix (1944)
 Vanderburg (1938)
 Willden (1964)

Buena Vista (Unionville) and Star Districts

Location.—East side of Humboldt Range, 10–15 mi south of Imlay, Nev. (fig. 1). Precipitation is about 4 to 8

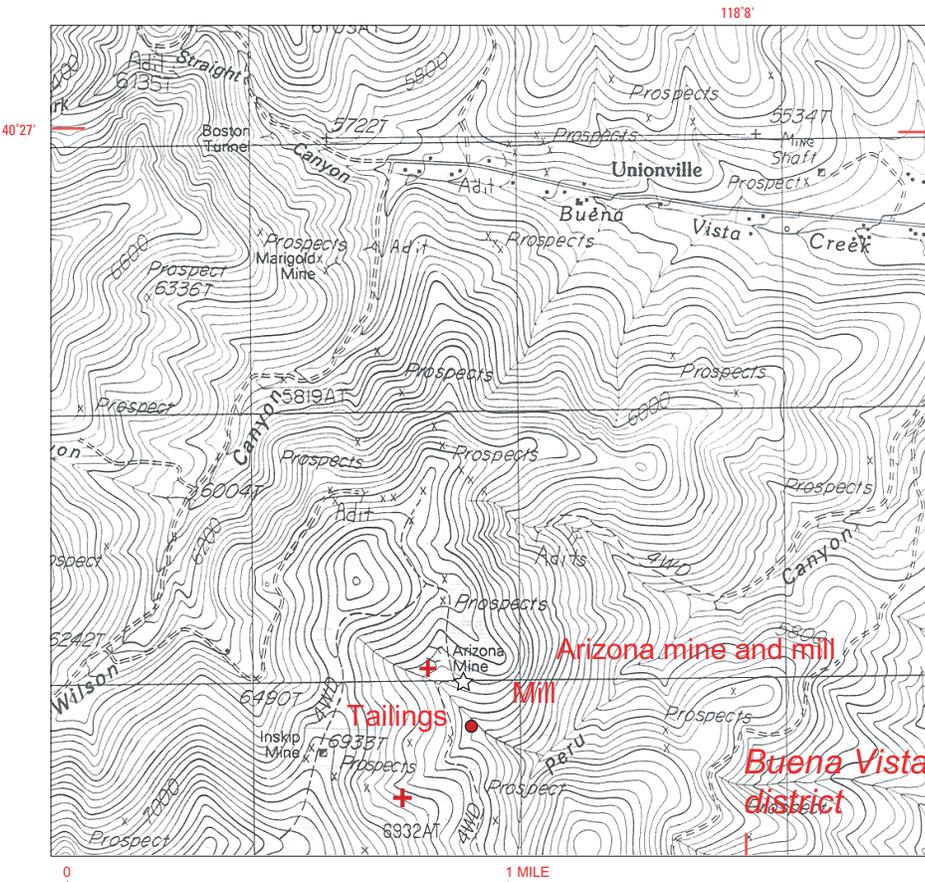
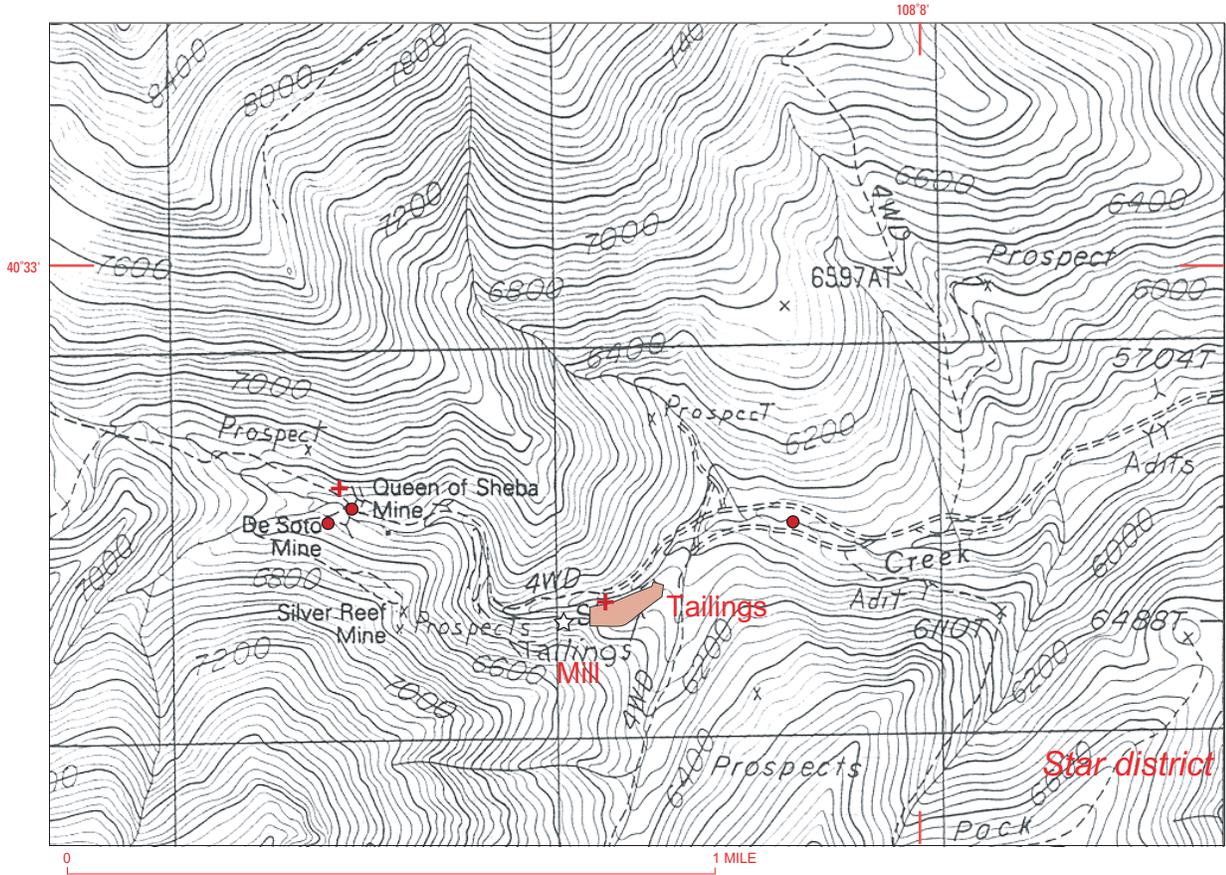
inches per year, with much more at the crest of the range. Features of the main mining areas in Star Canyon and near Unionville are shown on figure 13.

Principal commodities.—Ag; Au, Cu, Pb

Brief mining history.—Silver was discovered in Star Canyon in 1860, and exploration and mining exploded for the next 10 years. Very rich deposits were located at the Queen of Sheba and DeSoto mines, but the complex sulfide mineralogy and crude reduction methods of the era made recovery of silver difficult. A small mill was erected at the mouth of the canyon; ores were trammed to the site, and tailings were placed on the south bank of the creek (photo 22). The bonanza zones were exhausted by 1868 and only small-scale mining continued for the rest of the century.

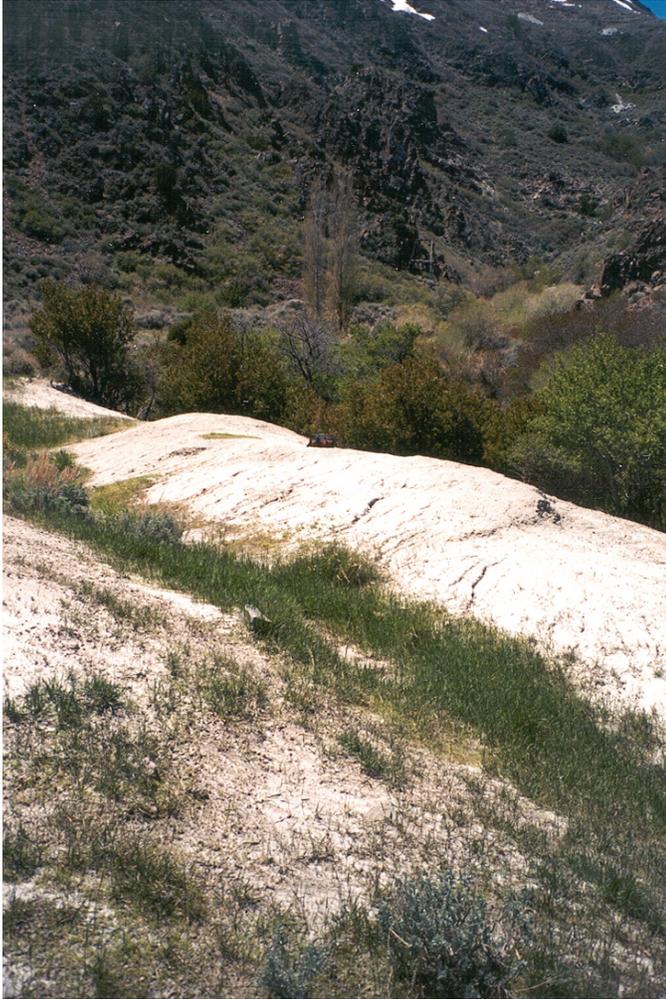
Prompted by the Star Canyon discovery, prospectors found more silver ore a few miles to the south in Buena Vista Canyon in 1861. The major mine in the area, the Arizona mine was discovered in 1862 and mined through 1880, and again from 1909 to 1959. The Arizona mine was supported by a mill of modest size that poured out a heap of dark-colored tailings that resembles a haystack (photo 23). Small gold placer and lode deposits were discovered in the 1860's and worked intermittently on a small scale. Stibnite deposits were also located, and these have yielded modest tonnages of antimony.

Production.—The rich silver ores of the Queen of Sheba mine are estimated to have been worth \$5 million. Substantial amounts of antimony, associated with the silver, was also recovered, making the Star district one of the largest antimony



- Water sample
- + Dump or tailing sample
- ☆ Mil site

Figure 13. Features of the Buena Vista and Star districts, showing sample localities.



Photograph 22. The Sheba mill created a few thousand tons of tailings in the 1880's. The ore was trammed to the mill at the mouth of the canyon (to left of this view), and the tailings were placed along the edge of Star Creek (right side of photo). An unknown volume of tailings has been lost to the creek.

producers in Nevada with about 1,200 tons Sb metal to its credit. The Buena Vista district produced about \$2.9 million, mostly from silver from the Arizona mine. Gold was a by-product in the Arizona mine, and stibnite deposits in the district yielded antimony that, of course, was not nearly as valuable as the silver.

Geology.—Triassic rocks dominate the east side of the Humboldt Range. The Koipato Group is older than the carbonate-bearing sedimentary rocks that are the main ore hosts, but some ore occurs in the rhyolite. The richest ores are found in unusual veins that have flat dip and are sub-parallel to bedding—this is best illustrated by the lode at the Arizona mine.

Ore deposits.—The silver deposits of the Star and Buena Vista districts are presumed to be similar vein-type polymetallic deposits. The primary ores were rich in pyrite-sphalerite

tetrahedrite and stibnite in pods and veins of massive white quartz. Supergene enrichment enhanced the silver concentrations in near-surface zones; silver grades tended to decrease in the deeper, less oxidized parts of the deposits that proved uneconomic at the times of mining. The stibnite deposits are related, but contain lower quantities of silver minerals.

Mineral-Environmental Investigations

My investigations in these districts focused on the behavior of polymetallic sulfide ores and tailings in a setting of carbonate rocks:

1. Would the expected buffering capacity of the host rocks control acid generated by sulfide minerals? and
2. What metals are mobile in the neutral to alkaline waters?

Sulfide minerals, especially pyrite and sphalerite are evident in the dump rocks. Total chemical analyses of three dump samples and two tailings samples from the districts confirm the polymetallic character of these ores: concentrations of Ag, Pb, and Zn are very high, and concentrations of As, Cu, Hg, Mo, Sb, and Se are high. The high concentrations of Mo-Hg-Se are not expected of this ore type but could also reflect sources in black shales of the host rocks. In passive leach tests, the dump and tailings samples generated little or no acid, and generally low metal concentrations. Two samples from the Arizona mine (dump and tailing) generated moderately high As and Mo concentrations, and two samples from the Star district generated moderate Sb and Zn concentrations. The mobility of As, Mo, Sb, and Zn and the low concentrations of Cu, Pb, and Fe in the near-neutral pH leachates is typical behavior for these elements.

Surface waters flow near mines of these districts, but mine drainage was observed only at the Queen of Sheba mine in May 1998. The streams and Queen of Sheba mine drainage had pH values in the range of 7.6 to 8.3, and metal concentrations were below concern levels. The small creek southeast of the Arizona mine had a notably high Se content of 24 ppb, and Mo concentrations in all samples were higher than in most streams. The mobility of Mo and Se is, in part, a reflection of the pH near 8.

The near-neutral pH of these waters appears to play an important role in minimizing transport of potentially problematic metals from these polymetallic ores. Although there is more near-surface flow of waters through these mines, dumps, and tailings than in most Nevada mining areas, there is little evidence for chemical degradation. The high selenium concentrations may warrant further study.

References

- Cameron (1939)-
Johnson (1977)-
Wallace and others (1969)-



Photograph 23. The Arizona mill south of Unionville was a major silver mine. The upper flat pile is waste rock carried on tracks from the lower adit. The mill (stone foundation, three levels) poured out tailings into two mounds (dark gray).

Imlay District (Standard Mine Area)

Location.—West side of Humboldt Range, about 5–15 mi south of Imlay, Nev., on Interstate 80 (fig. 1). Precipitation is 4–8 inches per year at low elevations, much higher at the crest of the range. Features of Standard mine area and sample localities are shown on figure 14.

Principal commodities.—Au, Ag; lesser Cu, Hg, Pb, Sb.

Brief mining history.—Some of the earliest discoveries in Pershing County were at the north end of the Humboldt Range, and by 1860 the town of Humboldt City serviced several gold-silver mines. This early production was very small. In 1907, mercury was discovered, and this caused another brief period of mining activity at mines such as the Eldorado and a bit later at the Star Peak mine. In 1930, a new variety of gold deposit was discovered, and the Standard mine operated as the major mine in the district from 1932 to 1952 (photo 24). In the 1980's, the Florida Canyon gold deposit was defined in an area that had long been known for hot springs, clay deposits, and native sulfur. The Florida Canyon open-pit operation mined very low grades of gold and recovered it from one huge heap-leach pile that is easily visible from I-80; mining continued in 1999 at a reduced rate.

Production.—Total production is somewhat confused because mining districts were redefined, but the total through 1965 was about 891,000 tons worth about \$1.74 million,

chiefly from gold and silver (Johnson, 1977). Production from the Standard mine is the greatest part of this total and included 47,000 oz gold and 103,000 oz silver. Production from the Florida Canyon mine has been about 1 million oz gold from more than 50 million tons of reserve and identified resources (average grade about 0.02 oz Au/ton, one of the lowest in the gold industry).

Geology.—Rocks on the west side of the Humboldt Range are the Triassic Koipato Group (rhyolite tuffs and felsite and associated intrusions), overlain by limestones. These rocks are complexly folded and faulted. They make bold, cliffy outcrops up to the impressive ridgeline of Star Peak.

Ore deposits.—Several distinct types of ore deposits are found in this district:

1. Polymetallic sulfide deposits, rich in antimony and silver, with gold, that are similar to the more famous ones of the Star and Buena Vista districts on the east side of the range,
2. Sediment-hosted gold-silver deposits, as at the Standard mine, which are arguably the first deposits of the Carlin-type found in Nevada,
3. Hot-springs gold-silver deposits, as at the Florida Canyon mine, in highly fractured and altered sedimentary rocks adjacent to the known geothermal area that actively produces steam, and
4. Miscellaneous other small deposits or occurrences of



Photograph 24. The Standard mine was one of the first open-pit gold mines in Nevada. This view is to the south, looking down the fault structure that contained the best gold ore. The light-gray colors come from limestone, and the tan colors come from iron oxides in the oxidized ore zone.

tungsten skarn, uranium veins, and other deposit types with small to no production.

Genetic relationships among the first three types is unclear.

Mineral-Environmental investigations

The Florida Canyon mine is operating and does not fall under the scope of this study. Brief study of the silver-gold lodes near Humboldt City and Imlay in 1994 indicated that they are small in size, highly oxidized, and in or near carbonate rocks. No acidic mine or dump drainage is apparent, and most metals seem stable in oxide minerals. No problems are apparent, but no studies have been made to confirm this prediction. Observations of the Standard mine in 1994 suggested that there could be mining-related problems for these ores and tailings that are known to be enriched in metals such as As, Mo, and Se (Ronkos, 1986), and these are potentially mobile in near-neutral waters.

A brief visit was made to the Standard mine in May 1998 to characterize the dumps and tailings and to search for possible water draining through mined rocks. Water in the unnamed creek north of the mining area had a substantial flow, but the path of this creek suggests that it does not traverse

mined rocks. The focus thus shifted to mineralized rocks and the potential for metals to be mobilized from them.

Mineralized rocks exposed in the pits (photo 24), on mine dumps, and mill tailings are rich in As (130–900 ppm), but base metals such as Cu and Pb are low. Zinc is enriched (200–300 ppm), as are Ag, Sb, Hg (3–9 ppm), and Se (3–7 ppm). Some of the highest Tl concentrations found in the study (9–28 ppm) are in these rocks. Thallium is a poorly documented metal in ore deposits but is recognized as highly toxic in some situations; Carlin-type gold deposits are known to be enriched in Tl (Ikramuddin and others, 1986).

Leach tests were made on three samples to examine acid generation and metal mobilities. The leachates attained a pH of 9, the highest group in this study, and metal concentrations were very low. Arsenic in leachates was slightly elevated; the highest As concentration of 57 ppb came from a sample of tailings.

The tailings impoundment is on the alluvial fan to the west of the mine, and occupies a relatively large area, possibly 10–20 acres (photo 25). The tailings are deeply eroded in unusual patterns like those of badlands, and some tailings have been carried west for more than a mile. There is a series of six or more berms or dams, constructed to impound the tails, or perhaps to control tailings after storm floods broke through the

first dams. Leach tests show that the tailings generate alkaline pH and moderate As concentrations. Other metals, such as Mo, Hg, Se, and Tl, that are enriched in the mined rocks and tailings are potentially mobile in alkaline waters but were not determined to be so in leach tests. If metals were mobilized in a storm event, the storm waters would probably infiltrate the permeable alluvium within a mile or two and any metal contaminants would be added to ground water. In a worst-case scenario, arsenic from the tailings could be mobilized into ground water and then to the Humboldt River at the Rye Patch Reservoir, 3 mi west of the impound. The alkaline nature of the waters are effective for transporting As and other oxyanion metals (molybdate, selenate), and reactions with caliche or

other sources of carbonate would not attenuate them, unlike reactions in acidic drainage. The chances for contamination of the Humboldt River by a storm event are low to very low, but preventative measures such as drainage controls may be appropriate.

References

- Bonham and Hess (1995)
- Ikramuddin and others (1986)
- Johnson (1977)
- Ronkos (1986)



Photograph 25. Tailings from the Standard mill, placed on the alluvial fan west of the mine, have been eroded and dissected by surface waters. Fluvial tailings are in the arroyo for about a mile to the west of this berm.

Discussion

Environmental Standards and Use of This Report

Standards for evaluation of contamination of surface waters and goals for reclamation of mined lands are in a state of flux in 2000. Regulatory standards based on beneficial use, which are the domain of the NDEP and posted on their web site, are specific for only the main stem of the Humboldt River. To my knowledge, the only stream (and related shallow ground water) near the studied mining districts that is developed for domestic drinking water is the lower (western) part of Rochester Canyon Creek near Oreana that serves the municipality of Lovelock. Streams in the vicinity of mines are not rated as fisheries, but Star Creek supports fish (at least some fisherman believe so). Some of the streams feed ground waters developed for irrigation. The majority of mining districts investigated have only ephemeral streams, and few if any human residents. Thus, there appear to be questions regarding what water-quality standards should be applied and what the goals for restoration of quality and habitat should be.

The intent of this investigation is to geochemically characterize the districts and mined materials, not point out environmental violations. Where chemical criteria for water quality, such as those for aquatic life, have been cited, this has been done to provide a frame of reference to allowing ranking of sites or to indicate a level of concern. If the chemical criteria I have used are inappropriate for the area, or if the standards change, the user should apply the new criteria to the data in this study. Where there are concerns regarding the ranking of water quality, or if the analytical data are in question, new studies and new sampling and analysis should be undertaken, using protocol appropriate for the concern. Geochemical evaluation of mining areas for impact on water and biota is a relatively new undertaking, and it is hoped that the results and recommendations in this report will be a useful step forward as scientists describe the natural environment and separate fact from fiction. Given the reality of limited staff and limited funds for reclamation work on public lands, prioritization is necessary. The observations and chemical results from this investigation should assist land managers and the public focus on the most significant of the geochemical problems related to historic mining in the western Humboldt Basin.

Risk of Tailings Erosion in a Major Storm

Features seen at tailings impoundments in this investigation are a reminder that possibly the most damaging process to impact the environment would be catastrophic failure of an impoundment during a major storm event (flash flood). Tail-

ings impoundments in this region show varying amounts of erosion during storm events, and breached impoundments in the Tenmile, Seven Troughs, Rochester, and Imlay districts show the consequences of a flash flood: movement of many thousands of tons of tailings. Elsewhere in Nevada, tailings have been significantly eroded and moved 1 to 10 mi from the original impoundments at Belleville (Candalaria district), Castleton (Pioche district; photo 26), Goldfield (photo 27), Leadville (photo 28), Mt. Hope, Tonopah (photo 29), and Tybo (Nash, unpub. fieldwork, 1999). Canyons and arroyos in western Nevada are capable of focusing substantial amounts of storm water with incredible power that can create debris flows of large boulders and fine-grained materials (Blatt and others, 1972)—this is commonly seen in Quaternary sedimentary deposits. When a flash flood encounters a tailings impound, the normally stable fine sands are ripped up and transported as a viscous mud or sand flow. Passive leach tests done in this investigation provide a minimum estimate of possible solution compositions. There are several dire consequences for the environment: (1) tailings are spread as overbank and channel-filling sand deposits for a mile or more down the canyon or arroyo, perhaps spreading out onto an alluvial fan if it reaches the range front as in the Tenmile and Seven Troughs districts. (2) Water in the debris flow is likely to attain more extreme metal concentrations than in simple runoff, or greater than that determined by passive leach tests, because mechanical mixing and abrasion will stimulate reactions. In most cases, these waters will infiltrate alluvium when their lateral flow slows, but in a worst-case scenario the waters might flow for several miles to reach a stream or even the Humboldt River.

More study and interpretation of catastrophic tailings failure is needed for Nevada. There is ample evidence in historic literature and in geoscience publications of the intense and widespread impacts of failures over the past hundred years, as at Anaconda, Mont., into the Clark Fork River (Nimick and Moore, 1991; Moore and Luoma, 1990), at Eureka, Colo., into the Animas River (Vincent and others, 1999), or Puerco River, N. Mex.—Ariz. (Wirt, 1994)—these tailings failures impacted more than 100 mi of stream and flood plain. Numerous risk analyses have been undertaken for failure of uranium mine tailings. One study (Shepherd and Nelson, 1978) concluded that engineering aspects of tailings impoundments are important for short-term effects, whereas geomorphological processes, especially natural events such as floods and earthquakes, are more significant for the long-term and major impacts. Fluvial processes, geomorphic evidence, catastrophic floods, and extreme hydrologic events as discussed by Schumm and others (1981) seem relevant to better understanding of tailings in Nevada. Based on geologic analogs and studies of flash floods, the worst place to place tailings is in a narrow canyon below a relatively large (>10 mi²) upland basin. Studies of eroded tailings impoundments in Nevada show that even sites below small basins are susceptible to erosion if the tailings are in a flood plain.



Photograph 26. Unconfined tailings southeast of Castleton, Pioche district, that are subject to erosion and reactions with surface waters. The major Castleton tailings impounds are southwest of this arroyo.



Photograph 27. This large tailings impound northwest of Goldfield shows significant erosion. These tailings are unusually fine grained, and clays are carried in suspension in storm runoff for several miles to the north.



Photograph 28. These tailings have been transported more than a mile east from the Leadville mill. In the 1920's, the mill tailings were placed in an arroyo with no containing structures.



Photograph 29. Tailings placed in Slime Gulch on the west side of Tonopah have been swept away in flash floods. This site is 7 miles west of the mill, and fluvial tailings can be traced for at least another 3 miles. Episodic storm events appear to do most of the erosion and transport. One flash flood was so strong that it dislodged concrete piers for a railroad bridge and carried the car-sized piers (50 tons?) more than 100 ft downstream.

Conclusions

Mining-related contamination of water and the environment is less widespread and less severe than in many metal-mining areas of the Western United States. Acid drainage from mines, dumps, and tailings are rarely a problem, as concluded by Lechler and others (1995). Only a few sites in the study area generate acidic waters, and in those cases the acids are mitigated by carbonate-bearing rocks and alluvium within a short distance of the source. In most cases, the neutralization occurs before the surface waters infiltrate alluvium, and in other cases it is reasonable to expect neutralization in the subsurface. The abundance of carbonate-bearing rocks and alluvium, and caliche in soils, in the study area is sufficient to naturally mitigate observed sources of acidic waters. However, the evolution of most waters to near-neutral and weakly alkaline pH creates conditions that are rarely emphasized in the field of mine-related pollution: alkaline transport of potentially toxic elements, including As, Cd, Hg, Mo, Sb, Se, and Zn.

No sites investigated here are producing sufficient contamination of water to merit high priority or immediate attention for reclamation. This generalized statement is made in the context of my understanding of water quality regulations in Nevada and my perceptions relative to other sites I have investigated in Nevada, Arizona, and Colorado. For instance, the worst of the problems seen in this area are only a fraction of the magnitude of the problems caused by the Big Mike mine and associated infrastructure on BLM lands south of Winnemucca. From a geochemical perspective, the worst mine-related problems tend to be those in which attenuation by natural processes are ineffective and allow contamination to extend for many miles beyond the mining district (Nash and others, 1996). I saw no case of this scale of contamination of surface waters in the study area, although there could be local contamination of ground water. If present, this contamination probably is below regulatory standards at distances of more than about 2 mi because natural processes are expected to mitigate ground-water quality, just as for surface waters. However, lands near several of the sites described here would benefit from reclamation work of some kind or scale.

There could be long-term cumulative effects of metal transport by alkaline surface or ground waters in closed basins of western Nevada that do not appear to be covered by current discharge regulations. Quantitative analysis of metal loads and metal fates over tens of years is beyond the scope of this investigation. However, there are sufficient indications of transport of elevated concentrations of As, Mo, Se, Zn, and possibly a few other metals to raise concerns regarding cycling of these elements and gradual enrichment by evaporation in closed basins.

Mill tailings in the study area pose a risk that is not easily answered by conventional AML methods. As in other mining areas, the tailings were typically placed in or near small streams and arroyos where they are subjected to episodic erosion during major storm events. No tailings in the area were

contaminating surface waters in May 1998 at concentrations in excess of aquatic life standards. But this is not the only standard for evaluating risk. All tailings in the study area show evidence for episodes of erosion, and in several areas major erosion during flash floods has carried thousands of tons of tailings several miles onto alluvial fans. Catastrophic failure of a tailings impoundment in a major flash flood, a low likelihood of occurrence, could produce a major release of metals and also spread metal-rich materials over a large area that would be prohibitively expensive to clean up.

The generally dry climate of the region minimizes potential water-quality problems compared to wetter regions of the Western United States. Water-waste reactions in dumps and tailings are less likely to release metals into ground water than in wetter regions, but there is high potential for contaminated runoff during storm events. In the dry climate, efflorescent salts tend to accumulate on dumps and tailings, and these very soluble salts dissolve to create a "first flush" of runoff that can carry high concentrations of many toxic metals. In this region of alkaline transport and high evaporation, there is high potential for As, Mo, and Se to accumulate in local transient puddles, playas, and ultimately in the Humboldt Sink.

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Appendix 1: Water Sampling and Analysis

Water samples were collected from mines and streams when the water was deemed to be representative of a geologic or mine setting and would thus yield information on the mobility of metals in that environment. The sampling methods have been used by the author since 1994 for reconnaissance characterization of geologic units, rock alteration, mine drainage, and reactions with tailings or dump materials (Nash and others, 1996); these methods are similar to but simplified from those described by Ficklin and Mosier (1999). First, flow rate and water characteristics (color, suspended material, bed colors or mineralogy) are recorded, and pH and conductivity are measured using portable instruments. The pocket-sized conductivity meter (Corning CD-55), with an upper limit of 2,000 $\mu\text{S}/\text{cm}$, 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. I consider the measurements of pH to carry an uncertainty of about ± 0.1 standard unit, even though the meter reports to 0.01 units. The water sample for analysis was collected with a disposable 60-mL syringe, then pushed through a disposable 0.45- μm cellulose filter. The syringe and the 60- or 120-mL polyethylene bottle were rinsed twice in the sampled water prior to collection. The filtered sample was acidified to a pH of about 2 at the site with 5 drops of ultrapure 1:1 HNO_3 per 60 mL. The acid stabilizes metals for periods of more than 2 years without the use of refrigeration, based on replicate analyses over a 2-year period. At appropriate localities (with pH >4) an unfiltered sample was collected for determination of alkalinity. Lab and field blank tests using deionized water indicated that contamination introduced by the sampling procedure and equipment is in the low parts per billion level (1–10 ppb), which is considered adequate in the search for metal concentrations orders of magnitude greater than the sampling error.

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 in Appendix 1 (table A1), generally to levels below 1 ppb, but in detail the limit of determination varies with sample composition and element mass. For many samples the actual limit of determination is lower than that shown in table A1, but in this report only 10 to 15 elements of prime environmental concern are tabulated and discussed. This analytical method is appropriate for determination of many metals of potential concern that are expected to have a wide range in concentrations; it is especially good for trace metals in water such as As, Cu, Pb, and Zn. (Crock and others, 1999). If water compositions reported here are a concern, follow-up work should be

done using trace-metal sampling protocols and more precise analytical methods.

Table A1. Elements determined in water and leachate samples by ICP-MS.

[Elements listed by atomic weight]

Element	Lower limit of determination (ppb)	Element	Lower limit of determination (ppb)
Li.....	0.1	Nb	0.01
Be	0.5	Mo	0.04
Na	0.8	Ag	0.01*
Mg.....	0.5	Cd.....	0.01
Al.....	0.4	Sn.....	0.01
Si.....	1	Sb.....	0.04
K.....	1	Te.....	0.2
Ca.....	1	Cs.....	0.01
Sc.....	0.1	Ba.....	0.01
Ti.....	0.04	La.....	0.01
V.....	0.04	Ce.....	0.01
Cr.....	0.04	Eu.....	0.01
Mn.....	0.04	Yb	0.01
Fe.....	0.3	Ta.....	0.01
Co.....	0.01	W.....	0.01
Ni.....	0.01	Re.....	0.01
Cu.....	0.01	Os.....	0.01
Zn.....	0.01	Pt.....	0.01
Ga.....	0.01	Au.....	0.01
As.....	0.04	Tl.....	0.01
Se.....	0.04	Pb.....	0.02
Br.....	1	Bi.....	0.01
Rb.....	0.01	Th.....	0.01
Sr.....	0.01	U.....	0.01
Y.....	0.01		

* Results unreliable.

Quality control for water analyses.—Standards and replicate samples were routinely submitted with field samples through the course of these studies. Approximately 5 percent of the analyzed samples were standards and replicates. A detailed accounting of quality control is beyond the scope of this report and statistical calculations, such as percent RSD (percent relative standard deviation) are deemed overly complex for the intended user of this report. Readers desiring such information should consult Lamothe and others (1999) for the performance of the USGS ICP-MS system; the commercial lab used for the analyses reported here is similar but is not run in a research mode. Quality control issues for the ICP-MS analyses of waters and leachates are discussed elsewhere (Fey and others, 2000), and a spreadsheet file of ICP-MS analyses (commercial lab and USGS) of standards, replicate samples, and blanks is given along with other analytical data for the Humboldt watershed (Nash, 2000a). The performance differs for various elements, as mentioned below. A contributing factor to analytical error can be the carryover effects when

an analyte of low concentration is sequenced after one with high concentrations; the very large range in composition of the Nevada samples and the fact that the 1998 samples were not sequenced for analysis by increasing conductivity or likely metal concentrations probably degraded those ICP-MS results. The following trends are evident:

Experience with the laboratory from 1996 to 1999, analysis of replicate samples (repeat analyses of water from the same bottle or duplicate bottles collected at the same time) and of reference standards allows the following generalized comments on precision (reproducibility) and accuracy (approximation of the correct value).

1. Results are reported for five or six orders of magnitude for most elements of interest in these natural waters and leachates, from less than 0.1 ppb (part per billion or microgram per liter) to 100,000 or more than 1,000,000 ppb in some unusual waters. This is a difficult challenge for any method or chemist. These samples often required dilution by amounts of 1:10 to 1:100 to keep the analyte within the calibration range.
2. Precision and accuracy are complex issues and are not the same for all elements and all concentration levels. I assume that analytical error is greater at the very high concentration levels of some unusual mine or leachate solutions because there are no standards at this level, but documentation of that error is difficult and incomplete at this date. Replicate samples suggest that precision at very high concentration levels is not much worse than at normal concentrations. Because reliable standards do not exist for waters with very high "trace" metal concentrations (>10,000 ppb), it is not possible to evaluate accuracy at high levels the way it is done at more normal levels. For reasons that I cannot explain, the precision and accuracy for "major" elements (Al, Ca, Mg, etc.) by this method are much lower than for trace metals. The user of these results should consider them semiquantitative with errors of about 50 percent in some cases (but less in others).
3. Based on standards and replicate samples, the precision for trace metals (such as As, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, Se, V, and Zn) appears to be about 10 percent (1 standard deviation) for normal water concentrations and possibly 20 percent at very high concentrations. The accuracy of determinations on these trace metals seems to be about 10 percent for normal concentrations. The precision and accuracy for Fe, which generally is not a trace metal in these waters, is not as good as most others and possibly is about 20 percent.
4. Some trace metals pose special problems. Mercury is analyzed, but it is well known that Hg is not stable unless preserved by special methods. For my samples, the Hg originally present probably became adsorbed on the bottle and was present in the analyte (the analysis is valid, but the sample is not). Silver, a potentially toxic trace metal, should be high in many of my samples, but analytical results are erratic and nearly always very low (despite good results for neighboring atomic masses); results for Ag are not considered reliable. Results for Se, Te, and Tl appear to be reasonable but no standards contained these elements; precision is about the same as for other trace elements.
5. These ICP-MS results are deemed satisfactory for the objectives of this study: classification or ranking of water compositions. The protocol used for 4 years in Arizona, Nevada, and Colorado AML studies (sampling, storage, analysis, and quality control) is reproducible from day to day, year to year, at a total error of about 20 percent for most trace elements. Replicate analyses show that the composition of these acidified water samples change by less than a few percent after a year of storage at room temperature (D. Fey, oral commun., 1999). Many replicate samples have an error of about 10 percent, and a few have a higher error. These error numbers are best understood by examination of figure 15.
6. The error bars show that an analysis for a metal with a concentration of about 10,000 ppb is easily distinguished from one having 1,000 ppb or 100 ppb. This is the real goal of these studies, characterization of sites with high to very high metal concentrations, not discriminating Zn at 220 vs. 240 ppb to determine compliance with regulatory standards.
7. For water analyses that appear suspect to the user, or where concentrations are close to a regulatory standard, further sampling and analysis by special protocols is recommended.

Figure 15 shows graphically the magnitude of 5, 10, 20, and 30 percent error bars over a wide range of hypothetical metal compositions. Many of the trace metal determinations (e.g., Cu, Pb, Zn) have error bars like those shown for 10 percent, a few (Cd) may be closer to the 5 percent example, and some (e.g., Fe) are like the 20 percent example. This plot shows that, even with high analytical error (20 or 30 percent), the reported concentrations for about 10,000 ppb do not overlap those of a sample with 1,000 or 100,000 ppb. Thus, the ICP-MS results are appropriate for ranking of water compositions spanning 4 to 6 orders of magnitude (1 to 1,000,000 ppb).

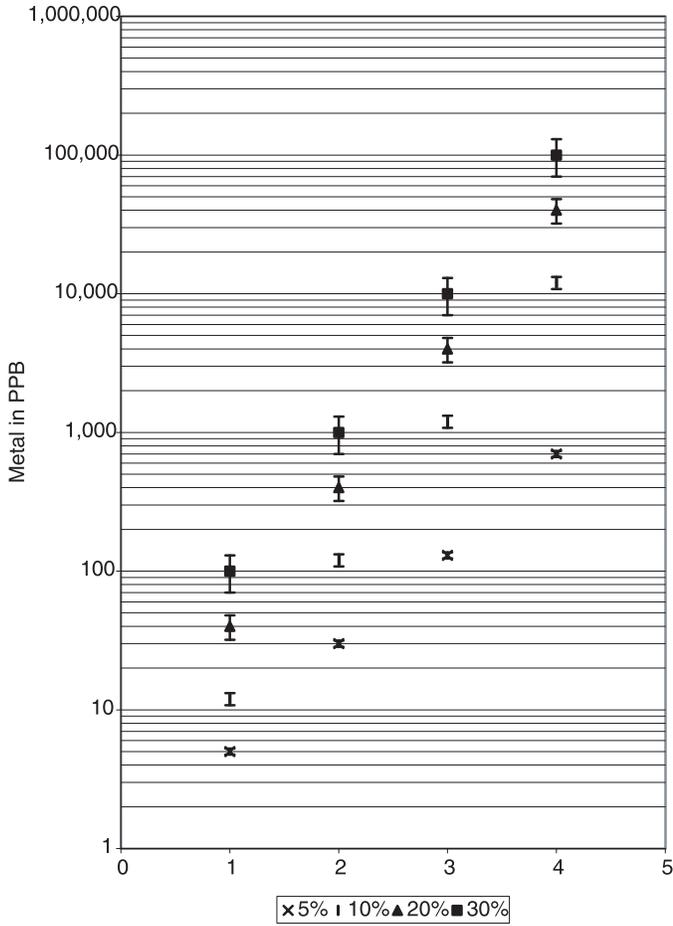


Figure 15. Analytical error diagram showing the magnitude of error at various concentration levels.