Historic Mills and Mill Tailings as Potential Sources of Contamination in and near the Humboldt River Basin, Northern Nevada

By J. Thomas Nash

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Chapter D *of*

Geoenvironmental Investigations of the Humboldt River Basin, Northern Nevada

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Preface

Northern Nevada is one of the world's foremost regions of gold production. The Humboldt River Basin (HRB) covers 43,500 km^2 in northern Nevada (Crompton, 1995), and it is home to approximately 18 active gold and silver mines (Driesner and Coyner, 2001) among at least 55 significant metallic mineral deposits (Long and others, 1998). Many of the gold mines are along the Carlin trend in the east-central portion of the HRB, and together they have produced 50 million ounces of gold from 1962 (when the Carlin mine first opened) through April 2002 (Nevada Mining Association, 2002). Mining is not new to the region, however. Beginning in 1849, mining has taken place in numerous districts that cover 39 percent of the land area in the HRB (Tingley, 1998). In addition to gold and silver, As, Ba, Cu, Fe, Hg, Li, Mn, Mo, Pb, S, Sb, V, W, Zn, and industrial commodities such as barite, limestone, fluorite, sand and gravel, gypsum, gemstones, pumice, zeolites, and building stone, have been extracted from the HRB (McFaul and others, 2000).

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

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

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Historic Mills and Mill Tailings as Potential Sources of Contamination in and near the Humboldt River Basin, Northern Nevada

By J. Thomas Nash

Abstract

Reconnaissance field studies of 40 mining districts in and near the Humboldt River basin have identified 83 mills and associated tailings impoundments and several other kinds of mineral-processing facilities (smelters, mercury retorts, heap-leach pads) related to historic mining. The majority of the mills and tailings sites are not recorded in the literature. All tailings impoundments show evidence of substantial amounts of erosion. At least 11 tailings dams were breached by flood waters, carrying fluvial tailings 1 to 15 km down canyons and across alluvial fans. Most of the tailings sites are dry most of the year, but some are near streams. Tailings that are wet for part of the year do not appear to be reacting significantly with those waters because physical factors such as clay layers and hardpan cement appear to limit permeability and release of metals to surface waters. The major impact of mill tailings on surface-water quality may be brief flushes of runoff during storm events that carry acid and metals released from soluble mineral crusts. Small ephemeral ponds and puddles that tend to collect in trenches and low areas on tailings impoundments tend to be acidic and extremely enriched in metals, in part through cycles of evaporation. Ponded water that is rich in salts and metals could be acutely toxic to unsuspecting animals. Rare extreme storms have the potential to cause catastrophic failure of tailings impoundments, carry away metals in stormwaters, and transport tailings as debris flows for 1 to 15 km. In most situations these stormwaters and transported tailings could impact wildlife but probably would impact few or no people or domestic water wells. Because all identified historic tailings sites are several kilometers or more from the Humboldt River and major tributaries, tailings probably have no measurable impact on water quality in the main stem of the Humboldt River.

Introduction

From about 1870 to about 1970, mills in numerous historic mining districts of northern Nevada treated millions of tons of ore to recover metals of value and, in doing so, created large quantities of waste materials that can release acid or metals to the environment. Although the term "tailings" is often applied to any kind of mined material, regardless of ore grade or amount of processing, the term will be used here only for material that was ground and processed through a mill. Mine-waste dumps, of various compositions from barren rock to ore-grade material, are a separate topic of concern for release of contaminants and acid to the environment. At most mines, more than 90 percent of the ore-grade material mined was processed, yielding mill tailings with grains finer than beach sand and containing minerals that either escaped recovery or had too little value to recover. Other recovery methods, such as retorts for mercury or heap-leach pads for precious metals, left piles of crushed rock containing substantial amounts of metal.[1] These processing operations placed the tailings in nearby locations that were convenient, but often unstable and subject to episodic contact with surface water. Because most mills utilized water in their chemical processing of ores, and most tailings emerged as a wet slurry, tailings tended to be placed in arroyos or stream channels that carry water. There were no Federal or State regulations against placing tailings in streams prior to 1935. The fine grain size of tailings tends to make them more reactive when exposed to water and more vulnerable to erosion than mine waste on dumps that has not been crushed or ground. In some situations, mill tailings can be significant sources of pollution to surface and ground waters; an extreme example in Nevada is the sulfidic tailings from the Rio Tinto mine that releases acid and metals to the Owyhee River, currently under consideration as a Superfund-caliber site for reclamation.

This report provides an overview of historic mills and their tailings materials in 40 mining districts in northern Nevada that are in or near the Humboldt River basin (fig. 1). Observations in eight districts outside of the Humboldt River basin that have especially large mill-tailings impoundments provide additional insights, especially on the topic of catastrophic tailings failure. Although mills and tailings are part of

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[1] The word "metal" will be used in a broad sense in this report, to cover base metals (Fe, Cu, Pb, Zn), transition metals and metaloids (As, Sb, Se), with no connotation of speciation for elements that form oxyanions (MoO_4, AsO_4).

abandoned mine lands, they have not received scientific study proportional to their potential impact on the environment: most geologic references and databases include less than 10 percent of mill or tailings sites; there is even less information on their size, physical situation, and composition. Milling facilities of active or recently active mining operations by major corporations are not included because they are subject to several regulatory processes for operation and closure; a few mill sites that were abandoned without reclamation during the last 10 years are included because they are of interest to land managers. During the course of geochemical studies of 40 mining districts from 1996 to 1999, I made special effort to locate mills and tailings because they are inadequately recorded in the literature. Mention is made here of 83 mills (or mill sites), 11 smelters (or slag sites), 13 heap-leach facilities, and 11 mercury retorts. Waste from these sites was located and sampled in the field where possible.

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

In the interest of brevity and simplicity, this overview cites relatively few references for details on geology, geochemistry, and mining. The series of Nevada County Reports provide a wealth of information: Elko (LaPointe and others, 1991); Eureka (Roberts and others, 1967); Humboldt (Willden, 1964); Lander (Stewart and McKee, 1977; Stager, 1977); Nye (Kleinhampl and Ziony, 1984); Pershing (Johnson, 1977). Lincoln (1923) provides good information on mines in all of the districts studied.

Acknowledgments—Suggestions from several Bureau of Land Management (BLM) scientists in district offices, especially Steve Brooks, helped identify important sites. Reviews by Roger Ashley, Bob Carlson, and Lisa Stillings of the U.S. Geological Survey (USGS) clarified the science and descriptions in this report.

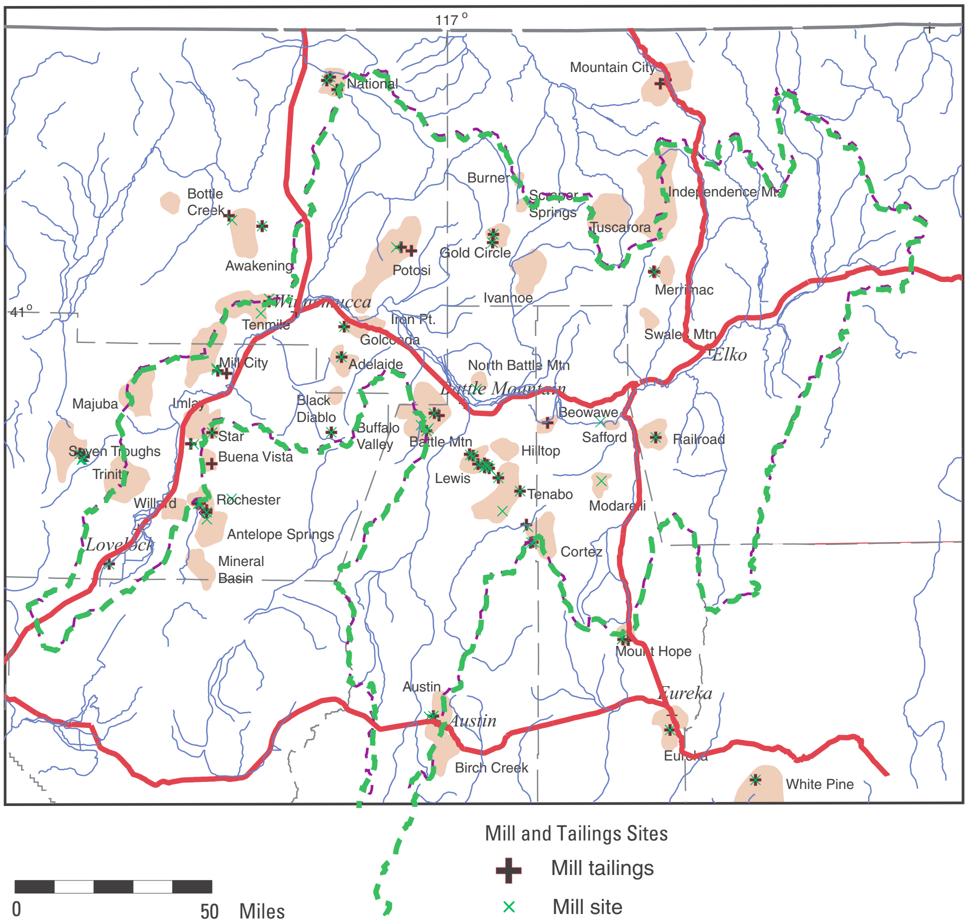

Figure 1. Location of mining districts studied in the Humboldt River basin and adjacent areas of northern Nevada. Metal mining districts (salmon-colored areas) from Tingley (1998).

Methods and Data

Field observations of mills and tailings were made during nine visits between September 1995 and June 2000. A summary of the findings is in table 1. Sites with the identifier NH and number (e.g., NHM717) are from observations by Nash for the Humboldt project; the third character is the type of site (G, smelter or slag; M, mill; T, tailing). Sites lacking a number (e.g., NHMczg) were observed from a distance and the location was determined from a topographic map. Locations in table 1 are generally those from a GPS (global positioning satellite system) and are accurate to about 100–150 ft, based on field tests; a few site locations are measured from 1:24,000-scale topographic maps and have similar accuracy. During reconnaissance field studies, not all mills and tailings were identified, and some were not accessible; thus, table 1 is a minimum estimate of sites. Possibly as many as 50 percent of mills or tailings impoundments could have been missed in this reconnaissance. Also, it was common for mills to burn and be replaced by newer structures, and that history is not indicated in my observations. One site is shown for most tailings impoundments, even if multiple impoundments exist. For some, but not all, mill-tailings systems, a location of eroded fluvial tailings gives an approximate indication of how far tailings have been transported. Flood transport of tailings is described in more detail elsewhere (Nash, 2002a). Finally, the names given to mills are taken from nearby features and are not the legal names as used in county land records.

Smelters identified in this study, or the piles of slag that they created, are listed in table 1. Smelters and slag pose environmental concerns that differ from those of mills, and, because both are related to historic mining activities, some mention will be made of smelters. Some smelters are easily identified in the field by their brick or concrete smokestacks, and smelter slag is a distinct material when viewed from less than 5 m (photograph 1). Black color and high luster are typical, and the high density distinguishes slag from otherwise similar-appearing vesicular basalt. For various reasons, many smelters dating from 1880 to about 1900 may have escaped detection (such as the one at Golconda, the site of which is now populated by private homes and businesses).

Photograph 1. These piles of black smelter slag are all that remain of the smelter at Bullion in the Railroad district. The smelter was located at a spring, about a mile east of the mines.

Properties of Mill Tailings

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

Identification of Mill and Tailings Sites

Mills vary greatly in size, style of construction, and preservation. The older mills tend to have stone foundations (photograph 2), but concrete foundations were used after about

Table 1. Summary of mill and tailings sites identified in the Humboldt River basin and nearby areas, Nevada.

[District abbreviations: AS, Antelope Springs; AU, Austin, AW, Awakening; BD, Black Diablo; BL, Belmont; BM, Battle Mountain; BT, Bottle Creek; BV, Buena Vista; BW, Beowawe; CN, Candelaria; GC, Gold Circle (Midas); GF, Goldfield; GO, Golconda; GR, Gold Run; HT, Hilltop; IV, Ivanhoe; LM, Lone Mountain; LW, Lewis; MAJ, Majuba; MC, Mill City; MH, Mt. Hope; MN, Manhattan; MtC, Mountain City; MD, Modarelli; NBM, North Battle Mountain; NT, National; NU, Northumberland; PO, Pioche; PT, Potosi; RO, Rochester; RR, Railroad (Bullion); SF, Safford; SR, Star; ST, Seven Troughs; STm, Standard mine; TB, Tenabo; TL, Toulon; TN, Tonopah; TR, Trinity; TU, Tuscarora; TY, Tybo; WL, Willard; WP; White Pine. Type: M, mill site; Mh, heap-leach site; Mr, mercury retort site; S, smelter (or slag); T, tailings or tailings impoundment; Tc, mercury calcine; Tf, fluvial tailings. Latitude and longitude in decimal degrees]

Site	District	Type	Latitude (N.)	Longitude (W.)	Description
NHM744	AS	Mr	40.1289	118.1672	Retort for mercury, elaborate, 1970s?
NHM746	AS	Mr	40.1333	118.1731	Pershing mine mill and retort
NHM747	AS	Mr	40.1650	118.1774	Nevada Quicksilver mill and retort
NHM746h	AS	Mh	40.1333	118.1731	Pershing mine, heap leach from calcine
NHT744	AS	Tc	40.1289	118.1672	Red retort calcine
NHT746	AS	Tc	40.1333	118.1731	Pershing mine retort calcine, same as on recent leach pad (for Au?).
NHT747	AS	Tc	40.1650	118.1774	Red calcine, Nevada Quicksilver mine retort
NN0M263	AU	M	39.4985	117.0801	Stone and tin mills(2), Pony Canyon, at haulage tunnel
NHM467	AU	M	39.5072	117.0956	Mill, concrete, 6 levels, very few tailings found
NHMau1	AU	M	39.5097	117.0744	Newer mill, 70s?, Slaughterhouse creek, small tailings pond
NHMquito	AU	Mh	39.3972	117.1375	Heap-leach facility, Quito (reclaimed)
NHT467	AU	T	39.5097	117.0744	Tailings from mill, Pony Canyon
NHM714	AW	M	41.2947	117.9030	Daveytown mill, small foundation, tailings to east
NHM717	AW	M	40.3014	118.0503	Jumbo mill, concrete foundation; tailings to west (reclaimed)
NHMslp	AW	M	41.3166	118.0483	Sleeper cyanide mill
NHT714	AW	T	41.2947	117.9022	Daveytown mill tailings, from gold-qtz vein?
NHTslp	AW	T	41.3330	118.0630	Sleeper mill tailings impoundment
NHT715	AW	T	41.2947	117.9028	Daveytown mill tailings
NHM726	BD	M	40.5433	117.5681	Old mill, pre-Big Mike, tailings pond nearby
NHM728	BD	Mh	40.5428	117.5711	Big Mike heap-leach facility
NHT726	BD	T	40.5433	117.5681	Big Mike, mill tailings from early shaft mining, reddish, granular
NNM964	BL	M	38.5886	116.8583	Combination mill, Belmont
NNM965	BL	M	38.5808	116.8592	Highbridge mill, brick, Belmont
NNT966	BL	T	38.5794	116.8556	Tailings east of Highbridge mill, small volume
NNT964	BL	T	38.5881	116.8581	Tailings, red, Combination mill; very small volume
NHG101	BM	S	40.5653	117.1294	Slag, Galena smelter
NHG102	BM	S	40.5675	117.1311	Slag Galena smelter #2
NHM205	BM	M	40.5490	117.1072	Iron Canyon mill, not much left
NHM817	BM	M	40.5694	117.1342	Galena or White and Shiloh mill, old stone foundation, red tailings
NHMgal	BM	M	40.5581	117.0972	Stone foundation, mill site, old and small, Butte Canyon
NNM136	BM	M	40.6128	117.0711	Buckingham mill, small concrete foundation
NHT201	BM	T	40.6047	117.0468	Tailings by Long Canyon Creek, south of Copper Basin dumps
NHT157	BM	T	40.6133	117.0694	Buckingham mill tailings
NHT205	BM	T	40.5490	117.1072	Iron Canyon mill tailings, rusty brown
NHM607	BO	Mr	41.3606	118.3150	White Peaks mill/retort
NHM609	BO	Mr	41.3586	118.3181	Mercury mill/retort site, no structure, large calcine pile
NHT607	BO	Tc	41.3606	118.3150	Calcine, opal-Hg from retort

Table 1. Summary of mill and tailings sites identified in the Humboldt River basin and nearby areas, Nevada—*Continued*.

Site	District	Type	Latitude (N.)	Longitude (W.)	Description
NHT609	BO	Tc	41.3586	118.3181	Calcine, opal-Hg from retort
NHT611b	BO	Tc	41.3583	118.3169	Opal-Hg from retort(calcine)
NHT739	BV	T	40.4289	118.1467	Arizona mill, medium size, concrete, 3 levels
NHT739	BV	T	40.4289	118.1467	Arizona mill, stack of tailings, dark gray, fine grain size
NHM511	BW	Mr	40.5836	116.4878	Mill and retort, small operation, small calcine pile
NHT509	BW	T	40.5783	116.5214	Barite mine, crushed rock, barite rejects?
NHT511	BW	Tc	40.5836	116.4878	Retort tailings or rejects, siliceous conglomerate
NNM938	CN	M	38.2194	118.1761	Belleville big stone mill
NNM937	CN	M	38.2233	118.1778	Belleville, wooden mill
NNT934	CN	M	38.1594	118.0911	Stamp mill, west side Candelaria
NNT941	CN	T	38.2242	118.1786	Belleville, large area of red tailings, reprocessed?
NNT946	CN	T	38.1647	118.0819	Candelaria, brown tailings, east
NNT934	CN	T	38.1594	118.0911	Stamp mill tailings, Candelaria
NN0M314	CZ	M	40.1433	116.5889	Cortez new silver mill, concrete foundation, 1920s
NHM105	CZ	M	40.1421	116.5996	Old Cortez mill, stone foundation
NHMczg	CZ	M	40.1988	116.6167	Cortez gold mill
NHT105	CZ	T	40.1414	116.6044	Old Cortez mill tailings, carbonate
NHT260	CZ	T	40.1435	116.5933	Cortez silver mill tailings (new)
NHTcz	CZ	T	40.2072	116.6240	Cortez gold mill tailings impoundment
NHT260f	CZ	Tf	40.1223	116.6240	Cortez silver tailings, fluvial, west limit of flood deposit
NNGes1	EU	S	39.5077	115.9592	Smelter slag heap, south side Eureka
NNGes2	EU	S	39.5195	115.9632	Smelter slag heap, north side Eureka
NNM969	EU	M	39.4656	115.9844	Diamond tunnel, mill
NNM975	EU	Mh	39.4555	115.9692	Windfall heap-leach facility
NNT969	EU	T	39.4656	115.9844	Tailings near Diamond tunnel, red
NHM411	GC	M	41.2647	116.7836	Elko Prince mill, modest foundation
NHM415	GC	M	41.2350	116.7883	Jackson mill foundation steps down
NHMmid	GC	M	41.2186	116.7689	Esmeralda mill
NHT411	GC	T	41.2647	116.7836	Midas; tan to pink tailings from Elko Prince mill
NHT415	GC	T	41.2350	116.7872	Jackson mill tailings, tan
NNM928	GF	M	37.7403	117.2356	Goldfield Consolidated mill, large tailings impoundment
NNM931	GF	M	37.7100	117.2183	Goldfield, Florence mill, east of town
NNT932	GF	Tf	37.7689	117.2356	Fluvial tailings carried north from G.C. impoundment
NNT928	GF	T	37.7403	117.2364	Goldfield Consolidated mill tailings, light tan
NNT931	GF	T	37.7094	117.2183	Florence mill tailings
NHM402	GO	M	40.9283	117.5056	Kramer small mill, tan tailings to north
NHT402	GO	T	40.9283	117.5056	Kramer small mill, tan tailings
NHG639	GR	S	40.8053	117.4981	Adelaide smelter, slag only remains at site
NHM103	GR	M	40.8180	117.5190	Adelaide Crown millsite, concrete foundation
NHM637	GR	Mh	40.8075	117.5233	Heap-leach facility, Adelaide Crown
NHT103	GR	T	40.8178	117.5186	Adelaide Crown tailings impoundment, tan, stable
NHM592	HT	M	40.4106	116.8011	East Hilltop mill, small concrete foundation, tailings northeast

Table 1. Summary of mill and tailings sites identified in the Humboldt River basin and nearby areas, Nevada—*Continued*.

Site	District	Type	Latitude (N.)	Longitude (W.)	Description
NHM842	HT	M	40.4210	116.8104	Hilltop mill, newer, concrete foundation
NHM853	HT	M	40.4255	116.8550	Dean Morningstar mill, tailings to west
NHM853	HT	M	40.4272	116.8230	Pittsburg millsite, tailings in drainage to northwest
NHM334	HT	M	40.4164	116.8272	Small mill, Kattenhorn?, small tailings to east
NHMdmh	HT	Mh	40.5080	116.8327	Heap-leach facility for Dean mine; reclaimed 1998
NHT211	HT	T	40.4305	116.8268	Pittsburg mill tailings, yellow, two lobes in draw
NHT218	HT	T	40.4280	116.8587	Morningstar mill tailings, light color
NHT228	HT	T	40.4252	116.8132	Hilltop mill tailings, lite, in stream
NHT229	HT	T	40.4128	116.8040	Hilltop east mill tailings, crème
NHT334	HT	T	40.4164	116.8272	Tan mill tailings, small, Kattenhorn?
NHM430	IV	Mr	41.1228	116.5711	Butte #1 mill and retort
NHM436	IV	Mr	41.1450	116.6208	Governor mill and retort
NHM438	IV	Mr	41.0525	116.6244	Silvercloud mill and retort, calcine to north
NHM443	IV	Mr	41.1558	116.6267	Newer rotary kiln and retort, 70s?
NHMnew	IV	Mr	41.1558	116.6272	New reort, rotary kiln, 70s?
NHMot	IV	Mr	41.1092	116.6069	Rotary kiln and retort, calcine to east
NHT430	IV	Tc	41.1228	116.5711	Butte #1 mine; white opalite calcine from retort
NHT436	IV	Tc	41.1450	116.6208	Governor mine/retort, calcine from retort
NHT438	IV	Tc	41.0525	116.6244	Silvercloud Hg mine, white silica with red matrix
NHT443	IV	Tc	41.1558	116.6267	Calcine from 70s(?) retort; opal and vitreous tuff
NHM108	LM	M	41.1272	116.0050	Rip Van Winkle mill, concrete, tailings to NW in Coon Creek
NNT983	LM	T	41.1300	116.0067	Rip Van Winkle mill tailings, side canyon
NNT986	LM	T	41.1294	116.0078	Westernmost tailings in Coon Creek, final catch pond?
NNT987	LM	T	41.1286	116.0069	RVW tailings, second pond west
NNT989	LM	T	41.1281	116.0056	RVW tailings pond 3 west
NNT990	LM	T	41.1269	116.0031	RVW largest tailings pond, 4 west
NNM112	LV	M	41.0983	119.4028	Leadville mill site, burned
NNT117	LV	Tf	41.0903	119.3869	Leadville, fluvial tailings, east end
NNT105	LV	T	41.0969	119.3992	Gray tailings, lower area, unconfined; Leadville mine
NNT113	LV	T	41.0972	119.3992	Leadville mill tailings, upper valley fill, ocher and gray
NHM566	LW	M	40.4608	116.8958	Betty O'Neal mill, structure intact
NHM566h	LW	Mh	40.4606	116.8958	Betty O'Neal, heap leach attempt on tailings
NHT238	LW	T	40.4637	116.8988	Betty O'Neal mill tailings, med gray
NHM858	LW	M	40.4572	116.8810	Lewis Canyon mill, stone foundation
NHT858	LW	T	40.4587	116.8822	Lewis Canyon mill, very small layer gray tailings in arroyo
NHM713	MC	M	40.7708	118.1222	Pacific Tungsten Co. mill
NHMmc	MC	M	40.7770	118.1235	New Springer mill, tungsten
NHT713	MC	T	40.7680	118.1170	Tan mill tailings, older Springer tungsten mill
NHTmx	MC	T	40.7580	118.0745	New tailings impoundment, modern
NNT977	MH	T	39.7867	116.1308	Mt. Hope, fluvial tailings, southeast
NNT978	MH	T	39.7889	116.1567	Mt. Hope mill tailings, lower pond
NNT979	MH	T	38.5328	117.0506	Mt. Hope mill tailings, upper pond

Table 1. Summary of mill and tailings sites identified in the Humboldt River basin and nearby areas, Nevada—*Continued*.

Site	District	Type	Latitude (N.)	Longitude (W.)	Description
NNM979	MH	M	39.7900	116.1610	Mt. Hope zinc mill, floatation, steel building
NN0M244	MN	M	38.5400	117.0820	Mustang Hill mill--some tailings on hillside below
NN0M245	MN	M	38.5300	117.0502	White Caps mill, with roaster; burned
NN0M247	MN	M	38.5333	117.0556	Old mill just west of White Caps--tan tailings
NN0T248	MN	T	38.5339	117.0494	North fork smaller impoundment, red tailings
NN0T247	MN	T	38.5333	117.0556	Tan tailings from old mill
NN0T249	MN	T	38.5336	117.0528	Middle dam, breached, Consolidation Gulch
NNT962	MN	T	38.5331	117.0506	Whitecaps, main impoundment, red tailings
NHM685	MO	M	40.3661	116.2608	Modarelli iron processing facility
NHT109	MtC	T	41.8281	115.9483	Golden Ensign mill tailings, tan
NHTriot	MtC	T	41.8138	115.9759	Rio Tinto sulfidic mill tailings impoundment
NHM534	NBM	M	40.7017	116.8650	Barite mill, slimes separation
NHM613	NT	Mr	41.7828	117.6444	West Buckskin mill/retort, rotary kiln
NHM618	NT	M	41.7922	117.5400	Buckskin mine, flotation mill
NHM631	NT	M	41.8381	117.5736	National mill, concrete foundation, tailings to north in creek
NHM633	NT	M	41.8256	117.5900	Birthday mill tailings, green; small wooden building, small volume of tailings
NHT618	NT	T	41.7922	117.5400	Sulfide floatation tailings, Buckskin mine
NHT631	NT	T	41.8381	117.5736	Sulfide tailings,medium gray, from upper impoundment, National mill
NHT633	NT	T	41.8256	117.5900	Birthday mill tailings, green
NNM967	NU	M	38.9600	116.8700	Old Northumberland mill
NNT968	NU	T	38.9361	116.8614	Northumberland mill tailings, gray, lower impoundment
NNT967	NU	T	38.9433	116.8511	Northumberland mill tailings, gray, middle impoundment
NNM103	PT	M	41.2180	117.2538	Getchell mill (original, 1930s?)
NNT013	PT	T	41.2180	117.2303	Getchell mill tailings impoundment
NNT103	PT	T	41.2047	117.1803	Fluvial tailings east of road, washed from Getchell impoundment
NNG901	PO	S	37.8061	114.4044	Bullionville smelter, few remains; slag
NNM900	PO	M	37.7997	114.4047	Bullionville mill, old stone foundation, tailings removed
NNM902	PO	M	37.9300	114.4700	Pioche Mines mill, intact
NNM905	PO	M	37.9080	114.4720	Prince mill, steel, intact
NNM910	PO	M	37.9250	114.4920	Castleton, large modern mill active through 1960s
NNM209	PO	M	37.9000	114.6170	Comet mine and mill
NN0T211	PO	Mh	37.9575	114.4920	Heap leach attempt on mill tailings, recent
NNT905	PO	T	37.8936	114.4786	Prince mill tailings impoundment
NNT911	PO	T	37.8947	114.4886	Castleton, series of large tailings ponds
NHM773	RO	M	40.2522	118.1711	Nevada-Packard mill, tailings to southwest
NHM782	RO	M	40.2269	118.1703	Rochester Combined mines mill, large concrete, small production
NHM783	RO	M	40.2828	118.2114	Looney mine, stamp mill. Burned, jig table
NHM799	RO	M	40.2850	118.2044	Lower Rochester mill, concrete foundation, large tailings impoundment to west
NHM800	RO	M	40.2842	118.2017	Buck and Charley mill, tin, recently operated
NHM775	RO	Mh	40.2489	118.1781	Leach facility 1980s(?), on top of tailings impoundment
NHT773	RO	T	40.2517	118.1717	Nevada-Packard mill tailings, pinkish tan, fine
NHT778	RO	Tf	40.2503	118.1814	Fluvial tailings from original N.P. impoundment, west edge

Table 1. Summary of mill and tailings sites identified in the Humboldt River basin and nearby areas, Nevada—*Continued*.

Site	District	Type	Latitude (N.)	Longitude (W.)	Description
NHT782	RO	T	40.2603	118.1710	Tailings from Rochester Combined Mines mill, small volume in draw
NHT783	RO	T	40.2828	118.2125	Coarse stamp mill tailings, Looney mine
NHT797	RO	T	40.2847	118.2175	Lower Rochester, main tailkings impoundment, pale tan
NHT800	RO	T	40.2847	118.2028	Ocher tailings from Buck and Charley small mill
NN0G308	RR	S	40.5347	116.0003	North Bullion smelter, medium volume slag
NN0G307	RR	S	40.5342	115.9989	South Bullion smelter, large volume of slag
NHM670	RR	M	40.5250	115.9983	Bullion mill, small impoundment, 1950s(?)
NHT670	RR	T	40.5250	115.9981	Tan mill tailings, small impoundment
NHM687	SF	M	40.5811	116.2658	Barth iron processing facility
NHM736	SR	M	40.5425	118.1450	Star mill, old (1870s?) stone foundation, served by tram to west
NHT736	SR	T	40.5425	118.1450	Star mill tailings east of mill
NHM759	ST	M	40.4662	118.7846	Seven Troughs mill, on creek, tailings in creek
NHM761	ST	M	40.4544	118.7646	Mazuma mill, small concrete foundation
NHM763	ST	M	40.4442	118.7736	Tunnel Camp, newer mill
NMH762	ST	M	40.4444	118.7742	Tunnel Camp mill, older mill at portal
NHT759	ST	T	40.4664	118.7844	Ocher mill tailings, center Seven Troughs; tailings in creek
NHT761	ST	T	40.4544	118.7644	Gray and tan mill tailings from Mazuma mill
NHT764	ST	Tf	40.4361	118.7636	Fluvial tailings in draw, east of Tunnel Camp
NHT765	ST	Tf	40.4269	118.7603	Fluvial tailings, ocher and yellow, way out east on fan
NHT768	ST	Tf	40.4367	118.7681	Similar fluvial tailings, next arroyo to south
NHM805	STm	M	40.4997	118.2331	Standard mill, medium concrete foundation, tailings far to west
NHT812	STm	T	40.5019	118.2478	Standard main tailings impoundment, fine, clay-rich
NHM517	TB	M	40.3778	116.7597	Gray Eagle mill, small foundation, tailings to south
NHT517	TB	T	40.3778	116.7597	Gray Eagle mill tailings, tan; much erosion; failure?
NHMga	TB	M	40.2565	116.7397	Gold Acres mill (removed, under Pipeline mine complex)
NHM512	TB	M	40.3294	116.6547	Small custom mill(?), N side of Tenabo
NHT512	TB	T	40.3294	116.6547	Mill tailings, N of Tenabo near Indian Creek
NHM787	TL	M	40.0633	118.6431	Toulon mill, tailings to NE?
NHT787	TL	T	40.0644	118.6431	Toulon mill, tailings fine, windblown
NHM596	TM	M	41.0300	117.8692	Pansey Lee mill, concrete foundation below headframe
NHM597	TM	M	40.9769	117.9086	Tenmile mill site, tailings reclaimed or covered in 1998
NHT596	TM	T	41.0203	117.8692	Yellow mill tailings, Pansey Lee
NHT701	TM	Tf	40.9842	117.8681	Fluvial tailings from Pansey Lee mill, tan and ocher
NNM958	TN	M	38.0694	117.2161	Tonopah Belmont mill, large concrete foundation
NNM957	TN	M	38.1311	117.4606	Millers, larger of two mills
NNM955	TN	M	38.1300	117.4672	Millers, smaller of two mills, west
NNM959	TN	M	38.0728	117.2228	Tonopah, old mill, stone, Montana Tonopah?
NNT949	TN	T	38.0767	117.2361	Tonopah, pale tailings in gulch
NNT959	TN	T	38.0733	117.2272	Tonopah, pale tailings on hillside below stone mill
NNT957	TN	T	38.1300	117.4636	Pink tailings, big mill, Millers
NNT950	TN	Tf	38.0664	117.2975	Fluvial tailings, Slime Gulch, Tonopah
NNT954	TN	Tf	38.1081	117.3839	Fluvial tailings in Slime Gulch, 10 mi west of Tonopah, still going

Table 1. Summary of mill and tailings sites identified in the Humboldt River basin and nearby areas, Nevada—*Continued*.

Site	District	Type	Latitude (N.)	Longitude (W.)	Description
NNT957	TN	T	38.0706	117.2150	Belmont (Tonopah) mill tailings
NN0T243	TN	Tf	38.0678	117.1750	Fluvial tailings in arroyo east
NN0T242	TN	T	38.0717	117.2000	East Tonopah mill tailings impoundment, mostly stable
NHM769	TR	Mh	40.3958	118.6222	Trinity silver mine, heap-leach facility
NHMG654	TU	S	41.3211	116.2322	Brick chimney from mill or smelter, Commonwealth, no tailings or slag
NHM658	TU	Mh	41.1761	116.2194	Dexter heap-leach operation
NNG915	TY	S	38.3706	116.3986	Tybo smelter, medium volume of slag
NNM916	TY	M	38.3805	116.3982	Tybo, newer mill (1920s), concrete foundation
NNM915	TY	M	38.3810	116.3970	Tybo mill, older stone foundation
NNT923	TY	Tf	38.4108	116.2783	East of Tybo, fluvial tailings from flood
NNT916	TY	T	38.3706	116.3958	Tybo, early stage red tailings in creek
NNT920	TY	T	38.3761	116.3669	Tybo tailings impoundment, gray sulfidic tailings, mouth of canyon
NHM752	WL	Mh	40.2472	118.3444	Willard mine heap-leach facility
NN0G278	WP	S	39.2525	115.4672	Hamilton smelter
NN0M277	WP	M	39.2772	115.5153	Belmont (Hamilton) mill, intact
NN0M282	WP	M	39.1956	115.4803	Eberhard #2 mill east, with tailings
NN0M281	WP	M	39.1997	115.4669	Eberhard mill with tailings
NHMh1	WP	Mh	39.2520	115.4872	Heap-leach facility, Hamilton
NN0M277	WP	T	39.2772	115.5153	Belmont (Hamilton) mill tailings, small stack, brown
NN0T281	WP	T	39.1875	115.4800	Eberhard mill tailings light gray

1900 (photograph 3). Some mills are as small as a garage, and others are hundreds of feet wide; the larger mills generally have three to six levels up a hillside so that gravity could be used to move the materials from one operation to another. Some mills are remarkably intact and handsome structures, such as the Belmont mill near Hamilton, but many burned or were dismantled and have no superstructure. Mills generally were taken apart when mining ceased, so equipment is rarely present today. Many photographs of mills from Colorado can be seen in another report (Nash, 2000a) as a guide to what the industry used during the past century.

In nearly all cases, mills were placed at a lower elevation than the mine. Some mills in Nevada were served by a gravity-driven tram, but in most cases the ore was delivered by mine car, wagon, or truck. In many cases, the mill was placed at the nearest site having water, but, in some districts, water was piped in from distant wells. Some mills were several kilometers from the mine, as in the Tonopah district where mills were sited about 20 km to the west, at Millers, to obtain enough water. Some mills serviced just one mine, and others served an entire district. At mercury mines, mills and retorts tend to be small and serve a single mine. At some mill sites, there is enough evidence remaining to deduce the kind of milling used, such as the heavy steel rods of the stamp mills at the Looney gold mine (Rochester district) or the cylindrical tanks used for cyanide at the Buckskin mill (National district). In many situations, it is easiest to locate the mill and then search for the associated tailings. Identification of mill sites, however, is not the significant issue for land management because it is not the mill itself that causes problems. Although many mills used cyanide, which is highly toxic, the cyanide is not likely to persist today unless in a sealed container. Cyanide is degraded by many natural processes, including oxidation and biodegradation, and is unlikely to be significant in mills or tailings as old as those under discussion here. This issue will not be considered further, but the concerned reader should see other reports (e.g., Smith and Mudder, 1999). Mercury used to recover gold (by amalgamation) can contaminate mill sites but has not been investigated here.

Photograph 2. This mill at Cortez is typical of older mills with its stone foundation and three levels. Newer mills in the 20th century were made with concrete foundations, and many had four to six levels.

Photograph 3. This mill at Lower Rochester operated from 1913 to 1929 at about 150–300 tons/day. This relatively large mill utilized the best cyanide technology of the time. Concrete was used in foundations after about 1900.

Tailings can be obvious or difficult to identify, depending upon many aspects such as volume, color, and vegetation. Physical properties are highly variable by ore type and process. Tailings generally are of fine sand size (slightly gritty between the fingers), but tailings from 1880s stamp mills tend to be coarse. Tailings can be rich in clay (sticky when wet), or can be well-sorted like beach sand; at the surface, they can be soft or hard from cementing minerals. Individual minerals are difficult to identify by eye or hand lens. Large tailings impoundments can resemble flat ponds (that is how they were placed) or sand dunes if eroded by wind. In some places, tailings were simply poured onto a hillside less than 40 m from the mill, creating piles that resemble haystacks because the tailings are cohesive. At some sites, the tailings were sluiced through flumes or ditch-like channels to distant lowlands, such as at the Standard mine (Imlay district). When located far from the mill structure, tailings can be difficult to find, especially if they are concealed by vegetation. Because water was used in mills, and because there were no regulations prior to 1935, one can often find mill tailings placed along streams and infer that tailings were dumped directly into the streams and carried away. Tailings from silver mines of the 1880–1910 era can be difficult to find because many have been reprocessed to recover silver and gold that remained after processing by the early, inefficient mills. Tailings from the original mills at Pioche were placed in rail cars and hauled to Salt Lake City smelters in 1911, and today even a cupful of material is difficult to find. Some tailings impoundments are shown on

1:24,000 topographic maps, as for the White Caps mine near Manhattan, but more commonly the label “tailings” on maps is used more broadly to include all mine wastes. Some geologists map mill tailings as a distinct unit, which is an ideal indication of location and extent. But in most districts, one has to use careful observation and intuition to locate mill tailings.

In many cases, tailings have a distinct orange-yellow hue that the experienced eye distinguishes from ordinary alluvium. This criterion works well in the Hilltop district and similar polymetallic mining districts. Some mills roasted silver ores (the so-called Reese River process, named for the Austin mills) and this creates a brick-red color that is conspicuous at Eureka, Manhattan, Tybo, and Candelaria. Tailings tend to create changes in vegetation, killing trees or sage or reducing their abundance. Owing to distinctive colors and vegetation changes, tailings can be easy to see on air photographs or by remote sensing methods, as in the case of tailings from the Getchell mine (G. Raines, oral commun., 1995). Even with these guides, one can easily miss tailings during reconnaissance surveys. The inventory in table 1 may lack as many as 50 percent of the tailings sites, but I believe that the larger historic sites have been identified. Quantification of tailings tonnages would be possible by measuring the size of tailings impoundments or by estimation from production records, but the amount of tailings returned to underground mine workings as backfill is rarely known (R. Ashley, written commun., 2001).

Composition of Mill Tailings

Materials created by historic mining vary greatly in metal composition (fig. 2). Waste dumps and mill tailings contain mineralized rock materials that are enriched in many metals, with concentrations far higher than normal rocks or unmined altered rocks, as discussed elsewhere (Nash, 2000a, 2000b, 2001, 2002b; Plumlee and others, 1999). Compositions of these materials vary from mine to mine, district to district, and in my experience can not be predicted reliably. Some waste materials have metal concentrations high enough to require handling by hazardous materials specialists, chiefly in cases of mill concentrates that were abandoned at historic mills. Mill tailings vary in color and metal concentration between layers within a tailings impoundment, as well as from site to site. This variability reflects the efficiency of the mill and variations

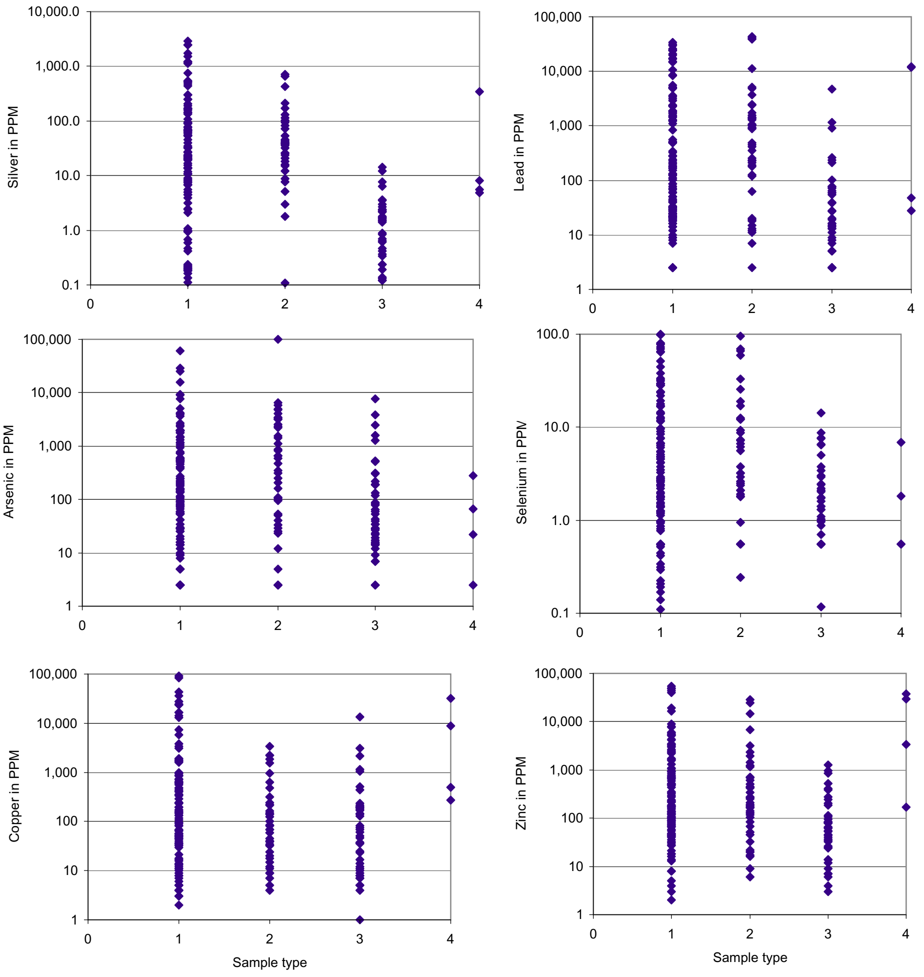

Figure 2. Range in chemical composition of mineralized materials in the Humboldt River basin area, northern Nevada. Sample type: 1, mine-waste dump; 2, mill tailings; 3, altered rock; 4, slag.

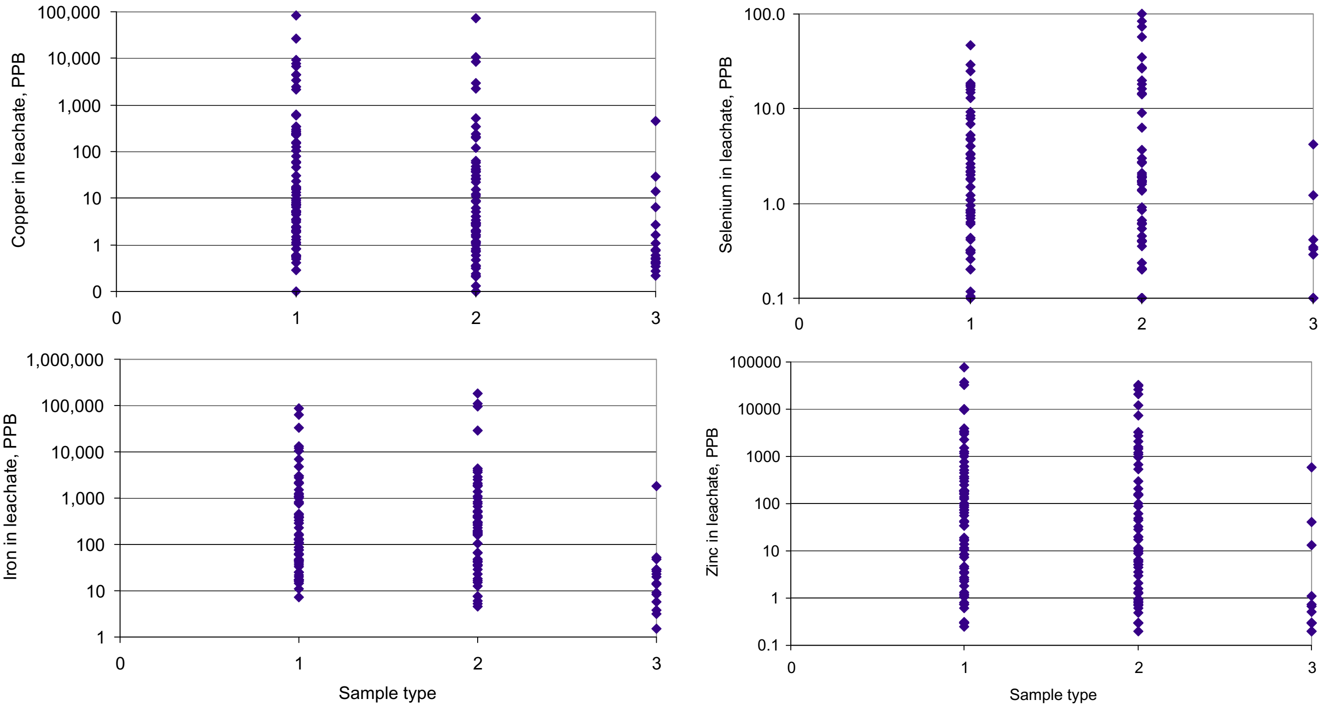

Figure 3. Range in leachate compositions from various sample media, northern Nevada. Sample type: 1, dump; 2, mill tailings; 3, altered rock.

in ore composition. Some variations in color and composition are produced by weathering of mill tailings after placement in an impoundment and are chiefly related to oxidation of sulfide minerals. Chemical analyses of representative mill tailings samples are given elsewhere (Nash, 2000b).

It is best to consider soluble or leachable metal concentrations in mill tailings, rather than total concentrations, if one is concerned with contamination of water or influence on wildlife. Soluble metal concentrations can be determined by using weak acids to dissolve the materials prior to chemical analysis or by other tests in the laboratory that mimic the effects of surface water on the materials. Passive-leach tests (Fey and others, 2000) that utilize 100 g of rock or tailings immersed in 2 L of deionized water for 24 or more hours provide much useful information on acid generation and the kinds and amounts of metals that are soluble. Analysis of the leachate solutions by ICP-MS (inductively coupled plasma–mass spectrometry) provides quantitative results for 40 to 60 elements (depending upon the laboratory) down to concentrations less than 1 ppb (part per billion). Numerous other methods used by the mining industry and researchers are described in technical literature (e.g., ICARD, 2000). The passive-leach method used by the author on 67 tailings samples from the Humboldt study area (Nash, 2000b) show that tailings are generally similar to mine-waste-dump materials in their ability to generate acid and release metals (fig. 3). Some deposit types tend to generate more acid and higher metal concentrations than others (Nash, 2001), but even those that do not generate acid can release potentially significant amounts of some metals, such as As, Se, Mo, or Zn. Specific sampling and testing of tailings is required to determine their chemical characteristics, but as a first approximation one should ask the same questions as for mine dumps, which generally have been given much more attention than tailings, and look for evidence of interaction with water.

Evidence for reaction of tailings with surface waters is difficult to obtain and, in some situations, is ambiguous. Geochemical evidence for contamination of shallow ground waters is even more difficult to obtain at historic sites because wells are required for sampling and generally are not in appropriate locations. My field studies endeavored to investigate the release of metals to surface waters, but the results and interpretations to date are not as conclusive as expected at the outset. One of the problems is the timing of sampling studies: the window of opportunity at typical sites appears to range from a few days to a few hours after a storm. Another problem is how the results are interpreted: in places it is possible to sample pore waters inside tailings impoundments, generally finding very acidic, metal-rich compositions, but it is difficult to quantify the actual flow of these waters from the impoundment. At many sites, pore waters could be stagnant because of low permeability. Data for surface-water compositions downstream from tailings impoundments are in Nash (2000b), and some are discussed elsewhere (Nash, 2001, 2002b). The geochemistry of mine waters in Nevada, which is useful for comparison with results for tailings, is discussed by Price and others (1995).

Water quality in relation to mill tailings will be mentioned in later sections. The regulatory framework for water quality in Nevada is discussed elsewhere (Nash, 2001; NDEP, 2001).

Composition of Other Mill Products

Three other products of mining also are rich in metals and may have potential to contaminate waters: (1) crushed ore on heap-leach pads, (2) calcine produced by mercury retorts, and (3) slag from smelters. Each of these differs in many ways from mill tailings but are mentioned here because all are solid materials produced by processing of ores.

Heap-leach processing has been used for about 50 years on ores that generally are bulk mined and have lower metal concentrations than ores processed through conventional mills. Cyanide typically is sprayed on the piles of crushed ore, and metals are recovered from the leach solution. Although many questions can be raised about heap-leaching facilities, the focus here is on pads or piles that have been abandoned with little or no reclamation. The largest tonnage of inactive heap-leach materials on public lands that I have seen in the study area is at the Big Mike mine (several million tons). More commonly one observes small leach pads lined with standard household plastic sheeting (6 mil) for crude operations on a few hundred tons of material. Some operations were speculative promotions, such as the elaborate operation in northwestern Humboldt County that promised recovery of platinum from crushed, unaltered (glassy) volcanic rocks. Management and possible reclamation of abandoned heap-leach sites involving moderate tonnages (thousands of tons) poses technical questions for Federal land-management agencies (FLMAs) that cannot be answered here. The heap-leach sites listed in table 1 are only a fraction of the sites that might be evaluated by FLMAs for reclamation. The general issue at the majority of these heap sites is the possibility of acid generation and metal mobilization in surface or ground water. At some heaps having mostly intact liners, leach and rain water can accumulate and attain unusual concentrations that could be unhealthy for wildlife; these heaps probably would not pose a threat without the concentrating influence of evaporation. Comments will be made on heap-leach piles in a few of the districts described.

Mercury mines have used retorts for more than a century to recover elemental mercury. The process involves coarse crushing of ore, heating in a retort (many ingenious shapes are seen, some modern ones being rotary designs similar to those used to make lime), and release of red-colored material called calcine. Calcine generally comprises mixed coarse (> 2 cm) and fine material, with the red color being chiefly in the fines. Calcines are highly mineralized in a predictable suite of metals that accompany mercury, including arsenic and antimony, but base metals such as Cu and Pb generally are present at low concentration levels (Nash, 2001; Gray and others, 1999; Gray 2003). Leach tests show that calcines generally create alkaline solutions, but these solutions with a pH of about 8 can carry significant levels of As and Sb. Most mercury mines and retorts in northern Nevada are in arid areas and are not close to streams with significant seasonal flow.

Prior to about 1900, local smelters were used to recover metals of value, chiefly silver and gold, from complex ores that were not amenable to milling or from mill concentrates. Smelters, used in Nevada before the construction of railroads to mining districts, were neither large nor of long life; thus, they created relatively small slag piles (thousands of tons). There are special environmental problems caused by smelters, including particulates or gases from early crude stacks that may have contaminated soils within a few kilometers of the smelter (Nash and others, 1996). The slag produced by smelters is tough and relatively unreactive with water under normal conditions, according to leach tests (Nash, 2000a). However, slag contains high concentrations (several percent) of base metals such as Pb, Zn, or Cu, and these are potentially toxic if ingested. The smelter slag piles at Eureka probably are the only ones in northern Nevada that pose threats to wildlife or human health, in part because others are in remote locations.

Failure of Tailings Impoundments During Extreme Storms

Failure of a tailings impoundment or waste dump during an extreme storm event (flash flood) is a concept that is rarely mentioned in mine-lands assessments, yet the dire consequences of such a failure have become known in the past century and the probabilities are high enough to demand consideration in land planning. A few tailings-impoundment failures are described in the literature, such as for Anaconda, Montana (Moore and Luoma, 1990), but most failures were not deemed important enough at the time to be described in the literature. I suspect that many of the breached impoundments that I have found may have failed during active use of the facility (Nash, 2002a). A detailed report of a 1975 tailings-dam failure (Stiller, 2000) provides many insights into weather, water, and transport conditions. There are indications of significant historic erosion at many tailings impoundments in the study area, and at least a dozen impoundments in northern Nevada appear to have failed catastrophically during the past century; the dates and weather conditions are not known, but the results are well preserved. Failure of mine-waste dumps, not mentioned in the literature, also is a possibility. The major concern is for tailings placed in lowlands, not far from streams, and what would happen to them if hit by the “wall of water” that forms during a cloudburst in a confined upland watershed. Geologic evidence shows that boulders the size of a car can be moved by these rushing waters that rise 2–5 m above normal levels and have flow volumes more than 100 times normal. Whether mined materials fail by erosion or sliding, mass movement—in conjunction with unusual amounts of water—can carry and spread both solids and dissolved metals.

Flash floods in mountain canyons, caused by cloudbursts or several days of rain, are known for their violence, property damage, and loss of life (Follansbee and Sawyer, 1948; Stiller, 2000) but are not as well described as the regional flooding of valleys in the Western United States that typically occurs when snow melts in the mountains. For flash floods, witnesses and meteorologists describe intense rainfall of 2 cm or more an hour, or 10–20 cm in 48 hours; accumulations of water in fields sufficient to drown a horse; and "walls of water" several meters high in local creeks occurring within minutes of a downpour. There are numerous historical reports and photographs of flooded homes, broken bridges, and eroded stream banks. The floods and damage done to mining properties do not seem to merit publication in newspapers or scientific literature. A flood in 1912 destroyed the mining community at Seven Troughs, took nine lives, and demolished an active cyanide mill (Gibson, 2000). The record of the 1975 flood and tailings dam failure in Montana (Stiller, 2000) is the most detailed I have read. Some floods are reconstructed from geologic evidence many years after the fact (Vincent and others, 1999; Nimick and Moore, 1991; Wirt, 1994). In Nevada, small- to medium-sized tailings impoundments hit by flash floods have lost 20 to 90 percent of their tailings, which were transported 2 to 15 km down arroyos or across alluvial fans (Nash, 2001, 2002a). Drainage-control devices used in mine reclamation, such as straw bales and plastic netting, commonly are ripped away within a few years by storm runoff. More systematic studies are needed to document the frequency and distribution of stormwaters and flood deposits to help in the estimation of the effects of storm events.

Because rainfall in upland watersheds generally is not measured by gages and many floods are not witnessed, the database for thunderstorms and flash floods in these settings is not well developed. As an alternative to weather predictions and databases, the behavior of flood runoff can be modeled by evaluating physical characteristics of watersheds (Black, 1996). Factors that influence peak runoff in storms include (1) capacity for water storage, (2) amount of infiltration, (3) basin shape and size, and (4) elevation. A watershed is said to be "flashy" (prone to flash floods) if it produces high flows of runoff in a short time during a storm event or snowmelt. Flashy character is increased in watersheds whose rock units provide little water storage and low infiltration, and basin shapes that are elliptical. Smaller watersheds at high elevations tend to be most conducive to "flashy" high flows; elevation influences temperature and the ways extreme storms develop. Many of the headwater basins in the Humboldt River basin have these characteristics.

Canyons and arroyos in Nevada are capable of focusing substantial amounts of stormwater with incredible power that can create debris flows of large boulders and fine-grained materials (Blatt and others, 1972), such as those commonly found in Quaternary alluvial deposits. However, the sedimentological properties of transported tailings probably are not those of debris flows, as I assumed in my early studies. The largest transported tailings deposits, where catastrophic dam failure seems to have occurred, are nearly pure tailings with weakly developed to massive bedding; sorting is not evident (Nash, 2002a). Where seen, coarse clasts are rare and seemingly random rather than in distinct beds. These features are more akin to those of hyperconcentrated flows (Costa, 1988), defined as having 40 to 70 percent sediment by weight and properties intermediate between normal fluvial sediments and debris flows (moderate viscosity and shear strength) controlled by a dominance of fine-grained materials (silt and clay). The sedimentary features might also be explained by one dominant source of materials (impounded tailings). The term "fluvial" tailings, used by many students of transported tailings, may be inappropriate for these massive deposits but will be retained here. Tailings are spread as overbank and channel-filling sand deposits for 1 to 15 km down the canyon or arroyo. Redeposition of fluvial tailings increases at sites where the channel widens or gradient decreases, either of which decreases flow velocities. Much more study of these unusual sediment deposits is needed to properly evaluate the conditions of formation. Water in the debris flow is likely to attain more extreme concentrations of metals than in simple runoff. The metal concentrations probably will be even higher than determined by passive-leach tests because mechanical mixing and abrasion during flow would promote reactions. Many years after a flood, tailings continue to react either with stream water or precipitation, slowly releasing metals to vegetation, streams, or ground water.

Risk Analysis of Impoundment Failure

The statistical framework for prediction and risk analysis of floods is complex (Cohon, 1988; Kite, 1988). Because processes in these modern events are clearly the same as those in the geologic record, geomorphological and sedimentological information may be good guides for evaluating effects and risk of future storm damage. For instance, the 100-year-flood level could be estimated from Quaternary alluvial terraces. Numerous risk analyses have been undertaken for failure of uranium mill tailings. Fluvial processes, geomorphic evidence, catastrophic floods, and extreme hydrologic events were discussed by Schumm and others (1981) as a guide to planning uranium-mill-tailings sites. Another study (Shepherd and Nelson, 1978) concluded that the engineering aspects of tailings impoundments are important for short-term behavior, whereas geomorphological processes (especially natural events such as floods and earthquakes) are more significant for the long term. At present, it seems that scientists are monitoring the relatively predictable effluent from mining areas while giving little thought to the risks posed by rare natural events, such as flash floods, that have the potential to cause great impact.

Observations in this study (table 1 and Nash, 2002a) suggest that there were at least seven tailings-dam failures within the Humboldt River basin in the Cortez, Mt. Hope, Potosi, Rochester, Seven Troughs, Tenabo, and Tenmile districts. Elsewhere in northern Nevada, there is evidence for significant tailings impoundment failures in the Leadville, Manhattan, Tonopah, and Tybo districts. Fluvial tailings in small to large amounts have been identified below 16 tailings impoundments. These observations indicate that there is a high probability,

Photograph 4. Large piles of red calcine were created at the Pershing mercury mine, Antelope Springs district. Calcine can release significant amounts of Hg, As, and Sb.

possibly on the order of 20 percent, of tailings being transported from impoundments and widely dispersed in the flood plain below.

District Descriptions

Antelope Springs District

This district has a history as one of the more productive mercury-mining areas in Nevada, producing more than 12,500 flasks through 1975 (Johnson, 1977; Gray, 2003). There are at least four retorts with substantial volumes of calcine, and others presumably existed at various times. The calcine from the Pershing mine (photograph 4) was placed on a leach pad in the mid-1980s in an apparent attempt to recover precious metals. None of the calcine piles, waste dumps, or heap-leach pads have been reclaimed. Three leach tests on samples of calcine yielded leachates with alkaline pH values (8.3 to 9.5) but mostly low[2] metal concentrations; one sample yielded very high As and Se concentrations and all samples yielded high Sb concentrations.

The arid climate in this area minimizes potential problems here. Even in the very wet late spring of 1998 there were only a few small flows of water at the surface and some small ponds of water (much less than an acre in size) in mining excavations that collected runoff from mine waste and altered rocks. The high mercury concentrations in these ephemeral ponds are possibly a threat to wildlife (Nash, 2001). In the prevailing dry climate, little or no water is contaminated by the calcine piles.

Austin (Reese River) District

This was the site of the first gold-silver boom in the area, following the initial discovery of a silver-rich rock along the Pony Express trail in 1862. Early mining and milling operations are treated in detail by Vanderburg (1939), who noted that 11 mills were erected prior to 1868, many of them speculative and unproductive. Numerous “firsts” were made here, including the Reese River process for roasting silver ores with salt to improve the recovery of silver and gold (this process creates the distinctive red tailings seen at many mills in the region). The numerous mills described in the literature are difficult to reconcile with features seen today because they often burned or were dismantled, and tailings commonly were reprocessed as technology improved. Because the veins were mined underground and ores were hand-sorted underground and again at the mill, the volume of tailings produced is much smaller than expected for a district that produced $20 to $50 million in silver. Today, five mills are evident, but several pre-

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[2] The terms “low,” “high,” and “very high” will be used here to describe the concentration levels relative to the median value for 67 leachate analyses in this study; low is below the median, high is above the median, and very high is reserved for the highest 20 percent of values.

1900 mills were not recognized. Significant tailings are present only in Pony Canyon on the west edge of Austin, Nev., west of the Clifton tunnel that extends under the mines on Lander Hill. One reason for the discrepancy in observed tailings is the common practice of re-treating or removing early (pre-1900) tailings, which commonly contained substantial amounts of silver that the early processes failed to recover. Two mills are at the Clifton tunnel, an older one built of stone and a newer one of wood and tin, probably built in 1935. A large concrete mill foundation can be seen in New York Canyon, 5 km north of town, near the True Blue mine; no tailings could be located at this site. Two relatively modern mills are located at the western mouth of Slaughterhouse Gulch, a mile north of town, but they appear to have had only small production.

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

The Pony Canyon tailings are possibly at risk to erosion in an extreme storm. The canyon setting and geometry seem favorable for focusing stormwaters, and a substantial part of the tailings remain in the flood plain after reclamation. A well, possibly used for drinking water, was removed by the BLM in 1999, thereby eliminating one concern for water quality. Many of the questions for this site relate to regulatory criteria that deal with impacts on human or wildlife health. Erosion of tailings in a storm event probably would have little impact on property as there are no structures downstream. These tailings are relatively unreactive, judging from their composition, and stormwaters carrying tailings probably would have only a transient effect on wildlife or ground-water quality upon infiltration.

The heap-leach facility for the Quito gold mine, at the western base of the Toiyabe Range, 10 km south of Austin, was reclaimed with appropriate methods in the mid-1990s. There were no indications of complicating factors when observed from a distance.

Awakening District

There are two conventional mills and two heap-leach facilities in this district. The Sleeper mine mill and heap-leach pads are being reclaimed and eventually will meet standards for closure. The heap-leach facility for the Jumbo mine, south of Sleeper, Nev., was reclaimed in about 1997 and appears to be stable. The Daveytown mill on the east side of the Slumbering Hills range, created a modest area of tailings, about 7 acres. Leach tests on two samples of tailings from the Daveytown mill yielded alkaline-pH leachates with low metal concentrations, but a very high concentration of As was released from one sample, along with high Mo. Placed on a playa, these tailings show no signs of erosion and appear to be among the driest in the area. Although little vegetation grows on the tailings, they do not appear to pose a threat to wildlife and there are no residents nearby.

Battle Mountain District

This district has had a long and productive history, including one of the first smelters in the region and a large mill at Copper Canyon that was on standby as of 2001 for use in a planned expansion of gold mining in that area. The mill tailings at Copper Canyon and the copper-leach facility at Copper Basin were not investigated. Mills and associated tailings were identified at the Buckingham, Iron Canyon, and Galena sites, but others may have existed (considering the substantial production in the district). Other mills may have operated in Copper Basin, which could not be examined closely; a small volume of tailings was observed at the edge of waste-rock piles from the Copper Basin mine and may have been covered by 1970s mining waste. Only small volumes of tailings were observed at Iron Canyon and Galena, and neither site appears to pose a risk of failure in a storm event. The red tailings near Galena are the scant remains of a larger volume that was removed for reprocessing by the 1930s (Vanderburg 1939). The two small piles of slag at the Galena smelter does not appear to pose problems.

Leach tests on a sample tailings from the Iron Canyon mill yielded a leachate with a pH of 5.6, very high As, and high Mo, Pb, and Zn concentrations. Although reactive when wet, the small volume of tailings suggests they are a minor source of contamination in a watershed that has huge waste-rock piles.

One area of tailings may cause problems: the tailings pile at the Buckingham mill, which appears to date to the 1940s–50s. The mill and some of its equipment are partly intact. The unconfined mill tailings were placed in the channel of Licking Creek, which is ephemeral. Erosion of the tailings piles is moderate, and thin layers of transported tailings are in the creek bed for about a kilometer downstream. In June 1998, a week of rain created a small flow in this creek; 400 m below the mill tailings the creek had a pH of 5.1, and concentrations of Al, Cd, Cu, and Zn were very high. Mill tailings are the most obvious source of these contaminants, but mine dumps and altered rocks also are likely contributors in this watershed. The situation of the tailings across the ephemeral stream bed, and the basin to the west, suggest that the Buckingham tailings pose a high risk of reacting or eroding during a major storm event.

The catch pond at the White and Shilo mine complex releases water on rare occasions, as in June of 1998 when the overflow pipe carried water with a pH of 4.5 and a conductivity of 1,800 µS/cm. Concentrations of Al, Cd, and Zn were extremely high, and concentrations of Cu, Fe, Mn, and Pb were very high. There are some red tailings on the edge of this

Photograph 5. A tailings pond at the Big Mike mine complex, dating to the 1930s, collects runoff for short periods of time. The combination of reactive tailings and evaporation creates acidic waters with extremely high metal concentrations.

pond (most were removed for reprocessing), but the major source of contaminants probably is the mine-waste piles to the west of the pond.

Beowawe District

There was relatively minor production from this district prior to the discovery of the Mule Canyon gold mine in the 1990s. A mercury mine, with retort, created a small amount of waste rock and a small amount of calcine. An open-pit barite mine, small by Nevada standards, processed barite, but a leach test on low-grade crushed barite showed it to be unreactive.

Black Diablo District

The major mine in this district is the Big Mike, which exploited a small volume of very high grade copper ore in a massive sulfide deposit. The high-grade ore was mined quickly in 1971 and shipped to Europe for smelting. Later in the 1970s, the lower grade copper was bulk-mined, and much of this material was treated on a heap-leach pile to make copper cement (copper reacted with iron scrap); the heap remains in place. The heap-leach pile, probably a few hundred thousand tons, is on a concrete pad but a very concentrated (viscous) green fluid seeps from the pads. The seeps have a pH of 3 and contain extremely high copper and sulfate concentrations (Cu is >100,000 ppb). The seeps evaporate, forming green crystals of copper sulfate, or react with caliche (calcite), which is abundant in the alluvium. No surface waters flow more than about 200 m, but the fate of the pollutants in the subsurface is not known.

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

An earlier stage of mining by small shafts, prior to 1940, had a small conventional mill. Mill tailings, mostly in a tailings pond, are surrounded by, and possibly partly covered by, the later waste rocks from the Big Mike open-pit mining. The volume of tailings is relatively small, possibly 20,000–40,000 tons by visual estimate. Normally dry, the pond collects runoff in wet periods (photograph 5). The ephemeral pond waters are very acidic (pH 3.6) and Al, Cd, Co, Cu, Fe, Mn, Ni, and Zn concentrations are extremely high (orders of magnitude greater than aquatic-life standards). Some of the metal enrichment probably reflects cycles of evaporation. A leach test on a sample of the tailings produced a leachate with a pH of 4.7 and very high Cu and high Zn concentrations. The tailings pond appears to be physically stable on a gentle slope, with no streams or arroyos nearby, but the ephemeral pond water is toxic to wildlife and may contaminate ground water.

Bottle Creek District

This was one of the larger mercury-producing districts in Nevada through the 1940s. There are many piles of calcine from the retorts that may amount to 50,000 to 100,000 tons. A leach test on one sample of calcine produced a solution with a pH of 6.4 and low metal concentrations, but the concentration of As (29 ppb) was higher than the median in this study. The district was studied in more detail by Gray and others (1999). The calcine piles are dry most of the time and are more than a quarter mile from the nearest stream (ephemeral). Some mercury could be seeping into the subsurface after storms, but it is not clear that this would have a significant impact on the ground water that is used for irrigation, livestock, and domestic drinking water at ranches several kilometers to the east-southeast.

Buena Vista (Unionville) District

The mines near Unionville date to the 1860s, and mining at the Arizona mine was intermittent from 1860 to 1959. The mill at the Arizona mine is located near the lower tunnel, and an unusual mound of tailings is just south of the mill. The slurry from the mill was thick enough to build a cone more than 10 m tall. It is possible that early tailings were removed for reprocessing and that the cone of tailings reflects only relatively recent milling. These tailings are stable, with only a small amount eroding into the small creek below. A leach test on a sample of tailings produced a solution with a pH of 8.6 and very high concentrations of Mo, Sb, and Se (an unusual composition compared to most in this study, reflecting carbonate host rocks).

A small stream near the Arizona mine appears to be somewhat contaminated by mining and mill tailings. The pH of 7.6 is lower than expected of carbonate rocks nearby; the conductivity is relatively high; and the concentrations of Se and Mo are high (Se was 24 ppb).The mobility of Mo and Se is, in part, a reflection of the pH near 8 but might also reflect nearby black shale beds.

Buffalo Valley District

The early mining in this district does not appear to have been supported by a mill. In the 1980s the open-pit mining at the Buffalo Valley mine was supported by a relatively small heap-leach facility to recover gold from low-grade, oxidized ores. In 1997, the heaps were inactive and at least partly reclaimed while the company explored for more ore. The status of the heaps is not known, but they appear to be stable and are not releasing water beyond the pads.

Bullion (Tenabo) District

This district was active in the early years of mining (1880s) and has had periods of revival, including the present cycle of gold production from huge open-pit mines at the Gold Acres and Pipeline mines. Much of the district is private property and was not studied by the author. There are at least two small mills on peripheral sites, at Grey Eagle (to the west) and at Indian Creek (to the northeast). The latter appears to have been a custom mill for miscellaneous ores that were hauled from distant mines. A leach test on these tailings produced a leachate with a pH of 3.8 and very high Al, As, Cd, Cu, Se, and Zn concentrations. The relatively small volume of tailings is in an arroyo and has been partly eroded by storm flows. The location on a relatively gentle slope with a wide channel suggest that the tailings have a better chance of surviving an extreme storm than a site in a canyon.

The Grey Eagle mine was a modest producer of polymetallic sulfide ores; a small mill was located at the lower mine tunnel. The mill is typical of the small (about 50 tons/day) mills of the 1920s–1940s. The tailings, however, are noteworthy for the large amount of erosion that has taken place. Based on brief observations, I surmise that there was at least one failure and tailings were carried down the canyon to the south for more than a kilometer. The few tailings remaining in the breached impoundment, and the fluvial tailings to the south, probably are releasing acid and base metals when wet (based on tests on similar tailings). They are not a threat to human health because there are no residences for many kilometers; their impact on wildlife would be for brief periods at most.

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

Burner District

No mills were recognized during a brief visit to this district.

Cortez District

Like the nearby Bullion (Tenabo) district, this district had a period of mining and milling for silver and, in, recent years has been the scene of gold mining and milling. Actually, milling at the Cortez gold mill for the last 10 years has been on ore from mines on the western side of the valley in the Bullion district. The mills of interest here are the two that treated silver ores from the Garrison and related mines near the Cortez town site. The original mill, with stone foundation, was built in 1886 and used a unique hyposulfate leaching process. Tailings from the original mill were placed on the gentle slope to the west. These tailings, amounting to about 125,000 tons, were reprocessed by the cyanide method in 1908–1915 (Vanderburg, 1938a). Today, these tailings have the appearance of sand dunes. They seem to be stable, except for some movement by wind.

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

The Cortez tailings provide good lessons on what happens to tailings in Nevada. These tailings are highly eroded, with gullies 2 to 4 m deep (photograph 6), and the tailings now extend for 3 km down the wash (Nash, 2002a). There is evidence of two impoundments below the mill in which the operators piled wet tailings to a depth of 3 to 5 m. The operators used flumes with spigots to direct the slimes and sands to appropriate places; the dams were made from tailings sands with some boards. The dams have been breached on one or more occasions. The 1980s haul road has acted as a dam about 3 m high, and it too has been eroded by stormwaters, as shown by repairs made in recent years. The downslope tailings surround mature pine trees, and have killed some; the large trees must have been growing before the tailings were deposited. The materials to the west are stratified, as in the ponds closer to the mill, indicating deposition from water; the extreme length of the tailings deposit suggests that they were not intentionally placed where they are now. I interpret this geometry as the result of erosion and downstream redistribution of tailings in extreme storm events. The bedding sequence in the fluvial tailings, with lower brown (coarse grained) middle gray (fine grained) and upper pink (fine) tailings is the same as in the impoundments, which can be explained only by a series of erosional events or dam failures.

The fluvial (redeposited) tailings west of the haul road are probably causing little or no damage to the environment. There is some vegetation kill, and some metals (As, Se, Zn, etc.) may be soluble in wet episodes that create weakly alkaline waters in these calcite-rich materials. There are no residences in the vicinity and no wells for irrigation or drinking water. Land status is not clear, but I suspect that much of the western portion is on public land. There is no obvious need to reclaim these tailings and restore the gulch to its premining condition. The importance of these features is what they indicate about how tailings can move during extreme storms in Nevada.

Photograph 6. Tailings from the new (1920s) mill at Cortez were placed in a wash and now are deeply eroded. Fluvial tailings from one or more major storm events have been carried 4 km to the west.

Eureka District

This famous district was visited briefly and is too complex to treat properly here. Smelters in this district were important in its history and created a legacy of slag piles that is unique in central Nevada. The slag piles at Eureka, easily seen at the north and south ends of the town on U.S. Highway 50, contain an estimated 1,000,000 tons of waste (Vanderburg 1938a) including at least 100,000 tons of speiss (iron-arsenic slag containing about 30 percent As). Curiously, some of the speiss was reprocessed for arsenic when As had value. The environmental concerns regarding these smelters include possible contamination of soils by particulates from smoke. A detailed geochemical study by Chaffee (1987) included 593 soil samples in the district with a goal of finding exploration guides in an area of smelter contamination. The contamination was shown to cover an area of about 3 km by 6 km, but the magnitude of contamination was not defined. Modern environmental studies have not been published.

The Windfall mine was a significant producer in the early 1900s, after the early bonanza days. It originally had a cyanide mill with 200 tons/day capacity and treated a “large tonnage of ore” (Vanderburg 1938a). The Windfall ores were unique in the district for their amenability to cyanide treatment, which allowed easy recovery of gold and silver. Those mill tailings were not evident in 1999; they may have been moved for reprocessing or could be covered by recently mined materials. Features labeled “tailings” on the topographic map are waste dumps or screened waste materials. The amenability of Windfall ores to cyanide leaching became prominent in a 1980s operation at Windfall that utilized heap leaching to recover gold. In 1999, water within the heap had a pH of 8.6 (raised by lime added during leach processing?) and high concentrations of some elements that might reflect evaporative enrichment. Base-metal concentrations were not high, but As was extremely high, and Co and Mo were high. This heap, situated in a narrow canyon, was not reclaimed as of 1999; questions regarding physical stability and ongoing chemical reactions were being investigated by BLM and the owner.

Golconda District

This district appears to have had one early (ca. 1880s) smelter, described as being near the railroad—the site was not located during my study (probably obscured by newer homes and businesses). There is a mill site and small tailings pile at the Kramer mine. The tailings amount to a few thousand tons, at most, and are stable on a hillside. The tailings are not near a stream or arroyo.

Gold Circle (Midas) District

The gold-silver boom at Gold Circle in 1907 resulted in the construction of as many as 11 mills (Ken Snyder, oral commun. to Alan Wallace, 1997). Three of the mills can be located today, but none created a large volume of tailings. The unconfined tailings piles are distant from streams and houses. The most notable feature of these tailings is their high selenium content, and the selenium is soluble according to leach tests. Leach tests on three samples of tailings yielded solutions with pH values in the range of 4.2 to 6.8. The only metal of notably high concentration in the leachate was Se. Selenium is not unexpected in this district, known to have silver-selenide minerals, but the high concentrations suggest that Se may become concentrated near the surface by wicking of solutions to the surface and evaporation to form a selenate efflorescent crust. Selenium might be a problem for wildlife or livestock if they were to drink from puddles or eat Se-enriched plants over long periods of time (chronic exposure).

Gold Run (Adelaide) District

Copper-silver-gold ores were mined prior to 1900, and two smelters were built to recover the metals, one near the railroad in Golconda and one in the center of the district. Substantial flows of slag can be found near the Adelaide shaft, but there are no other indications of the smelter or mill. The Adelaide smelter is not mentioned by Vanderburg (1938b), who did describe the Golconda smelter and railroad to it from Adelaide in the period 1898–1905. The Adelaide slag is not far from Gold Run Creek but presumably is not reactive enough to contaminate the stream. Later (1930s to 1950s), precious metals were mined at the Adelaide Crown mine and processed by a modern mill with concrete foundation and served by electrical power. Tailings from this mill are in a meadow east of the mill and seem to be stable—there are few signs of erosion, and grasses and sage grow on the pond. In the 1980s, mining resumed by bulk mining of the veins previously mined underground; the ore was crushed and placed on a heap-leach pad of moderate size. No work has been done on the heap for about 10 years.

Surface water is sparse in this district but water collects in puddles and small pit ponds at the Adelaide Crown complex; the pH of these waters is 8.2 to 8.3. The waters are enriched in As, Cu, and Mo, possibly in part from evaporation. Some Cu and Mo concentrations exceed standards for wildlife. Gold Run Creek, east of the mining area, has a pH of 8.4 with elevated concentrations of As, Mo, and Se (but below wildlife and drinking-water standards). The effects on surface water by mill tailings could not be determined but appears to be minor.

Hilltop District

Major production in this district was from 1912 to about 1922 from several clusters of polymetallic vein deposits served by at least five mills (table 1). The smallest mill may have operated below the Kattenhorn mine prior to 1900. Two mills served the Hilltop mine area per se, the larger of which has a concrete foundation and is located west of the deep tunnel under the hill. According to Vanderburg (1939) this mill closed shortly after it was built in 1922, which is consistent with the modest amount of tailings to the north of the mill (photograph 7). The western part of the district (often included in the Lewis district), includes the Philadelphia and Morning Star (Dean) mines and associated mills that created tailings piles of moderate size (several acres, possibly about 50,000 tons). These tail-

Photograph 7. Tailings from the Hilltop mill were placed in the canyon across from the mill with no regard for the small creek, which has eroded through the dam. This was standard practice through 1935, when the first regulations were established for tailings disposal.

ings have been reprocessed one or more times as technology improved (Vanderburg, 1939).

The tailings in this district reflect the sulfidic character of the veins: they are yellow to ocher and contain fairly high concentrations of base metals. Leach tests on three samples produced solutions with a wide range in pH (3.7 to 8.4); the acidic leachate solutions were high in Cu and Zn and very high in Pb, whereas the alkaline solution was very high in As and Sb. Four of the tailings piles are located in or very close to streams that have substantial flow most of the year.

Water flowing through and below mill tailings piles at four sites was tested several times to determine possible inputs from the tailings. A small seep (ca. 1 gpm) from the Morning Star tailings has a pH of 6.9 and elevated Cd, Cu, Se and Zn concentrations, but only Se is above the aquatic-wildlife standard. Measurements on Dean creek above and below the tailings seeps did not indicate any significant changes associated with the tailings. The three other tailings impoundments did not appear to produce significant changes in nearby streams and definitely released much lower concentrations of metals than the mine and dump drainages (Nash, 2003).

Imlay District

This district has had a long history of production, being one of the early silver camps in the 1860s, and is active today at the Florida Canyon open-pit gold mine. In the middle years, the Standard mine was active and some consider it to be the first of the “Carlin-type” gold mines. There are few signs of the early mills, and no tailings piles are of significant size. The tailings from the Standard mill, however, are large in tonnage and occupy a broad area at the range front (Nash, 2002a). These tailings were sluiced more than 1 km to a gently sloping impoundment west of the range front, which is cut by several small arroyos and lies about 150 m from the largest creek in the area (unnamed), which is diverted for irrigation. The tailings are of finer grain size than most, which may play a role in the unusual erosion features in this impoundment (deep meandering gullies, some of which widen downward and create bridges where the upper part is undercut). There are four smaller ponds to the west. All five dams are cut by deep, narrow gullies, but the dams do not appear to have failed.

A leach test on one sample of tailings yielded a pH of 9.7—probably a reflection of lime added during the milling process. The leachate solution had high concentrations of As, Mo, and Se.

Iron Point District

Although there are some moderate-sized mines in this district that have substantial waste-rock dumps, no mill sites or tailings were recognized on a brief reconnaissance of the area and none are reported in the literature.

Ivanhoe District

This district is historically famous for mercury production but, in recent years, was the site of a gold mine. Most of the mercury production was from 1915–1928, and in the 1940s. Extensive work from 1958 to 1973 resulted in only a few flasks of production. The Hollister gold mine, with open pit and heap-leach facility, closed in about 1993; it was reclaimed in 1997.

There are numerous retorts of simple to complex design, and numerous associated piles of calcine, in this district. Only small seeps or puddles of water could be found during wet seasons; most of the time, these mines and calcine piles are dry. There are no perennial streams within a mile of these features. Leach tests on two samples of calcine produced solutions with pH values of 7.0 and 9.0 and carrying low concentrations of metals relative to other leachate solutions in this study. The highest risk at these abandoned mines may be ephemeral puddles that can collect runoff water enriched in mercury and a few other metals that could be unhealthy to wildlife if they drank that water over long periods of time, which seems unlikely. Tests have not be made to determine if the puddle waters might have concentrations sufficiently high to be acutely toxic in a few hours of exposure.

Lewis District

The major mine in this district, the Betty O’Neal, began production in 1880, and the early ore was processed by a mill at the mouth of Lewis Canyon. A stone foundation remains at the site, but only a few tailings could be located. The mine was reopened in 1922 with a new 100 tons/day flotation mill, which stands today. This mill evidently operated for only a few years (Vanderburg 1939), which is consistent with the modest volume of tailings (50,000 to 100,000 tons). An attempt was made in recent years to leach these tailings. The tailings sit on a gentle slope distant from any stream and away from any canyon that might focus stormwaters. A leach test on the tailings produced a pH of 5.7 and low (relative to the study median) metal concentrations. These tailings appear to pose few, if any, threats.

Lone Mountain District

Prospects were located in the 1870s, and there was some minor production about 1916 when the Rip Van Winkle mine was opened, but the main activity was from the mid-30s to the mid-50s. Many of the early prospects worked contact-metamorphic zones containing Cu-Pb-Zn and pods of magnetite; production was small, and no mills operated. The largest production by far was from the Rip Van Winkle mine, the largest zinc producer in Elko County. A small flotation mill near the lower tunnel (100 tons/day capacity) released tailings to five or more ponds in the valley of Coon Creek. Tailings ponds about

5–7 m deep were created with dams across the creek, forcing the ephemeral creek to flow over or through the tailings. Gullies cut the tailings, but erosion has removed only about 10 percent of the material. There is no evidence to suggest a failure in the past.

Because the tailings are of substantial volume (about 500,000 tons) and placed in the creek channel, I visited the area several times and took a large suite of tailings and water samples for analysis. There is both good and bad news from these geochemical studies: water in Coon Creek shows only traces of metals related to the mill tailings, but they have the potential to generate acid and release base metals, especially zinc and cadmium if conditions were favorable. Leach tests on three samples yielded solutions with pH values in the range of 3.0 to 3.3 and very high concentrations of Cd, Cu, Pb, and Zn and high concentrations of Se. Pore waters in the tailings are highly acidic ($\mathrm{pH} < 2$) and have extremely high concentrations of Cu, Fe, Zn, and Cd. (photograph 8). However, several tests show that Coon Creek below the tailings impoundments has a pH of 7.9 and metal concentrations that are elevated but below the standard for aquatic life. The zinc concentration may be high enough to be of concern, depending upon the regulatory standard applied. The water quality in Coon Creek may seem to be inconsistent with the chemical properties of the mill tailings. This paradox might be explained by high clay content in the tailings that makes permeability very low and minimizes reactions. An indication of the low permeability is the toughness of the tailings: attempts to drill into the tailings with a hand auger failed at 10-cm depth, which is rare in my experience. The cohesive clays appear to minimize erosion and chances of failure in an extreme storm.

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

Majuba District

This mining area west of the Humboldt River has produced a modest amount of copper and is famous for unusual associated metals including uranium and tin (Johnson, 1977). No mill sites were identified, and no tailings are evident.

Mill City District

The Mill City district was one of the most productive in Nevada and contains some of the largest tungsten mines in the United States (Stager and Tingley, 1988). Originally a modest

Photograph 8. Tailings from the Rip Van Winkle mill were placed in Coon Creek, which has small flow for part of the year. This view shows the white sulfate mineral crusts that form on the dried surface of these sulfidic tailings and a thin band of red coloration at the edge of the water. The red colors from iron are produced when acidic, metal-rich pore waters seep from the tailings and mix with the circum-neutral-pH waters of the creek.

producer of copper in the period 1861–1917, the discovery and utilization of tungsten after 1917 made this an important mining area. The large-capacity Pacific Tungsten Corp. mill operated from 1918 until it burned in 1944; a rebuilt mill operated from 1944 to 1958. A new Springer mill was built in 1981 but operated only a few years. Tailings from the original mills, more than 3 million tons, were placed on the alluvial fan south of the town site, where they cover tens of acres and resemble sand dunes. Tailings from the newest mill were piped to a smaller, engineered impoundment farther to the south.

Tungsten skarn deposits, as at Mill City, are generally considered to pose few geoenvironmental problems because calcite in wallrocks and ore neutralizes acids (Hammarstrom and others, 1995). However, there is evidence for mobility of Mo in alkaline waters. A sample from the older tailings on the slope south of the mill site yielded a pH of 8.2 in the leach test (consistent with buffering by calcite), and metal concentrations were generally low, but the concentration of Mo was very high. The amount of Mo contamination from the tailings, which generally are dry, cannot be estimated here. Considering the mobility of molybdate in alkaline waters and the high permeability of the tailings and underlying alluvium, there would be few if any geochemical limitations on the movement of Mo in ground water to the Humboldt River.

Modarelli District

The only substantial production from this district was iron in the 1950s. The iron-processing facility is a small structure that probably used no chemicals and created waste that is similar to that on several waste-rock dumps. There are no chemical or physical reasons to suspect that this mine or processing facility is a threat to the environment.

Mount Hope District

Zinc was discovered here in the 1870s but could not be recovered economically until flotation milling was developed in response to the demand for zinc after about 1915. The Mt. Hope zinc mine was developed in the 1940s but closed prematurely after a fire in 1947. The flotation mill released tailings to two relatively small (acre-size) impounds below the mill. Today, fluvial tailings more than a meter thick can be seen in the arroyo that trends east to within a few meters of Route 278 and then south. The ponds show some erosion, but no large breach that would explain the fluvial tailings. Possibly, the ponds failed during operation and new tailings filled the breach. Leach tests on two tailings samples produced solutions with pH values of 6.4 and 9.8 and very high Al (2 solutions) and As (1 solution), and high concentrations of Cu, Pb, Mo, and Zn. The impacts on water resources are difficult to evaluate. There are no residences in the vicinity. Shallow ground water tapped by a windmill that produces water for livestock might be influenced by impounded and fluvial tailings, but the ground water could not be sampled.

National District

The famous bonanza gold deposits at National were discovered in 1907, but veins and prospects were known and there was some minor exploitation on Buckskin Mountain in prior years. The National mine produced about $4 million in gold from 1909–11; production continued through 1936 but was not as lucrative. Considering the value of ore mined, the disturbance seen today is surprisingly small. On Buckskin Mountain, The Buckskin National mine (Bell vein) was a larger operation from 1906 to 1941, but produced much less gold than the National mine. Mercury production from Buckskin Mountain was minor.

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

The National district receives more precipitation than most of the study area, much of it as snow. Mine drainage from the National and Buckskin National mine adits is the chief concern here, especially because these acidic waters react with mine waste and mill tailings, further degrading water quality. The ores contained enough sulfide minerals to produce mill tailings with the potential to release acid. Leachate tests on two samples of mill tailings produced solutions with pH values of 3.7 and 5.5. The acidic leachate (National mill sample) contained high As and very high Se concentrations, but other metal concentrations were low. The Birthday mill sample yielded a high As concentration, but the volume of tailings is small, relatively stable, and distant from creeks.

Several studies (Price and others, 1995) have determined that Charleston Creek north of the National mine has degraded water quality. Some of the contamination probably comes from mill tailings, but the amount from this source is difficult to determine in the presence of several other sources in waste rocks and in the mine. The mine drainage has a pH of 2.8 and is extremely concentrated in Al, As, Cu, and Zn (Nash, 2003).

As discussed for the Hilltop district, mine drainage seems to be the major source of acid and metals.

North Battle Mountain District

This district is geologically distinct from the Battle Mountain district to the south and had only small metal production from some silver-bearing vein deposits. Barite was produced from several open-cut mines that were small relative to other barite mines in the region. There are no mills for metals; the mill site at the base of the slope is the remains of a barite-processing plant. The fine materials there are not metalliferous mill tailings but "slimes" produced by the barite plant. A leach test shows the barite slimes produce no acid and release low concentrations of metals.

Potosi District

This district was the site of some small- to medium-sized mines, and the large Getchell gold mine, and, in recent years, is the home of several very large open-pit gold mines. Only historic mill tailings from the Getchell mine complex will be mentioned here. The Getchell gold mine was one of the most productive in Humboldt County through 1960 and was famous for abundant arsenic minerals. A new mill with 400 tons/day capacity was built in 1937, when power was brought in from Winnemucca (Vanderburg, 1938b). The tailings are sufficiently large to be shown as several ponds on published 1:24,000 topographic maps. In the early 1990s Gary Raines (USGS, Reno Office) noticed an unusual dark feature on remote-sensing images of the Getchell area; field investigations by Raines and Vic Dunn (BLM, Winnemucca Office) identified a substantial area of tailings east of the impoundments and partly on BLM lands. Samples were studied in detail to understand the behavior of arsenic, which is highly enriched in these materials (Leventhal and others, 1996). Selective leaches by weak acids showed high solubility of the arsenic phases. My passive-leach tests on two samples, utilizing deionized water, yielded pH values of 5.3 and 7.7 and solutions containing very high concentrations of As and high amounts of Mo, Pb, and Zn.

Field studies of the eastern redistributed tailings in 1999 and 2001 revealed a wide swath of flood-deposited materials, about 2.5 km long (Nash, 2002a), on the gentle slope east of the main road to the Twin Creeks mine. The fluvial tailings are difficult to see from a distance but are well shown on the topographic map and are distinctive on air photographs. The ephemeral stream channel that carried the tailings has a broad channel, hundreds of meters wide, and is only slightly incised. Apparently, all flow was down one wash—nearby washes do not appear to contain fluvial tailings. The deposit of redistributed tailings ranges in thickness to more than 60 cm, is 150–300 m wide, and 2.5 km long. It is located 3 to 5.5 km east of the main impoundment. The redeposited tailings are massive to faintly laminated, and coarse-grained sand and cobble layers are rare to absent within or below the tailings layer. The absence of other clasts and lithologies suggests that only one source—the tailings impoundments—was involved. The fine-sand fluvial tailings can be traced to Rabbit Creek, but it is possible that tailings slimes were carried by flood waters farther east and south in Kelley Creek.

The important lesson from Getchell is that large tonnages of tailings can move during extreme storm events. In this case there is no basin above (west) of the impoundments to collect stormwaters. The flood waters deposited tailings where the slope decreased from about 2 to 1.5 percent.

Railroad (Bullion) District

This was one of the early producers of silver in the region, beginning in 1869. In the 1870s, two smelters were in operation: the slag, stone foundations, and yellow rose bushes from those operations can be seen at Old Bullion, a mile east of Bunker Hill and the mines. Mills and tailings are surprisingly hard to find in this district, considering its $4.7 million of production (LaPointe and others, 1991). One mill is located at the lower tunnel, and it has a small tailings impoundment. Possibly tailings from early years of milling were removed for reprocessing, as is known for other silver districts.

Rochester District

This is one of the most productive mining districts in the Humboldt River basin, so it is not surprising that there are many mills and abundant tailings here. Mining was most active from 1912 to about 1930 and renewed in 1980 with the present large-scale bulk-mining operation. The Nevada-Packard mine in the southern part of the district was active through 1930, and attempts were made to bulk mine the vein ores about 10 years ago. The Nevada-Packard mine had a cyanide mill at the base of the hill. Two km 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 was accessed from Rochester Canyon, with a town site in the canyon and several mills in the middle part of Rochester Canyon. The Rochester Mines Co. cyanide mill was a major producer through 1929. The sulfide-rich ores of the Buck and Charley mine were treated by a 50 tons/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 (Nash, 2001).

Leach tests on eight samples of tailings yielded similar results: pH values were alkaline (8.3 to 9.7) and metal concentrations generally were low. Two leach solutions had very high concentrations of Al. One solution had a very high Pb concentration, another had very high Mo, and two were high in Zn. The predominant silver ores processed prior to 1930 were oxidized, which may explain the lack of acid generation and relatively low metal release from these materials. Unlike some tailings elsewhere, these tailings look more hazardous than they are geochemically.

The large mill tailings impoundments of the Rochester Mines Co. and Nevada-Packard (about 20 and 40 acres, respectively) show deep erosion features and fluvial tailings that can be traced for at least 3 km west of each impoundment. Although there is no evidence for catastrophic failure, both sites are good examples of why tailings should not be placed in canyons. These sites will continue to erode, and flood waters will carry tailings down the canyons onto alluvial fans. There is abundant evidence for fairly recent flood waters in Rochester Canyon (scouring, deposition of boulder gravels), and the gradient in the lower canyon may be too high to allow deposition of tailings from flood waters: only a few backwater overbank deposits can be found.

Surface water is not abundant in the district, but in May of 1998 water flowed in lower Rochester Canyon (through the area of tailings) and out of the 1990s heap leach stacked on the Nevada-Packard mill tailings. The pHs 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-extraction processes). 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 bioaccumulation or evaporative concentration to significant levels should be considered for wildlife health. The domestic water well for the community of Lovelock, located about 8 km to the northwest, is down-gradient from the mill tailings, but contaminants probably are diluted or removed by natural attenuation reactions short of that site.

Safford District

The mines for precious metals are numerous but small. No mills or tailings were seen and none are reported in the literature. Iron was mined at the Barth mine and processed near the railroad.

Scraper Springs District

The mines in this district are only small prospects. No mill structures or mill tailings were seen.

Seven Troughs District

Bonanza ores rich in silver and gold were mined from 1905 to 1917, when water flooded the major mine, the Kindergarten. As many as 11 mills served these mines. A tunnel driven 3,700 m into the center of the district in 1928 did not reach the intended veins below where they had been mined earlier but did provide ore for a new 100 ton/day cyanide mill. Production after 1934 is not known.

Ruins and remnants of mill tailings that are visible today are generally consistent with literature descriptions, but details of the story are lacking. At least two early mills were on Seven Troughs Creek, a valued source of water. A cyanide mill in the canyon was destroyed by the flood of 1912 and the active vat of cyanide contaminated the flood waters (Gibson, 2000). The stone foundations and small lenses of tailings can be found; the 1912 and later floods dispersed most of the tailings far down the fan east of the canyon. Another mill, the Mazuma, was located east of the canyon on high ground but burned in 1912; the concrete foundation and a small amount of tailings are visible. Either this mill was not very productive, or the tailings have been removed for reprocessing. The biggest puzzle is the mill, near the deep tunnel (Tunnel Camp): production from the tunnel is stated to be modest (about 30,000 tons), yet a substantial volume of tailings can be located. The majority of those tailings are 1 to 4 km east of the mill, transported during a storm event at an unknown date.

Fluvial tailings from the Tunnel Camp mill were found in 1998 in an arroyo on the east edge of the district (Nash, 2002a). The tailings were traced down two arroyos to the break in slope and southward along the valley floor, a distance of about 3 km. The massive to faintly bedded tailings range from 3 to 90 cm in thickness, and the exposed deposits range from 4 to 90 m in width, spreading where there was essentially no channel. Surprisingly, the fluvial tailings deposits continue for about 1 km on the valley floor where there is very low slope (about 10 m/km). No tailings impoundment could be identified as the source, but it had to be somewhere in the small canyon near Tunnel Camp. The lack of coarse sand and gravel beds in the fluvial tailing sequence suggests that only tailings were carried from the breached impoundment, with little or no input of clasts from the headwater basin.

Tailings compositions reflect the ore of the district, here rich in Ag, As, and Se and relatively low in base metals. Passive-leach tests yielded solutions with pHs of 3.8 and 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 (this suite is mobile in near-neutral pHs). No leach tests were made on the fluvial tailings, but analyses of the solids shows them to be enriched in the metals detected in the Kindergarten tailings.

A stream-water sample collected in 1998 below the mines and mill tailings in Seven Troughs Canyon provided ambiguous evidence regarding contamination from tailings. The pH value of 8.3 is normal, but the conductivity value of 900 µS/cm is high for a stream, and metal concentrations were slightly elevated relative to other waters analyzed in this study. With numerous mines, mine-waste dumps, and mill tailings in Seven Troughs canyon, it is not possible to distinguish among the many potential sources.

Star District

This was one of the early mining camps in the region, with production dating to 1861. There is a small mill structure with stone foundation at the mouth of Star Canyon, and there are traces of a tramway system from the mines to the mill. The nature of the stone foundation suggests that the mill dates to 1860–80. Tailings are in a meadow adjacent to the creek. Although the tailings go right up to the creek, the tailings appear to be stabilized by grasses and willows. Because the tailings contain calcite from gangue and limestone host rocks, no acid is produced and few if any metals should be mobile.

Surface waters flow near mines and the mill of the Star district. The streams and Queen of Sheba mine drainage had pH values in the range of 7.6 to 8.3, and metal concentrations were low. The quality of Star Creek east of the mines and mill tailings is generally good but somewhat elevated in Zn. The tailings may be contributing some Zn to the creek but probably not as much as drainage from the mine adits to the west.

Swales Mountain District

Mines in this district are small and apparently were not supported by a mill. No mill sites or tailings were seen.

Tenmile District

This district is poorly described in the literature. The main mines seem to have been developed in the 1940s. The largest mine, the Pansey Lee, worked highly sulfidic veins that were rich in base metals; it was a small prospect in 1937 with no mill at that date (Vanderburg, 1938b). Later, the Pansey Lee had a small (about 100 tons/day) mill just below the headframe. Only a small volume of tailings remain in a 1-acre pond at the mill. Most of the tailings are in a gulch about 3 km south of the mill, redeposited as a swath about 2 km long, up to 70 m wide, and as much as 1.2 m thick (Nash 2002a). These fluvial-tailings deposits are yellow to ocher, massive to faintly laminated, and contain a few lenses of large clasts of sulfidic rocks from the waste-rock dumps. The tailings can be traced nearly as far south as the main road from Winnemucca to Jungo. Leach tests on four samples of tailings from the Pansey Lee mill (three fluvial, one from the mill site) produced solutions with pH values of 3.4 to 4.5, with high to very high concentrations of Cd, Cu, Sb, and Zn. Although these tailings are releasing acid and metals to episodic runoff, this probably is not a significant threat to the Humboldt River, about 6 km to the south. There are no residences in the area.

The gold-adularia vein deposits in the district were located in 1940 and attained modest production for about the next 20 years. There was a small mill at the Tenmile mine, and I saw the tailings in 1994, but the mine area was reclaimed in 1997 and the tailings were covered. The tailings pond was about an acre in size. Judging from the oxidized nature of the ores and their bulk composition, the tailings should release little or no acids and metals.

Tuscarora District

This district is famous in mining lore, but production was actually quite small compared to many other districts, albeit lucrative in the 1870s when bonanza zones were mined. Production increased in the 1890s when new mills were built, but was small after 1910. An open-pit mine with a heap-leach facility (Dexter mine) operated in the 1980s. Remains of the North Commonwealth mill and its brick smokestack are highly visible, but no traces of tailings could be found. The mill tailings presumably were moved when they were reprocessed in 1979–82 (LaPointe and others, 1991). The Dexter mine and heap-leach pads had not been reclaimed in 1997, but the oxidized character of the ore and the style of alteration appear to create neutral or weakly alkaline waters, thus low base-metal concentrations are expected. Geochemical studies of the Dexter pit lake (Balistrieri and others, 2000) provide an estimate of the character of runoff from the heaps.

Willard District

This district had very little production through about 1980. An open-pit mine for gold at the Willard mine worked oxidized deposits in altered siltstones. The ores were leached on one large heap pad. Because of the ore contained low concentrations of sulfide minerals and base metals, the heap should release little acid and metals. However, a sample of water leaking from the plastic liner showed surprisingly high concentrations of several metals such as Co, Cr, and Ni—unexpected in these ores (Nash, 2001). Concentrations of As, Cd, Co, Cr, Cu. Mo, Ni, and Se were very high relative to other analyses in this study. The unusual composition of the ponded water may be explained by cycles of evaporation and accumulation of elements normally present in trace quantities. Reclamation work in 1999 apparently corrected this minor problem.

Analogs in Other Nevada Mining Districts

Mills and mill tailings in several other parts of Nevada were studied briefly to gain insight on the chemistry and physical stability of tailings and possible inferences for historic or current mill-tailings disposal in the Humboldt River basin. The sites studied were some of the major historic mines in Nevada, and several of these sites were on the priority list of the Nevada Interagency Abandoned Mine Lands Taskforce (J. Crowley, BLM, written commun., 1999). Only brief highlights are provided here; chemical results and physical descriptions are included elsewhere (Nash, 2000b, 2002a).

Candelaria District

This was a major silver producer from the 1870s through the mid-1890s from oxidized polymetallic deposits in sedimentary host rocks. There was renewed mining in an open-pit operation in the early 1990s; that mine has ceased production and the lands have been reclaimed. Milling was a problem for the early miners because water was scarce; much of the ore was hauled about 10 km west to Belleville. Several mills can be seen at Belleville, at least one was for reprocessing of older tailings. The tailings at Belleville are brick red from a roasting process. A substantial ephemeral stream has eroded into the edge of the unconfined tailings, removing about 10 percent of the tailings. No fluvial tailings could be identified to the north along the high gradient stream. Another area of tailings is at the town site of Candelaria, northeast of a mill with stone foundation; this site is surrounded by, and perhaps partly covered by, waste-rock dumps from recent mining. The extent of the tailings at Belleville and Candalaria are shown well on USGS 1:24,000-scale topographic maps.

The Candelaria tailings are enriched in many metals, some of which are soluble in leach tests. Tests on three samples produced solutions with a range in pH values (2.1 to 7.3); the acidic solutions carried very high concentrations of Cu, Mo, and Se. The near-neutral solution carried very high concentrations of As, Mo, and Se.

Goldfield District

This district was one of the premier gold producers in Nevada between 1903 and 1947. As the mines were consolidated, two major companies emerged, each with a large mill. Tailings from those mills are in two large areas (tens of acres), at the center (Florence mill) and northeast corner of the district (Goldfield Consolidated mill, GCM); these tailings were reprocessed in the 1930s. The tailings impoundments were large enough to be mapped as a geologic unit by Ashley (1975). The gold deposits are a prime example of the “acid-sulfate” type that are rich in alunite (K-Al-sulfate mineral) as well as pyrite and arsenic-bearing sulfides (Vikre, 1989). The unusual character of the ores is evident in the tailings. Leach tests on three samples produced solutions with pH values of 2.1 to 2.8 and high to very high As concentrations. Also very high were Cu, Pb, Se, and Zn. Aluminum was very high, and fine material (clays or colloids?) stayed in suspension for more than 12 hours. The tendency for these acid-generating tailings to release fine colloidal(?) aluminum to stormwaters is well shown by a “chemical delta” of light-colored material in a gravel pit and pond 4.3 km north of the GCM tailings. The GCM tailings also show unusual erosion caverns that may, in part, reflect dissolution. Although the Goldfield area is arid and dry most of the time, the GCM tailings appear to have potential for erosion and release of flushes of highly degraded stormwaters.

Leadville District

The Leadville mine in the district of the same name, about 60 km north of Gerlach, was the largest producer of silver and lead in Washoe County (Bonham, 1969). The mine operated from 1910 to 1925, when a fire destroyed the mill. The polymetallic ore, rich in Ag-Pb-Zn-Au, has high sulfide content (less oxidized than most historically mined ores). Tailings from the mill were sluiced into the nearby canyon and were originally about 25–70 m wide over a distance of about 1 km (photograph 9). The tailings have been severely eroded in cuts up to 4 m deep, and redistributed fluvial tailings now extend east to the county road and then to the south in Leadville Canyon for at least 1 km beyond the original site (Nash, 2002a). Leadville Canyon has a steep gradient and no fluvial tailings are preserved. Erosion may have moved as much as 30 percent of the original tailings. This mining area, at an elevation of 6,000 ft (1,830 m), gets substantial precipitation as rain and snow. A creek, including mine drainage from the collapsed lower portal, flows through the tailings for at least a few months of the year.

Leach tests on three samples of tailings produced pH values of 6.3 to 7.7, higher than expected but probably explained by propylitic (green) alteration of the volcanic rocks. However, the leach solutions carried very high concentrations of Cd, Pb, and Zn, and also were high in Sb and Se.

These tailings are a good example of the erosion that can occur in a mountain canyon. Further erosion will happen during storms, but this channel is so deeply entrenched (it actually cuts into gravel below the tailings) that only an extreme storm would raise the water level high enough to erode the tailings. The composition of these rocks and ores is unusual for the region but may provide an analog for high-sulfide ores in propylitically altered mafic volcanic rocks elsewhere in northern Nevada.

Manhattan District

Several types of ore have been mined and milled in this district over the past 100 years (Kleinhampl and Ziony, 1984), but one type is of particular interest. The White Caps mine was one of the early, major producers of gold, and some consider it to be similar to Carlin and other mines in calcareous sedimentary rocks of northern Nevada. The White Caps mine was famous for its high arsenic content and colorful arsenic minerals orpiment and realgar. The Whitecaps ore was not amenable to early milling methods; milling difficulties were eventually solved by a roasting process that produced the distinctive brick-red tailings. Mining and milling were episodic from 1912 to 1964, when a fire caused closure of the mine. Tailings

Photograph 9. Tailings from the Leadville mine were placed in the canyon east of the mill in the 1920s and have been eroded by numerous storm events. The white color is from sulfate mineral crusts on the surface of gray and ocher sulfidic tailings.

were stacked in several ponds created across two gulches near the mill and in several subsidiary ponds to the west in Consolidation Gulch. The upper impoundments are eroded in places but appear to be intact; the ponds at lower elevation have been breached (photograph 10), and fluvial tailings extend to approximately the edge of the village of Manhattan.

A leach test on one sample of tailings from the White Caps mill produced a solution with pH 6.4, an extremely high As concentration, and high concentration of Mo and Sb. The As concentration of 2,100 ppb is much higher than in leachates from other samples tested in this study.

The White Caps tailings may provide information of use for other sediment-hosted gold deposits, but they could be an extreme composition. These tailings have the potential to release large amounts of As, Mo, and Sb—a suite of metals that is well known in Carlin-type, sediment-hosted gold deposits. The White Caps tailings may also be an example of a dilemma for land planners: the tailings dams have been breached in the past and the remaining impoundments may be at risk of failure in an extreme storm. Perhaps most significant, and unlike most mining areas in Nevada, the village of Manhattan lies in the path of flood waters, should a failure occur. Also, the town domestic water well is located a short distance from the mouth of Consolidation Gulch and probably would be contaminated by stormwaters or fluvial tailings in such a failure. The potential impact of high-arsenic waters and tailings on a domestic water well seems certain; the risk of tailings failure is uncertain and difficult to evaluate from available information.

Mountain City District

Several types of ore were produced in this district in northernmost Nevada, but the major production was from massive sulfide ore at the Rio Tinto mine from 1931 to 1947 (LaPointe and others, 1991). Processing the copper-rich massive sulfide ore created about a million tons of sulfide-rich tailings, which were placed in a series of ponds spanning about 1,200 m in the flood plain of Mill Creek. This site, shown on the USGS Mountain City 1:24,000-scale topographic map, is about 1 km from the junction with the Owyhee River, which flows north into Idaho. Contamination of the Owyhee by acid and metals from the tailings has been the subject of lengthy investigations. The magnitude of the contamination is considered to be “Superfund caliber” by the Nevada Department of Environmental Protection (NDEP); the site has been proposed for the National Priority List (Superfund). Although no samples could be taken for analysis, the combination of high sulfide content, large tonnage, and placement in a perennial stream are obvious problems. Ironically, limestone beds outcrop a short distance north of the ponds and would have made an ideal base for an engineered impoundment, but this was not appreciated in 1931.

Northumberland District

Disseminated gold was mined at the Northumberland mine, northernmost Nye County, in two periods, first from

Photograph 10. This was one of the smaller tailings ponds below the White Caps mill at Manhattan. The dam, about 3 m high, was breached and most of the tailings eroded in one or more storm events.

small open pits (1939 to 1942) and then from a large open pit in the 1980s (Kleinhampl and Ziony, 1984). This ore in carbonaceous, calcareous sedimentary rocks is of the Carlin type. The early production was processed through a cyanide mill with 300 tons/day capacity. Tailings were sluiced more than a mile to two sites where the canyon was wide enough to accommodate an impoundment, and the resulting ponds appear to be well designed and quite stable. Erosion appears to be much smaller than at most ponds of this era.

Leach tests on one sample produced a solution with a pH of 5.5; because the pH is not alkaline, it is likely that the carbonate minerals originally in the sedimentary rocks were replaced by silica or clay. The solution contained a very high concentration of As and high concentrations of Mo, Sb, and Se. This suite of elements is typical of Carlin-type gold ores. In the oxidized state, these oxyanions are predictably mobile in circum-neutral waters.

Pioche District

Polymetallic ores, rich in silver and lead, were mined episodically from carbonate rocks in this district from the 1870s to the 1970s (Gemmill, 1968). Many large mines were developed over the years and were supported by several large mills. The type of ore mined, oxide or sulfide, depended largely on available milling technology. The early bonanza silver ores mined prior to about 1900 were hauled to mills near water at Bullionville. Slag can be found near the early smelter, but hardly a trace of tailings can be found today: the silver-rich tailings were excavated after the railroad was built in 1911 and carried by train to Salt Lake City for use as smelter flux.[3] A modern mill stands on the east side of the district, east of the town of Pioche; it received its ore by tram and placed its tailings in a draw (shown on the USGS topographic map). In 2000, a residential subdivision was under development less than a kilometer north of the mill and tailings. Other mills probably are present on the east side of the district but were not located in my reconnaissance.

Two or more mills processed ore on the west side of the district at Caselton. The mill near the Prince mine, of apparent medium size, sluiced its tailings into several small canyons southwest of the main highway (Nevada Route 320); it processed sulfidic ores in the 1940s. The large Caselton (Combined Metals) mill utilized new flotation methods for the complex ores from 1939 to about 1970. It sluiced its tailings to numerous engineered and improvised tailings ponds southwest of Highway 320. The major tailings ponds and piles are shown on the USGS topographic map (Pioche, 1:24,000 scale), which was produced from photographs taken in 1951. All of the tailings piles are in or within a quarter mile of Caselton Wash, a major drainage incised about 20 m into alluvium. The ephemeral stream flows southeast into Caselton State Recreation Area.

The Caselton tailings comprise several million tons and cover as much as 300–500 acres if one considers the numerous spills and seemingly unplanned ponds. Because the practice in this area was to use natural gullies or ditches 3–7 m wide to sluice the tailings, it is difficult to distinguish between sluices (intentional), spills or overflow, and outwash from storms. The area of tailings is very complex, and I could study only some of the features during 2 days there. The history of these tailings is not described in the literature, but two stages are likely (Nash, 2002a): (1) an early stage of informal sluicing of tails to unconfined gullies on the alluvial fan, and (2) a later stage of engineered tailings disposal into a series of as many as a dozen ponds and catch ponds within Caselton Wash. The first stage placed or spilled tailings over a broad area of sections 32 and 33. The second stage placed the tailings out of sight in the deep wash, but the tailings extend from wall to wall and over a designed length of 2 km; fluvial tailings extend for another 2 km or more. This means that stormwaters that occasionally flow down the wash make contact with tailings for at least 4 km. However, the dams created in stage two appear to be strong, and the amount of erosion over the past 50 or more years is actually small (the fluvial tailings are a small percentage of the total volume). The stage-2 impounded tailings are cemented in most places by a layer of dark brown Fe-Mn minerals (a variety of hardpan) that make a very tough layer at a depth of a few centimeters. My attempts to drill into the hardpan with a small hand auger were not successful.

Chemically, the Caselton tailings are rich in Fe, Mn, and base metals in a matrix of carbonate and silica minerals. Much

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[3] Reported by Lee and Wadsworth (1964) in a history of the Panaca-Pioche area. Also reported is the lead poisoning of cattle near the mills and smelter: "Not until the middle of the twentieth century were cattle able to survive in the area of Bullionville. The density of lead on the ground caused lead poisoning in animals that grazed there." (Lee and Wadsworth, 1964, p. 17).

of the ore appears to have been oxidized prior to mining, but other sources of ore were rich in sulfides. In places acid generation is extreme—chiefly at some trenches that collect water on the low-permeability tailings pile. The ponded water has extremely low pH values (<2.5), extremely high total dissolved solids from evaporative concentration, and extremely high metal concentrations. Leach tests on three samples show a wide range of pH values (2.3 to 7.4), consistent with the visible mineralogy. The acidic leachate solutions carried very high concentrations of Al, Cd, Cu, Pb, and Zn, whereas the circumneutral solution carried very high concentrations of Pb and Zn.

The Caselton tailings appear to be a prime example of bad tailings-disposal practices into sites that are subject to reaction and erosion in storm events. Here, however, the situation is ameliorated by hardpan that appears to minimize permeability and erosion in stormwaters. The extent of chemical reactions in stormwaters is more variable here than in most districts. In some places, the low apparent permeability caused by clays and hardpan appears to negate the potential for acid generation and release of metals suggested by leach tests and chemical compositions. Some ponds do not develop the Fe-Mn hardpan, possibly due to a difference in composition, and these seem to generate more acid. The highly acidic waters in trenches on one pond may develop from a distinct ore composition that was rich in both sulfide minerals and clays. Extensive studies are needed on the chemical reactivity of various tailings piles in storm events, the physical stability of the piles, and the flowpaths of contaminated waters, before planning reclamation that will be effective.

Photograph 11. A trench in the large tailings impoundment at Caselton collects and retains surface runoff. The sulfidic tailings create acidic, metal-rich waters that are further enriched by cycles of evaporation. Native sulfur crusts on the surface are a reactive source of sulfuric acid.

Tonopah District

This was one of the great silver-gold producers in the United States, about $159 million from 1900 to 1961 (Bonham and Garside, 1979; Kleinhampl and Ziony, 1984). The production of more than 8 million tons of ore meant the generation of more than 8 million tons of mill tailings. The tailings are visible in and around the town of Tonopah, but they are not as prominent as the larger piles of waste rock. Larger tailings deposits are shown on the geologic map (Bonham and Garside, 1979). Actually, a large part of the milling was done 20 km to the west, at Millers, where more water was available. Many of the gulches in Tonopah are filled with tailings, notably Slime Gulch, which contains tailings for more than 18 km to the west (to the point that it fades into the playa). The tailings at Millers cover an area of about 200 acres with dune-like sands.

The tailings in Slime Gulch provide a field laboratory for the behavior of tailings during storm events. There are many kilometers of exposures of actively eroding banks and redeposition as fluvial sediments. One or more major storm events are recorded in tailings that were eroded and deposited about 2.5 m above current base levels as waters ponded behind railroad culverts that could not handle the flow. The flood waters 16 km west of town, way out on the alluvial fan, were at one time so violent that they ripped out heavy concrete bridge columns (5 m × 3 m × 1 m) and carried them 15 m downstream. The Slime Gulch tailings probably were released without confining dams (there were no regulations at the time). Because mill tailings do not flow very far on their own, the tailings probably were originally placed a few hundred meters from the mill, where eroded tailings can be seen today. Over the years, the tailings were swept many kilometers to the west. Some of the transport probably was by normal storms, but the physical evidence for flood waters and high strand lines suggests that one or more extreme storms transported large amounts of tailings.

The volcanic-hosted vein ores at Tonopah have a limited range in mineralogy and chemical composition (Bonham and Garside, 1979). Most of the tailings are light tan to cream, as expected of clay-altered volcanic rocks. Leach tests on three samples of tailings produce surprisingly different results. Leachate solutions had pH values in the range from 2.6 to 8.4. The acidic solutions contained very high concentrations of Cd, Cu, Pb, and Zn, whereas the alkaline solution contained very high concentrations of Mo, Pb, Sb, Se, and Zn. The element suites are expected of the Tonopah ores, but the wide differences in acid generation require further study of additional samples.

The mill tailings at Tonopah are unusual for Nevada in that large quantities of tailings are on private property in close proximity to residences. In some places the tailings are on public lands, or the effects of the tailings reach public lands. Because the gulches in the area are dry most of the time, it is not clear how often release of metals actually occurs. Most likely, storms create a flush of metal-enriched waters that would move toward the basins, in some cases reaching the playas. These waters do not appear to influence domestic water wells but the consequences for wildlife cannot easily be determined.

Tybo District

This district, 110 km east of Tonopah, was a major producer of silver from 1870 to 1937 (Ferguson, 1933; Kleinhampl and Ziony, 1984). Because the polymetallic sulfide ores are in carbonate host rocks, conventional wisdom is that there should be few environmental problems. Because all mining was from shafts, there is no surface mine drainage. However, the mill tailings create some unexpected problems, first pointed out to me by Steve Brooks (BLM, written commun., 1998). The major unexpected features are (1) acidic, metal-rich waters produced by the tailings, and (2) a large area of fluvial tailings that testify to one or more flood events that caused tailings impoundments to fail (Nash, 2002a). A smelter at Tybo may have contaminated the town site with airborne emissions in the 1870s, but the pile of slag probably is causing no harm today.

There were two substantial mills in Tybo Canyon near the main production shafts: an older one with a stone foundation that created red tailings (indicating the use of the Reese River roasting method, ca. 1900–1910) and a newer mill nearby with a concrete foundation that released gray to ocher sulfidic tailings. The latter mill was built in 1929 by the Treadwell-Yukon Mining Co. Pre-1900 mills existed, but those sites were not evident in my brief study. The contrasting red and ocher tailings colors are useful for reconstructing the history of where tailings were placed and their subsequent movement in floods. The early red tailings appear to have been sluiced down the hillside into Tybo Creek with no attempt at confinement. The red tailings can be traced down the canyon for about a kilometer to the east as overbank deposits. Small amounts are visible at the mouth of the canyon (east of the large impoundment) and also 10 km to the east in fluvial deposits that indicate a major flood event. Small lenses of gray to ocher tailings rest on red tailings in the canyon below the two mills, and a large volume of the ocher tailings are in a constructed impoundment 2 km east of the newer mill where the canyon widens. The impoundment measures about 300 m long by 150 m wide, as shown correctly on the USGS topographic map (Blue Jay Spring, 1:24,000 scale), with two dams about 5 m high. Tybo Creek has run across the tailings pond for many years, eroding gullies 1–2 m deep and depositing gravel. Judging from the current surface of the pond, it appears that 10 percent of the original volume has been eroded, which is fairly typical of Nevada tailings ponds. No features at the tailings pond would suggest that there was a major tailings failure here. The volume of fluvial tailings, described next, is approximately the same as in the impoundment, which probably means that the impoundment was filled or refilled after the flood event or events.

Fluvial tailings east of the Tybo pond provide scattered clues to what must have been one or more major flood events (Nash, 2002a). There are scant traces of fluvial tailings for the first kilometer east of the impoundment, but a decrease in the gradient as the canyon widens and merges with the alluvial fan brings on deposition of massive deposits of ocher tailings. For the next 3 km, the tailings are as abundant as if they were deliberately dumped by trucks and spread for as much as 150 m across the wash (photograph 12). In this stretch, the tailings deposits are continuously exposed at the surface, commonly more than 30 cm thick, massive to faintly bedded, and have virtually no interbeds of coarse sand or gravel, but younger boulders and gravel lie on top of the tailings in some places. The widest tailings deposits occur about 2 km east of the pond; here there was no channel and the tailings deposits create a low ridge on the sloping alluvial fan. Tailings deposits up to about a meter thick are found at the 3-km mark, where a channel developed. The tailings were thick enough and pure enough (very few clastic interbeds) that they were claimed for mining and an attempt was made to reprocess the fluvial materials! East of that mining operation, the alluvial fan has low slope; the fluvial tailings are in thinner beds and fill narrower channels 5 to 15 m wide. At a distance of 8 km from the tailings pond, the fluvial tailings are 4 to 10 cm thick, with a few coarse-sand interbeds. The flood deposits extended all the way to Hot Creek, an indistinct feature in the broad valley, 10 km from the impoundment. Thin beds of tailings can be found in the flood plain of Hot Creek, southeast of the junction with Tybo Creek. The ocher fluvial tailings are consistently the same fine-sand-grain size as at the impoundment, and no layers of finer clay-rich materials were seen that could rep-

Photograph 12. This swath of ocher materials that will not support vegetation is fluvial tailings, carried down Tybo Creek about 8 km from the tailings impoundment at the mouth of the canyon. The site shown here is near the terminus of the flood deposits where there is very low slope on the alluvial fan and virtually no channel for the ephemeral stream.

resent tailings slimes. My test of grain size is their grittiness between fingers: these tailings are sufficiently fine to be just a bit gritty, whereas slimes feel greasy and coarser tailings from other localities are scratchy.

Deposits of red-colored fluvial tailings were observed about 1 km east of the Tybo tailings pond and in several thin deposits 8–10 km to the east. The red tailings were always below the ocher tailings, which is best explained by a flood event prior to the one that carried the ocher tailings.

The fluvial tailings east of Tybo require an extreme storm event for their deposition—the details of which are not defined by my brief studies. Several main features emerge. (1) Source: The homogeneity of the fluvial tailings beds, with few or no other clastic layers, may indicate that there was only one source of material. (2) Date: The lack of evidence for a breached dam suggests that the storm event could have happened while the mill was in operation. Most of the presently impounded tailings could have accumulated after the dam was repaired. (3) Hydrology: The postulated storm event may have been centered on the tailings dam and not the entire upland watershed. Adjacent canyons do not contain flood deposits.

Reactions in the sulfidic Tybo tailings are not what is predicted of carbonate-hosted polymetallic deposits that typically are buffered by carbonate minerals (see Plumlee and others, 1999, who note some exceptional cases of acidic waters). There are several lines of evidence that the Tybo tailings generate large amounts of acid. First, storm runoff during a miserable June day, 1999, created waters with pH values in the range of 1.7 to 3. Samples of the runoff water contained extremely high concentrations of Al, As, Cd, Fe, Mn, and Zn, and very high concentrations of Cu, Ni, and Pb (Nash, 2000b, 2002a). Second, a yellow phase with the appearance of native sulfur is abundant just below the surface of the tailings; this was seen on a hot, dry day in June 2000. In theory and practice, native sulfur forms sulfuric acid very quickly when exposed to water. Third, a leach test produced a solution with a pH value of 2.5; the solution contained very high concentrations of Al, As, Cd, and Zn, and high concentrations of Cu and Pb. The explanation for the lack of acid-neutralization capacity in the tailings may be the fact that much of the mined ore was in and along felsic dikes (Ferguson, 1933) and that silicification along the veins destroyed carbonate minerals. There clearly is not enough carbonate in the tailings to neutralize the quantity of acid that is generated.

Discussion and Conclusions

Inventory

The 225 mill and tailings sites listed in table 1 are likely sources of contamination. These sites have been largely ignored in mined lands evaluation, in part because locations are inadequately recorded in the literature and are largely absent in electronic databases (one of the better databases, MILS from the former U.S. Bureau of Mines, shows less than 5 percent of historic sites). For an effective environmental assessment, tailings sites need to be evaluated in the same manner as is commonly done for mine openings and mine-waste-rock dumps.

The inventory of smelters (11 sites with slag piles) is only a starting estimate of the true distribution of historic smelters. There probably were two to five times this many originally. Although smelters can have a devastating effect on surrounding life and soils, the slag piles that remain today are relatively unreactive if left in place. Crushing, grinding, and use of slag increases its reactivity because more surface area is created and chances for ingestion by humans is more likely. The large slag piles at Eureka are probably of greatest concern because they are within the community and some of those materials have been crushed for local uses.

The 83 mills and associated tailings piles are a fair estimate of the original total, although in many districts there are unpublished reports of additional mills that I did not recognize. Some mill tailings were not identified, and I suspect this is especially likely for pre-1900 silver mill tailings that commonly were moved for reprocessing. Additional work should be done to identify other tailings sites; use of aerial photographs might be cost effective. The majority of the sites I observed in the field showed evidence for erosion by surface waters with approximately 10 to 90 percent of the original material removed. Wind erosion is a problem at some sites; dust from tailings that are allowed to dry is a known health risk (Ritcey, 1989) but was not investigated here. A small number of tailings sites are contributing fine materials to streams, but more typically eroded tailings are deposited in dry washes and as overbank deposits along those washes. Failed tailings dams and fluvial outwash tailings were identified at 11 sites (Nash, 2002a) and more cases must exist in northern Nevada.

The count of 13 heap-leach pads and 11 mercury retorts represents a bare start on the inventory process. This inventory only provides some typical examples. Many small heap-leach or retort operations were transient facilities that were dismantled after a few years of operation, but their waste materials can be significant for many years. Further compilation of information on these facilities is needed.

Implications for Water Quality

Most of the tailings sites identified in the Humboldt River basin are dry most of the time. The few tailings piles that are near streams that flow much of the year do not appear to be reacting significantly with those waters. As discussed earlier, physical factors such as clay layers and hardpan cement appear to limit permeability and release of metals to surface waters. It is possible that wet tailings release a small, slow flow of metal-enriched water to underlying alluvium and ground water. The major impacts of mill tailings may be (1) brief flushes of runoff during storm events that carry acid and metals released from soluble mineral crusts, and (2) small ephemeral ponds and puddles that can develop extreme metal concentrations, in part through evaporation. Runoff could impact wildlife or infiltrate alluvium and contaminate ground water, but in that process caliche in soils should mitigate extreme concentrations. Ponded water that is rich in salts and metals may not have a color or odor to warn unsuspecting animals but could be acutely toxic.

Tailings Dam Failures

Collapsed dams have been identified or inferred at 11 sites, and tailings have been transported 1 to 15 km down arroyos and over alluvial fans. The tailings deposits are well preserved and suggest that unusual flood conditions were involved, but the timing and flood conditions are difficult to define (Nash, 2002a). The massive deposits of tailings more than 10 cm to 2 m thick, deposited more than a kilometer from the likely source, probably were transported as viscous, high-density flows similar to mud flows or debris flows. Features of the massive deposits generally are much different from deposits created by normal storms that cause minor erosion and create deposits a few millimeters thick. Several of the tailings dams appear to have failed during the active use of the dams, as best illustrated by features at Cortez and Tybo, where the dams appear to have been repaired and additional tailings added to fill the pond (Nash, 2002a). Also, it is not uncommon for tailings dams to fail during their first years of use when operators are inexperienced with the techniques of building dams and confining slimes (Ritcey, 1989). Some of the older mill tailings, as at Tonopah and Leadville (which date to 1910–25), may have had small or no confining dams, allowing the tailings to be swept downstream almost annually. Most of the Nevada failures may have occurred prior to 1935, when there were few or no regulations for tailings disposal, and operators may not have been concerned about a failure or spill.

Liquefaction appears to be a significant factor in the historic failures (Nash, 2002a), and this process is critically linked to young, water-saturated tailings. There are several lines of permissive evidence for failure during active use of mills. Recently deposited tailings in an active pond contain large amounts of pore water and can behave like a liquid if the dam is breached by erosion or an earthquake. Liquefaction and flow are observed at modern tailings failures (Jeyapalan and others, 1981; Wegener and others, 1998). A major storm event that adds several centimeters of water to a pond can overtop the dam or cause it to fail by shear, setting off a flow of unconsolidated tailings that resembles a mudflow or the hyperconcentrated flow of Costa (1988).

The size and hydrology of the upland watersheds were thought to be important factors in catastrophic dam failure (Nash, 2001), but closer study of the Nevada failures suggests these are of less importance than properties of the tailings dam. The tailings flows thought to be related dam failure are in small headwater basins, and there is little or no evidence for flooding and erosion in the headwaters or in adjacent watersheds. Only one alluvial section showed evidence for significant amounts of trash and mine waste from the basin above the impoundment. Indeed, one of the surprising aspects of the flood tailings deposits is the absence of coarse clastic beds and mining waste interbedded with the flood tailings.

Risks from Historic Tailings

The likelihood of damage to the environment, wildlife, or human health from mill tailings falls in three classes: (1) release of metals or acid, with little or no transport of eroded materials, (2). release of metals, acid, and materials during a storm that causes erosion, (3) release of large amounts of materials, metals, and acid during a dam failure.

Damage from type-1 events is predictable if the composition of the materials, the volume of materials, and the magnitude of storms are known. The composition of storm runoff can be estimated from leach tests, described earlier. The magnitude of the flush can be estimated or ranked by including a factor for surface area or volume of the tailings, as discussed by Fey and others (2000). The potential for damage at each site or watershed must consider the environment downstream from the site, including features such as wildlife, livestock, wells, communities, or rivers. Only a few tailings impoundments are located where an extreme storm might carry water and debris into the Humboldt River or a major tributary. Only the tailings at Tonopah and Manhattan (outside the Humboldt River basin) are situated within communities where there is potential to harm wells and people. For the majority of tailings impoundments, the risk involves wildlife and scattered livestock, and the likelihood of impact on individual animals is relatively high—on the order of 1 in 10—based on the frequency of flash floods.

Damage from type-2 events is predictable by factors similar to those in type-1 events. The magnitude of damage is probably larger than in case 1 because metal concentrations probably will be raised by mechanical action during erosion, and the transported solids may cause long-term damage by slow release of metals or acid after deposition.

Damage from type-3 catastrophic failure of tailings dams is known to be large in several modern tailings failures (East, 2000) where there has been loss of life and destruction of homes. The massive flood tailings deposits in northern Nevada, described above and by Nash (2002a) suggest that the flows would have caused great damage to life and property in their path. However, these flows do not seem to be an appropriate model for historic tailings. Failure of this type is most likely when the tailings are young and water saturated and is highly unlikely for tailings more than 50 years old that are compact and partially cemented. The risk of tailings failure at historic sites is estimated to be low, on the order of 1 in 100 to 1 in 1,000, because the old tailings will not fail by liquefaction.

Conclusions

This reconnaissance of mills and tailings has identified more than 80 mills and associated tailings sites in the Humboldt River basin. The amount of tailings is variable from site to site and is approximately equal to the amount of waste rock from the associated historic mines. Because the tailings were generally placed in lowlands, commonly within flood plains of streams and ephemeral creeks, these mine-related materials are more likely to interact with surface waters than is mine-dump waste. Episodic release of acid or metals to flushes of storm runoff waters are likely but probably extend for distances of only hundreds of meters before the waters are attenuated by reaction with caliche or infiltrate into alluvium. In a few districts, surface waters and mine drainage flow through mill tailings to create severely degraded water; mixing with other sources of water and reactions with caliche in alluvium neutralize these acidic waters within a few hundred meters of the tailings, and water quality improves to levels acceptable to aquatic life. Rare extreme storms have the potential to cause catastrophic failure of tailings impoundments, carry away metals in stormwaters, and transport tailings as debris flows for 1 to 15 km. Catastrophic failure of tailings impoundments, evident at 11 sites in northern Nevada, probably occurred while the mills were active but appears to be unlikely at historic sites having partially lithified tailings. In most situations, stormwaters and transported tailings would impact wildlife but few or no people or domestic water wells. Because all identified historic tailings sites are several kilometers distant from the Humboldt River and major tributaries, tailings probably have no measurable impact on water quality in the main stem except possibly during a 100-year storm event.

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