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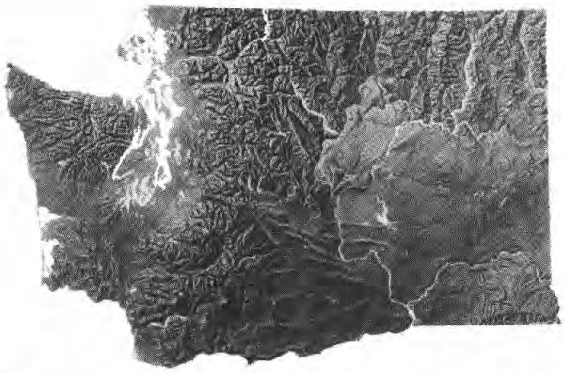

WASHINGTON GEOLOGY

VOL. 23, NO. 1
MARCH 1995

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Natural Resources
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Cover Photo: Hecla Mining Co. began driving its 7,000-ft decline to the Golden Promise orebody at Republic in January 1990. The opening is 11 ft high and 13 ft wide. It took 5 months to reach the first ore on the 600 level. At a constant slope of 15 ft per 100 ft of length, the 11 level was reached 1,050 ft below the surface. The decline was later extended to the 13 level, about 200 ft deeper than the 11 level. The decline cost $300/ft, or $2,100,000, to the 11 level. On January 2, 1995, the last ore was removed from the Golden Promise orebody.

The Cannon Mine and Regional Exploration Data

Raymond Lasmanis, State Geologist
Washington Division of Geology and Earth Resources
PO Box 47007, Olympia, WA 98504-7007

During 1982, Asamera Minerals, Inc., began drilling near Wenatchee for reserves at the 'B' and 'B-West' ore zones. Sufficient ore was outlined to place the Cannon Mine into production by July 15, 1985. By 1994, all available ore-grade material was mined. The last ton of ore was hoisted from the mine by Asamera on December 22, 1994.

During the course of 14 years, Asamera acquired an incredible amount of data about gold deposits in the Wenatchee area and the surrounding region. All data, including production information, has been donated to the Division under the stipulation that it be readily available to the public, explorationists, and the academic community.

On February 23, 1995, the Division took possession of six filing cabinets, three flat map files, and numerous boxes. These contain mine geology plans, sections, and assay plans, as well as all drill-hole data in both electronic format and hard copy. One cabinet contains photos of drill core and data for core geochemistry. Also included with the information are reports on the geophysics, metallurgy, and petrography of the Cannon mine deposits.

A detailed index of the data will be compiled in the near future and published in *Washington Geology*.

The Department of Natural Resources appreciates the foresight of Asamera in preserving these data for use by future generations of economic geologists. The state will benefit from Asamera's generosity. ■

Division Awarded Grant for Mount Rainier Guidebook

The Division has received a Scenic Byways grant from the Federal Highways Administration, administered through the Washington Heritage Corridors Program, to prepare a roadside geology guidebook for State Routes 410, 123, 7, and 706 and U.S. Highway 12 in the vicinity of Mount Rainier National Park. **Pat Pringle** and **Wendy Gerstel** will be starting the preparation of an Information Circular in July of 1995.

Our Area Code Has Changed!

The Division's Olympia Office has a new area code: 360. Some calls made with the new code may not go through. If this happens, please let your phone company know.

Do you want to get off our mailing list?

The Division pays for printing and postage for *Washington Geology* from an always-tight budget. Help us use our resources well by letting us know if you no longer wish to receive this 'journal'. We will take your name off the list immediately.

The Metal Mining Industry of Washington in 1994

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904 W. Riverside, Room 209, Spokane, WA 99201-1011

INTRODUCTION

All known metallic mineral production in Washington in 1994 was of precious metals, gold and silver. However, some base metals may have been recovered as by-products from ores shipped principally for their precious-metal content. Slightly more gold and silver were produced in Washington State in 1994 than in 1993—232,000 oz of gold and 507,000 oz of silver in 1994 compared to just under 230,000 oz of gold and 460,000 oz of silver in 1993 (Fig. 1). The estimated value of the precious metals produced in Washington in 1994 was $91.6 million compared to $84.8 million (estimated) in 1993. The increased value is attributed to higher metal prices and more gold and silver produced in 1994.

Major changes occurred in Washington's precious-metals mining industry late in 1994—the Cannon and Golden Promise mines were closed. The planned shutdown of the Cannon mine at Wenatchee took place in mid-December following depletion of reserves. During its peak years of operation, the Cannon mine employed approximately 200 workers with an annual payroll (including fringe benefits) of about $8,000,000. Employment dropped to about 150 workers as the planned closure date approached. Hecla Mining Co. closed its mill at Republic in February 1995 when low-grade ore processing was completed. A total of 87 workers at the Hecla facilities were affected by these changes; the effects were somewhat softened as 15 miners were hired by Echo Bay Mining Co. at the nearby Lamefoot deposit.

As in 1993, exploration for precious metals in Washington State continued to decrease. Most of the exploration centered around known producing gold mines near Wenatchee and Republic or in rocks similar to those hosting mineralization at the producing mines. Resource Finance Corp. continued as the major player in exploration for base metals (lead and zinc) with its continued work at the Pend Oreille mine. There was little reported exploration for volcanogenic massive sulfide-type or porphyry-type deposits.

According to figures compiled by the Washington State Employment Security Department for Standard Industrial Classification code 10 (metal mining), an average of 673 workers were employed in metal mining industries in 1993 (the last year for which data are available) compared to 851 workers employed in 1992. Of that total, 470 and 578 were employed in the sub-category gold ores (Fig. 2) in 1993 and 1992 respectively. This decrease is attributed to the closing of the Overlook mine at Republic and to decreasing numbers employed at the Cannon mine at Wenatchee. Although the figures for employment are available only through 1993, they do correspond to gold production (Fig. 1). The corresponding earnings of workers mining gold ores do *not* decrease. From 1986 through 1993, average wages in the gold mining industry rose steadily from just over $30,000 per year to over $50,000 per year (Fig. 3). (These numbers are not adjusted for inflation.)

Table 1 summarizes mining and mineral exploration activities in Washington for 1994. Numbers following deposit

ERRATUM: The first sentence last year's report "Washington's Mineral Industry—1993", p. 3 in *Washington Geology*, v. 22, no. 1 should read: Nonfuel mineral production is Washington State during 1993 had an estimated value of $480.4 million.

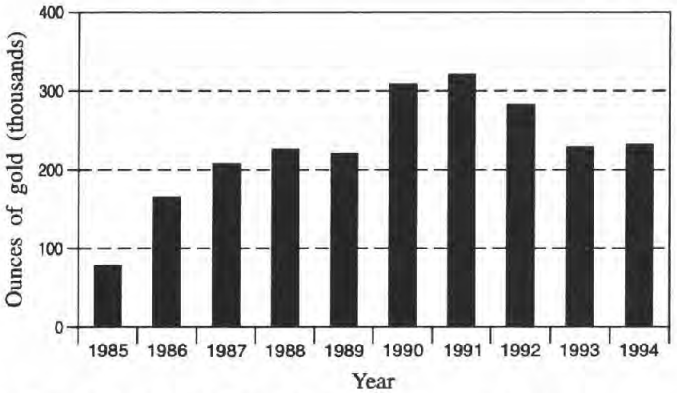

Figure 1. Gold production in Washington, 1985–1994.

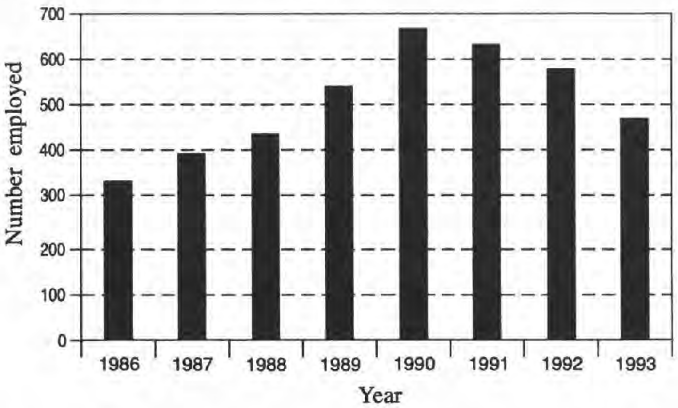

Figure 2. Average number of workers mining gold, 1986–1993. (Data from Washington State Employment Security Department.)

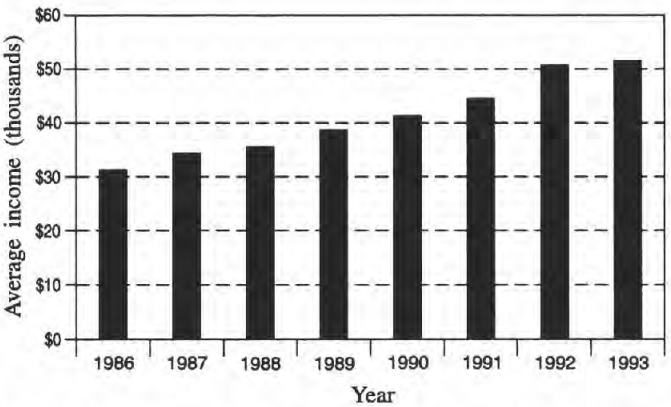

Figure 3. Average income of individuals mining gold, 1986–1993. (Data from Washington State Employment Security Department.)

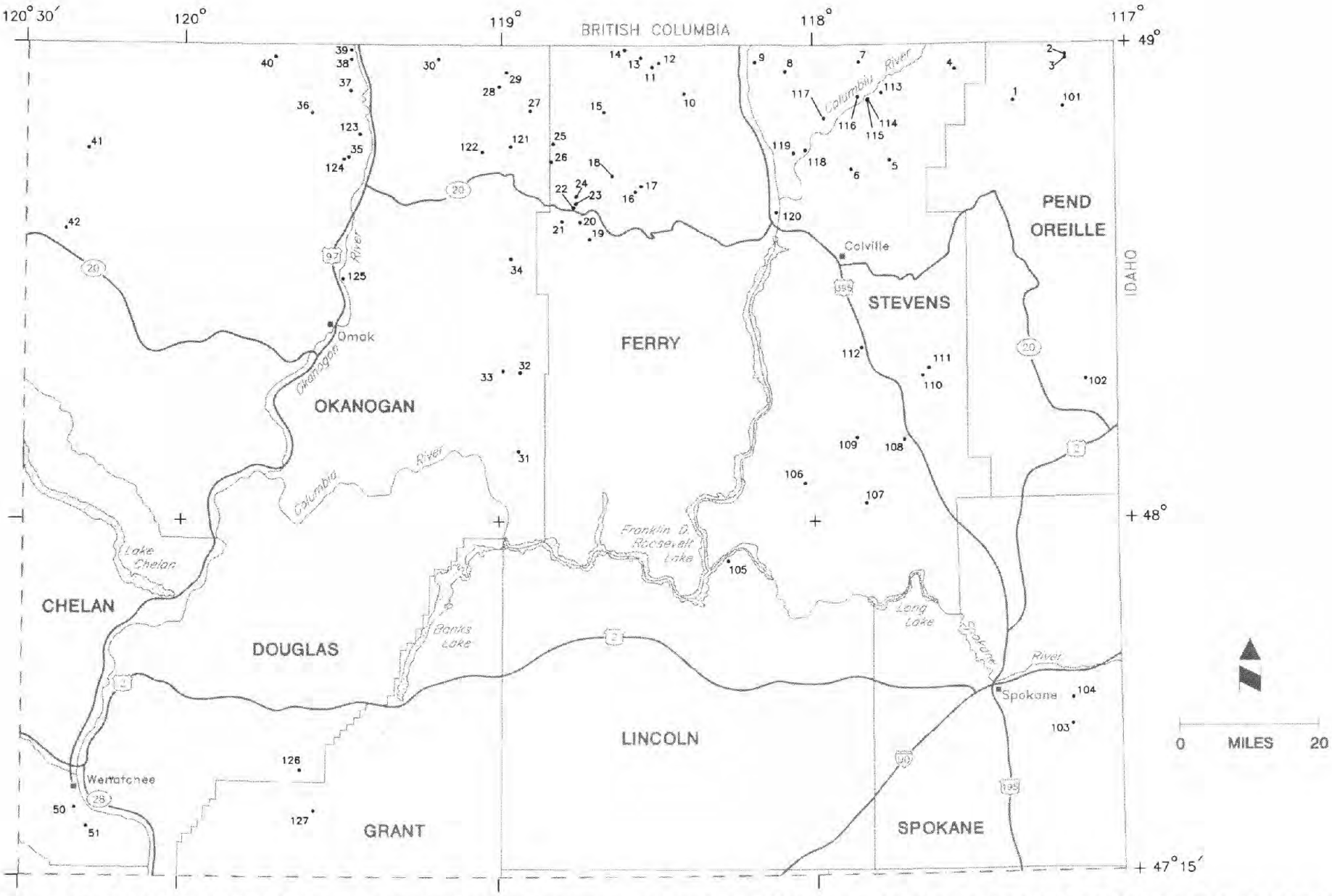

Figure 4A. Location of properties at which mineral exploration, development, or mining took place in 1994 in northeast Washington. See Table 1 for more information about each of these locations.

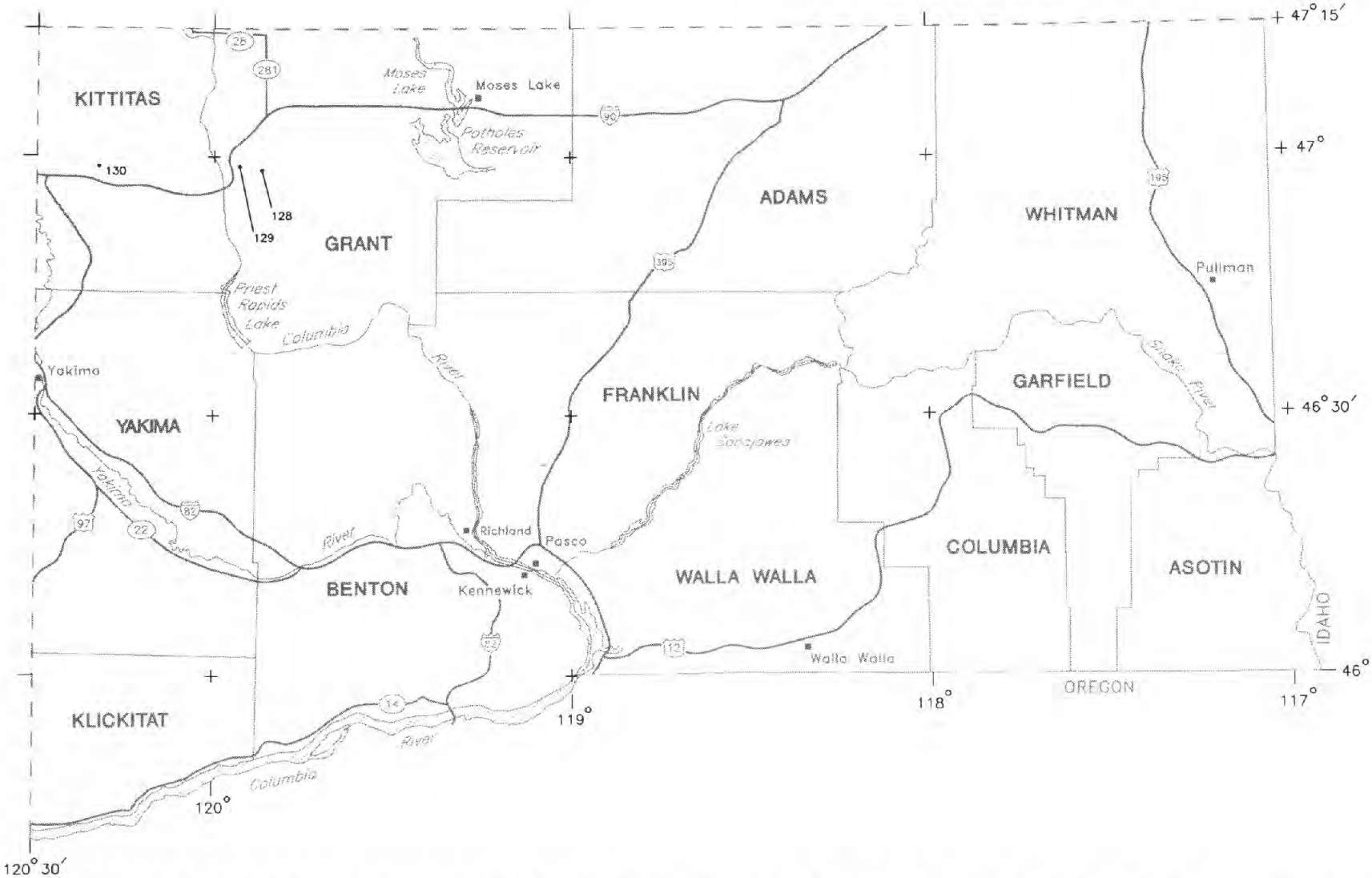

Figure 4B. Location of properties at which mineral exploration, development, or mining took place in 1994 in southeast Washington. See Table 1 for more information about each of these locations.

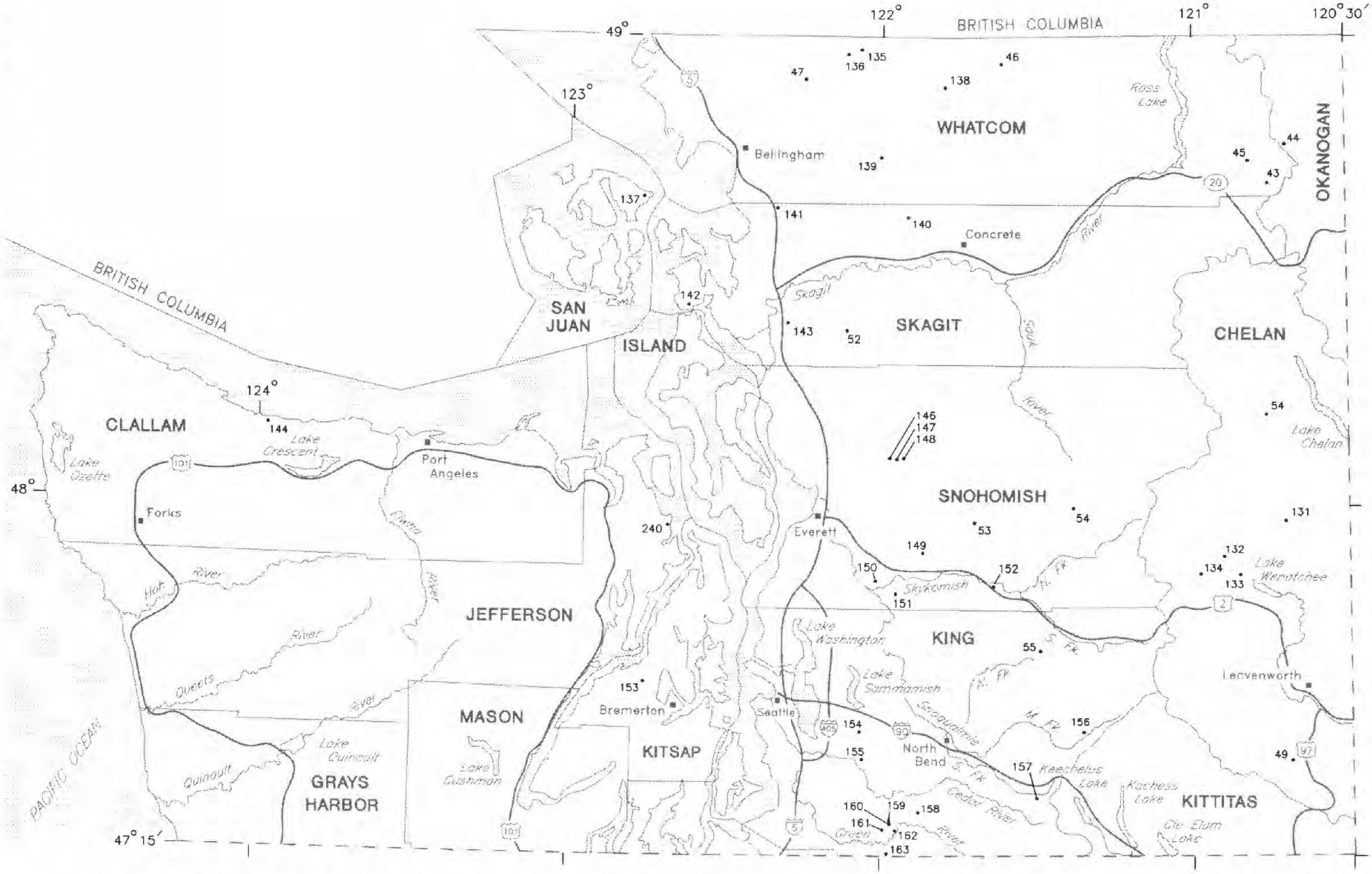

Figure 4C. Location of properties at which mineral exploration, development, or mining took place in 1994 in northwest Washington. See Table 1 for more information about each of these locations.

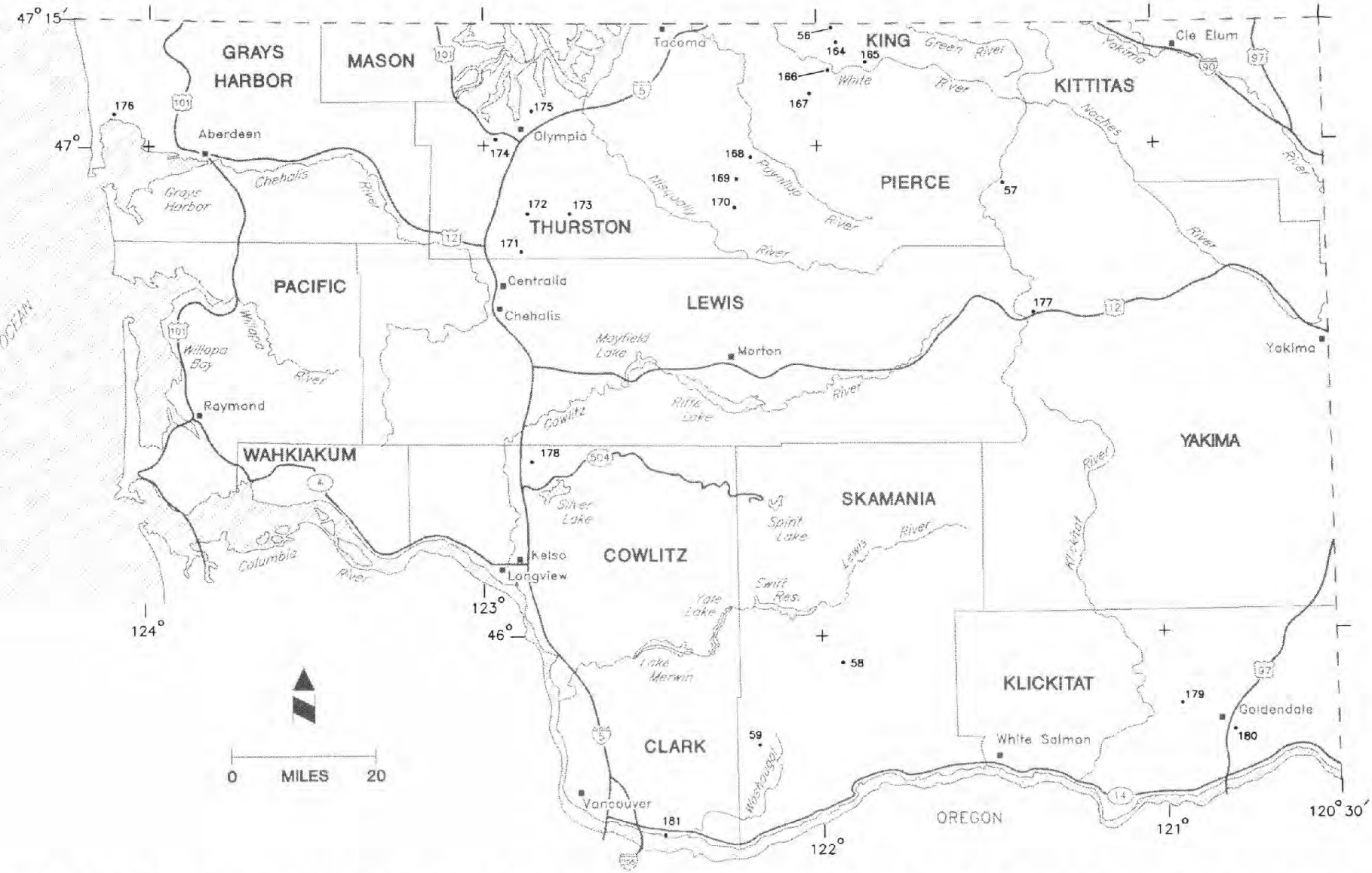

Figure 4D. Location of properties at which mineral exploration, development, or mining took place in 1994 in southwest Washington. See Table 1 for more information about each of these locations.

Table 1. Mining and mineral exploration in Washington, 1994. Property/project name is supplied by the company responding to the questionnaire. Order of entry is generally from the northeast to southwest; location numbers are keyed to Figures 4A through 4D. Entries 1–59 are base and precious metal properties; entries 101–181 are sites of industrial mineral activity

Loc no.	Property	Location	County	Commodity	Company	Activity	Area geology
BASE AND PRECIOUS METALS							
1	Pend Oreille mine	secs. 10-11, 14-15, 39N, 43E	Pend Oreille	Zn, Pb, Ag, Cd	Resource Finance Corp.	Driving exploration drift as access for additional underground drilling	Mississippi Valley-type mineralization in the Yellowhead zone of the Cambrian–Ordovician Metaline Formation
2	Lead Hill	secs. 11-14, 22-23, 27, 40N, 44E	Pend Oreille	Pb, Zn, Ag	Ramrod Gold USA, Inc.	Maintained property	Mississippi Valley-type mineralization in the Cambrian–Ordovician Metaline Formation
3	Lead Hill	secs. 11-14, 22-23, 27, 40N, 44E	Pend Oreille	Pb, Zn, Ag	Cominco American Resources Inc.	Drilling	Mississippi Valley-type mineralization in the Cambrian–Ordovician Metaline Formation
4	Iroquois	secs. 1, 19-20, 29-30, 40N, 42E	Stevens	Zn, Pb, Ag, Au	Mines Management, Inc.	Maintained property	Mineralization in a breccia zone in the Cambrian–Ordovician Metaline Formation
5	Van Stone mine	sec. 33, 38N, 40E	Stevens	Zn, Pb, Cd	Pan American Minerals Corp.	Maintained property, attempting to sell property	Mississippi Valley-type mineralization in the Cambrian–Ordovician Metaline Formation
6	Staghorn Mountain	sec. 3, 37N, 39E; sec. 34, 38N, 39E	Stevens	Cu, Zn, Pb, Ag, Au	Kennecott Exploration Co.	Geologic mapping, geophysics, drilling	Potential exhalative mineralization in Ordovician Ledbetter Slate
7	Ambrose Mining	sec. 16, 40N, 39E	Stevens	Au	A. Ambrose	Maintained property	Placer deposit
8	Cleta Group	secs. 22, 27, 40N, 37E	Stevens	Au, Ag, Cu	David Robbins and Associates	Geochemistry	Vein and replacement mineralization in sheared and contact-metamorphosed Permian Mount Roberts Formation
9	Uranwash 1-4 & New Indian Henry claims	sec. 13, 40N, 36E	Stevens	Au, Ag, Cu, Pb, Zn	Merle Loudon & Betty Sanstrom	Geochemistry	Vein-type mineralization in Jurassic metavolcanic rocks
10	Lone Ranch	unsurveyed, 39N, 35E	Ferry	Au, Ag	Platoro Inc.	Obtained property, staked additional claims	Gold-enriched sedimentary exhalative deposit in Permian metasedimentary rocks
11	Morning Star	sec. 16, 40N, 34E	Ferry	Au, Ag, Cu, W	Morse Bros.	Geophysics, drilling	Volcanogenic massive sulfide mineralization in Mesozoic accreted-terrane rocks
12	Irish	sec. 15, 40N, 34E	Ferry	Au	Johnson Explosives	Drilling	Gold mineralization in alkalic rocks of the Jurassic Shasket Creek complex
13	Gold Mountain	secs. 7-8, 40N, 34E	Ferry	Au, Ag, Cu	Gold Express Corp./ N. A. Degerstrom, Inc.	Maintained property	Gold-pyrite mineralization in an alkalic dike of the Jurassic Shasket Creek complex
14	Lone Star	sec. 2, 40N, 33E	Ferry	Au, Cu, Ag	BPG Resources, Inc., *subsidiary of* Britannia Gold	Maintained property, awaiting exploration permits	Disseminated and stockwork chalcopyrite and pyrite in Permian–Triassic greenstone, graywacke, argillite, and limestone
15	K-2	sec. 20, 39N, 33E	Ferry	Au, Ag	Echo Bay Minerals Co.	Baseline studies and drilling	Epithermal deposit in the Eocene Sanpoil Volcanics
16	Overlook mine	sec. 18, 37N, 34E	Ferry	Au, Ag	Echo Bay Minerals Co.	Underground mining	Gold mineralization associated with massive iron replacement/exhalative mineralization and stockwork of veinlets in Permian sedimentary rocks
17	Key deposits	sec. 18, 37N, 34E	Ferry	Au, Ag	Echo Bay Minerals Co.	Mined a small reserve by underground methods from Key west pit	Gold mineralization associated with massive iron replacement/exhalative mineralization in Permian sedimentary rocks

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
18	Lamefoot	secs. 4, 8, 37N, 33E	Ferry	Au, Ag	Echo Bay Minerals Co.	Commenced mining in December	Gold mineralization in massive iron replacement/ exhalative mineralization in Permian sedimentary rocks
19	Republic area state leases	Republic area	Ferry	Au, Ag	S. A. Jackson	Maintained leases	Epithermal mineralization in Eocene volcanic rocks of the Republic graben
20	Republic district properties	numerous secs., 36-37N, 32-33E	Ferry	Au, Ag	Hecla Mining Co.	Exploration on company-controlled properties	Epithermal mineralization in Eocene volcanic rocks of the Republic graben
21	Copper Lakes	secs. 3, 9-10, 14, 36N, 32E	Ferry	Au, Ag	Echo Bay Exploration Inc.	Geophysics, drilling	Vein-type mineralization in Permian–Triassic metasedimentary rocks
22	Seattle	secs. 33-34, 37N, 32E	Ferry	Au, Ag	Seattle Mine Partnership/Sunshine Valley Minerals, Inc.	Produced from several faces in the old mine; ore processed at Bow mill in Greenwood, BC; concentrate sent to Cominco smelter in Trail, BC	Epithermal deposit in the Eocene Sanpoil Volcanics
23	Republic Unit	secs. 27, 34-35, 37N, 32E	Ferry	Au, Ag	Hecla Mining Co.	Mining and milling scheduled to end in early 1995 as ore reserves of the Golden Promise deposit are depleted	Epithermal gold veins in dacite and andesite flows, flow breccias, tuffs, and tuff breccias of the Eocene Sanpoil Volcanics
24	South Penn	secs. 27-28, 37N, 32E	Ferry	Au, Ag	Crown Resources Corp./ Sutton Resources Inc.	Exploration	Epithermal deposit in Eocene Sanpoil Volcanics
25	Manhattan Mountain	secs. 7, 18, 38N, 32E	Ferry, Okanogan	Au, Ag, Cu, Pb, Zn, talc	Westmont Gold Inc., *subsidiary of* Ramrod Gold USA, Inc.	Maintained property	Epithermal gold in Eocene volcanic rocks of the Toroda Creek graben
26	Washington Silver (Silver Bell)	sec. 25, 38N, 31E	Okanogan	Au, Ag	Jopec Resources Ltd.	Maintained property	Epithermal mineralization in Eocene felsic volcanic rocks of the Toroda Creek graben
27	Ida	secs. 16, 21, 39N, 31E	Okanogan	Au, Ag, Cu	Crown Resources Corp.	Maintained property	Epithermal veins in the Eocene Sanpoil Volcanics and Klondike Mountain Formation of the Toroda Creek graben
28	Crystal	sec. 35, 40N, 30E	Okanogan	Au, Ag, Pb, Zn, Cu	Keystone Gold, Inc.	Maintained property	Skarn-type mineralization in the Permian Spectacle Formation intruded by Mesozoic rocks
29	Crown Jewel	sec. 24, 40N, 30E	Okanogan	Au, Cu, Ag, Fe	Battle Mountain Gold Corp./Crown Resources Corp.	Geotechnical studies, preparing draft EIS	Gold skarn mineralization in Permian or Triassic metasedimentary rocks adjacent to the Jurassic–Cretaceous(?) Buckhorn Mountain pluton
30	Molson Gold	numerous secs., 39-40N, 28-29E	Okanogan	Au, Ag	Crown Resources Corp.	Maintained property	Skarn- and epithermal-type mineralization in Permian to Triassic metasedimentary and meta-volcanic rocks intruded by Mesozoic granitic rocks
31	Agency Butte	secs. 31-32, 31N, 31E	Okanogan	Au, Ag	Santa Fe Pacific Gold Corp./Colville Confederated Tribes	Reconnaissance sampling and negotiating	Epithermal mineralization in the Eocene Sanpoil Volcanics
32	Strawberry Creek	secs. 28-33, 33N, 31E; secs. 4-5, 32N, 31E	Okanogan	Au, Ag	Santa Fe Pacific Mining, Inc./Santa Fe Pacific Gold Corp.	Reclaimed drill sites from 1993	Vein and disseminated mineralization in metamorphic rocks adjacent to Eocene intrusive rocks
33	Parmenter Creek	secs. 1, 12, 32N, 30E	Okanogan	Au, Ag	Colville Confederated Tribes	Detailed and reconnaissance geologic mapping, geochemistry, diamond drilling	Strata-bound or shear-zone mineralization in pre-Jurassic schist, gneiss, and quartzite

Table 1. Mining and mineral exploration in Washington, 1994 *(continued)*

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
34	Aeneas Valley property	sec. 8, 35N, 31E	Okanogan	Au, Ag, Cu, silica	Sunshine Valley Minerals, Inc.	Exploration/development	Possible gold mineralization associated with large quartz (high-grade quartz) bodies in probable Permian rocks
35	Lucky Knock	sec. 19, 38N, 27E	Okanogan	Au, Sb	Magill & Associates	Geochemistry, geologic mapping	Stibnite veinlets and disseminations in fractured and silicified limestone of the Permian Spectacle Formation
36	Palmer Mountain	secs. 20, 29, 39N, 26E	Okanogan	Cu, Au, Ag, Zn	Wilbur Hallauer	Reconnaissance geologic studies	Volcanogenic massive sulfide mineralization in the Permian–Triassic Palmer Mountain Greenstone
37	Blue Lake	sec. 5-6, 39N, 27E	Okanogan	Au, Ag	Wilbur Hallauer	Reconnaissance geologic studies	Gold anomalies found along margins of Permian–Triassic limestone
38	Hot Lake	secs. 7, 18, 40N, 27E	Okanogan	Au, Ag	Wilbur Hallauer	Maintained property	Low-grade gold mineralization adjacent to the Kelsey porphyry-type deposit
39	Kelsey	secs. 5-8, 40N, 27E	Okanogan	Cu, Mo, Ag, Au	Wilbur Hallauer	Maintained property	Porphyry-type mineralization in Jurassic–Cretaceous Silver Nail quartz diorite
40	Golden Zone	sec. 7, 40N, 25E	Okanogan	Au, Ag	El Bravo Gold Mining Ltd.	Maintained property	Vein or shear-zone Kobau Formation and Similkameen batholith
41	Billy Goat	sec. 15, 38N, 20E	Okanogan	Au, Cu, Ag	Sunshine Valley Minerals, Inc.	Maintained property	Stockwork in Cretaceous(?) andesite tuff and breccia
42	Mazama	secs. 17, 19-20, 36N, 20E	Okanogan	Au, Cu, Ag	Centurion Mines Corp.	Maintained property	Porphyry-type mineralization in fractures and in a breccia body of a Cretaceous stock
43	Azurite	sec. 30, 37N, 17E	Whatcom	Au, Ag, Cu, Pb	Double Dragon Exploration Inc.	Maintained property	Veins in sedimentary rocks of the Cretaceous Virginian Ridge Formation
44	New Light	sec. 27, 38N, 17E	Whatcom	Au, Ag	Western Gold Mining, Inc.	Maintained property	Quartz-carbonate-cemented slate-argillite breccia in the Lower Cretaceous Harts Pass Formation
45	Minnesota	sec. 2, 37N, 16E	Whatcom	Au, Ag, Cu	Seattle–St. Louis Mining Co.	Geologic mapping, maintenance and rehabilitation of old adits, limited exploration	Quartz veins in argillite and feldspathic sandstone of Lower Cretaceous Harts Pass Formation
46	Lone Jack	secs. 22-23, 40N, 9E	Whatcom	Au, Ag	Diversified Development Co.	Mining, shipped ore to East Helena, MT	Quartz veins in metasedimentary rocks
47	South Pass Nickel	sec. 2, 39N, 4E; sec. 35, 40N, 4E	Whatcom	Ni, Co, Cr	Jackpine Mining Co., Inc.	Drilling, dropped property	Laterite developed in peridotite at the base of Eocene sedimentary rocks
48	Holden mine	secs. 18-19, 31N, 17E; secs. 12-13, 31N, 16E	Chelan	Cu, Au, Zn, Ag	Holden Village, Inc.	Evaluated condition of old haulage adit	Metamorphosed volcanogenic massive sulfide
49	Gold Bond	secs. 2-3, 22N, 17E	Chelan	Au	Gold Bond Mining Co.	Rehabilitating underground workings	Vein mineralization in rocks of the Ingalls ophiolite complex
50	Cannon mine	sec. 16, 22N, 20E	Chelan	Au, Ag	Asamera Minerals (U.S.) Inc.	Mining continued until mid-December when reserves were depleted and the mine was closed	Mineralization in altered (commonly silicified) zones in Eocene arkosic sandstone
51	Matthews	sec. 35, 22N, 20E	Chelan	Au, Ag	Ramrod Gold USA, Inc.	Drilling	Mineralization in altered (commonly silicified) zones in Eocene arkosic sandstone.

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
52	Skagit Copper	secs. 1-3, 33N, 5E	Skagit	Cu, Zn, Au, Ag, Pb	Cannon Minerals	Discovered new zinc-rich zone on property	Massive sulfide mineralization in accreted-terrane (melange?) rocks
53	Lockwood	secs. 25, 30-32, 29N, 9E	Snohomish	Cu, Au, Zn, Ag	Island Arc Resources Corp./Formosa Resources Corp.	Maintained property	Kuroko-type volcanogenic massive sulfide mineralization in Jurassic volcanic rocks of the Western melange belt
54	Philo	secs. 22-23, 29N, 11E (unsurveyed)	Snohomish	Au, Ag, Cu	Alberg and Associates, Inc.	Applying for permits	Mineralized fracture zone
55	Apex - Damon	sec. 34, 26N, 10E	King	Au, Ag, Cu, Pb	CSS Management Corp.	Mining and milling	Quartz vein in granodiorite of the Miocene Snoqualmie batholith
56	Weyerhaeuser properties	Cascades area	Cowlitz, King, Lewis, Pierce, Thurston	Au, Ag, Cu, Mo, Pb, Zn, clay, silica	Weyerhaeuser Co.	Evaluation of minerals on company lands	Cascades province and adjacent volcanic, volcaniclastic, and intrusive rocks
57	Morse Creek	sec. 31, 17N, 11E	Yakima	Au, Ag	Ardic Exploration & Development, Ltd.	Maintained property	Tuffs of the Oligocene Ohanapecosh Formation
58	Wind River	sec. 9, 5N, 7E	Skamania	Au, Ag	DeLano Wind River Mining Co.	Preparing to mine	Epithermal mineralization in Oligocene–Miocene volcanic rocks
59	Silver Star	secs. 3-5, 8-9, 3N, 5E	Skamania	Cu, Ag, Au, Mo	Kinross Gold USA, Inc.	Maintained property	Tourmaline-bearing breccia pipe associated with porphyritic phases of the Miocene Silver Star pluton
INDUSTRIAL MINERALS							
101	Totem talc	secs. 23, 25-26, 39N, 44E	Pend Oreille	talc	First Miss Gold Inc./ United Catalysts Inc.	Maintained property	Talc along a high-angle fault in altered dolomites of the Proterozoic Z Monk Formation (Windermere Group)
102	No Name quarry	secs. 8, 9, 32N, 45E	Pend Oreille	decorative stone	Northwest Stone, Inc.	'Harvesting' talus	Meta-argillite in the Proterozoic Y Prichard Formation of the Belt Supergroup
103	Mica mine	sec. 14, 24N, 44E	Spokane	clay	Mutual Materials Co.	Reclamation and development work toward production of new reserves; no new mining at the Mica mine, Fruin property (sec. 33, 24N, 45E), or Pottratz pit (sec. 7, 21N, 45E); production of bricks	Lacustrine clay of the Miocene Latah Formation overlying saprolitic, pre-Tertiary felsic gneiss and locally underlying silty clay of the Pleistocene Palouse Formation
104	Somers clay pit	sec. 35, 25N, 44E	Spokane	clay	Quarry Tile Co.	Using stockpiled clay	Lacustrine clay of the Miocene Latah Formation overlain by silty clay of the Pleistocene Palouse Formation
105	Blue Silver quarry	sec. 21, 28N, 36E	Lincoln	dolomite	New lessee	Idle	Dolomite of the Cambrian–Ordovician Metaline Formation
106	Allan prospect	sec. 28?, 30N, 38E	Stevens	barite	Byron Boggs/Al Matovich	Property evaluation	Barite veins in Proterozoic Y metasedimentary argillite, dolomite, and quartzite of the Deer Trail Group
107	Gehrke quarry	sec. 2, 29N, 39E	Stevens	dolomite	Allied Minerals Inc.	Mining, milling	Isolated pod of Proterozoic Y Stensgar Dolomite(?) (Deer Trail Group)

Table 1. Mining and mineral exploration in Washington, 1994 *(continued)*

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
108	Nine quarries		Stevens	dolomite	Nanome Aggregates, Inc.	Mining, milling	Uniquely colored dolomite or dolomitic marble mined at nine sites in Stevens County: China White, Black, Lolo Martin, Primavera/Sage Green, Cream, Rose/Red, Grey/Chartreuse, Botte, and Watermary
109	Lane Mountain quarry	secs. 22, 34, 31N, 39E	Stevens	silica	Lane Mountain Silica Co. (*division of* Hemphill Brothers, Inc.)	Mining, milling	Cambrian Addy Quartzite
110	Chewelah Eagle quarry	sec. 5, 32N, 41E	Stevens	dolomite	Chewelah Eagle Mining Co.	Mining by Nanome Aggregates for their Sunlit White product	Devonian–Carboniferous(?) metacarbonate rocks
111	Eagle barite	sec. 33, 33N, 41E	Stevens	barite	Lovejoy Mining	Maintained property	Massive to brecciated barite veins in sheared argillite of the Proterozoic Y Striped Peak Formation (Belt Supergroup)
112	Addy dolomite quarry	secs. 13-14, 33N, 39E	Stevens	dolomite	Northwest Alloys, Inc.	Mining, production of magnesium metal	Dolomite of the Cambrian–Ordovician Metaline Formation
113	Sherve quarry	sec. 8, 39N, 40E	Stevens	limestone	Northport Limestone Co. (*division of* Hemphill Brothers, Inc.)	Mining, milling	Limestone in the upper unit of the Cambrian–Ordovician Metaline Formation
114	Janni limestone quarry	sec. 13, 39N, 39E	Stevens	limestone	Peter Janni and Sons	Leased to Pluess-Staufer Industries, Inc.	Reeves Limestone Member of the Cambrian Maitlen Phyllite
115	Joe Janni limestone deposit	sec. 13, 39N, 39E	Stevens	limestone	Joe Janni	Leased to Columbia River Carbonates	Reeves Limestone Member of the Cambrian Maitlen Phyllite
116	Flagstaff Mountain	secs. 4, 9, 39N, 39E	Stevens	barite	Mountain Minerals Co. Ltd. *dba* Mountain Minerals Northwest	Reviewing and ranking all barite properties	Massive bedded barite in the Devonian–Carboniferous Flagstaff Mountain sequence
117	Whitestone quarry	sec. 34, 39N, 38E	Stevens	decorative stone	Whitestone Co.	Mining	Recrystallized limestone (marble) in the Cambrian Maitlen Phyllite
118	Northwest marble mine; other quarries	sec. 19, 38N, 38E	Stevens	dolomite	Northwest Marble Products Co.	Mining, milling	Dolomite of the Cambrian–Ordovician Metaline Formation; additional colored dolomite products are quarried at several locations
119	Moonlight quarry	sec. 24, 38N, 37E	Stevens	decorative stone	Whitestone Co.	Mining	Dolomite
120	Kifer quarry	sec. 2, 36N, 37E	Ferry	decorative stone	Raymond Fosback Masonry	Mining	Foliated and lineated, thin bedded, white to light-brown, micaceous quartzite forming a belt along the eastern margin of the Kettle metamorphic core complex
121	Wauconda quarry	sec. 13, 38N, 30E	Okanogan	limestone	Columbia River Carbonates	Mining, milling	High-calcium, pre-Tertiary white marble lenses in mica schist, calc-silicate rocks, and hornfels
122	Bonaparte Meadows peat	sec. 20, 38N, 30E	Okanogan	peat moss	The Bonaparte Co.	Mining	*Hypnum* moss in a peat bog south of Bonaparte Lake
123	Poison Lake	secs. 4-5, 38N, 27E	Okanogan	gypsite	Agro Minerals, Inc.	Mining	Evaporitic lake in a small basin at the convergence of several ravines dammed by glacial deposits

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
124	Tonasket limestone quarry	sec. 25, 38N, 26E	Okanogan	limestone	Pacific Calcium, Inc.	Mining, milling	Metacarbonate rocks in the conglomerate-bearing member of the Permian Spectacle Formation (Anarchist Group)
125	Brown quarry	sec. 26, 35N, 26E	Okanogan	dolomite	Pacific Calcium, Inc.	Mining	Metadolomite member of the Triassic Cave Mountain Formation
126	Volcanic mine	sec. 13, 23N, 25E	Douglas	clay	Basic Resources Corp.	Final mine permitting for mid-1995 start-up	Calcium bentonite clay interbeds in the Miocene Columbia River Basalt Group near Moses Coulee
127	Rock Top	sec. 20, 22N, 26E	Grant	clay	Basic Resources Corp.	Geologic mapping, drilling	Montmorillonite-group clays (bentonite) as interbeds in the Columbia River Basalt Group
128	Sec. 7 pit	sec. 7, 17N, 24E	Grant	diatomite	Celite Corp.	Mining, milling	Miocene 'Quincy Diatomite Bed', a sedimentary interbed occurring locally at the base of the Priest Rapids Member (Columbia River Basalt Group)
129	Sec. 3/10 pit	secs. 3, 10, 17N, 23E	Grant	diatomite	Celite Corp.	Mining, milling	Miocene 'Quincy Diatomite Bed', a sedimentary interbed occurring locally at the base of the Priest Rapids Member (Columbia River Basalt Group)
130	Shale pit	sec. 10, 17N, 20E	Kittitas	clay	Western Resources Company	Permitting	Continental sedimentary deposits that occur between flows of the Columbia River Basalt Group
131	Chikamin quarry	sec. 22, 29N, 17E	Chelan	decorative stone	Joe Mahaffee	Mining	Extensive deposits of Glacier Peak pumice
132	Sears Creek	sec. 32, 28N, 16E	Chelan	soapstone	Ben Barke	Development work	Serpentinized peridotite and metaperidotite
133	Two Rivers quarry	sec. 15, 27N, 16E	Chelan	decorative stone, rockery	Two Rivers Sand and Gravel	Mining	Fine-grained to pegmatitic tonalite and granodiorite gneiss
134	Nason Ridge	secs. 10, 14-15, 27N, 15E	Chelan	marble	ECC International (English China Clay)	Maintained property	Podiform bodies of high-calcium, high-brightness marble in pegmatitic tonalite and tonalite gneiss of the Chelan complex
135	Maple Falls quarry	secs. 7, 18, 40N, 6E	Whatcom	limestone	Clauson Lime Co.	Mining	Sheared, jointed Lower Pennsylvanian limestone overlain by sheared argillite and underlain by argillite, graywacke, and volcanic breccia of the Chilliwack Group
136	Kendall quarry	secs. 14-16, 22-23, 40N, 5E	Whatcom	limestone	Tilbury Cement Co.	Mining	Lower Pennsylvanian limestone
137	Pt. Lawrence	sec. 25, 37N, 1W	San Juan	limestone, sandstone	Alberg and Associates, Inc.	Permitting	Pre-Devonian basement complex?
138	Wells Creek quarry	sec. 5, 39N, 8E	Whatcom	decorative stone	Frank Pullar	Mining	Bluish-green andesite marketed as 'Shuksan Stone'
139	Swen Larsen quarry	sec. 34, 38N, 6E	Whatcom	olivine	Olivine Corp.	Mining, milling, production of olivine (refractory) incineration systems	A portion of the 36-mi^2 outcrop area of the Twin Sisters dunite, Whatcom and Skagit Counties
140	Hamilton plant	sec. 17, 36N, 7E	Skagit	olivine	Unimin Corp.	Milling, production of olivine products	Twin Sisters dunite
141	Whatcom and Skagit quarry	sec. 6, 36N, 4E	Skagit	decorative stone	Whatcom Skagit Quarry	Mining	Darrington Phyllite
142	unnamed quarry	sec. 13, 34N, 1E	Skagit	decorative stone	Island Frontier Landscape Construction Co.	Idle	Andesite
143	Pacific quarry	sec. 33, 34N, 4E	Skagit	rockery	Meridian Aggregates Inc.	Mining	Diorite

Table 1. Mining and mineral exploration in Washington, 1994 *(continued)*

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
144	Twin River quarry	secs. 22-23, 31N, 10W	Clallam	clay	Holnam Ideal, Inc.	Mining	Mudstone(?) in three members of the upper Eocene to lower Miocene Twin Rivers Formation
145	Mats Mats quarry	sec. 33, 29N, 1E	Jefferson	rockery	General Construction Co.	Mining	Eocene basalt of the Crescent Formation
146	Mandan quarry	sec. 12, 30N, 6E	Snohomish	rockery	Universal Land Construction Co.	Mining	Basalt
147	Iron Mountain quarry	sec. 17, 30N, 7E	Snohomish	rockery	Iron Mountain Quarry	Mining	Andesite
148	Granite Falls quarry	sec. 8, 30N, 7E	Snohomish	rockery	Meridian Aggregates Inc.	Mining	Andesite
149	AAA Diorite quarry	sec. 23, 28N, 7E	Snohomish	rockery	AAA Monroe Rock Corp.	Mining	Diorite
150	Monroe Rock quarry	sec. 10, 27N, 6E	Snohomish	rockery	AAA Monroe Rock Corp.	Mining	Basalt
151	Cadman Rock quarry	sec. 19, 27N, 7E	Snohomish	rockery	Cadman Rock Co. Inc.	Mining	Basalt
152	Miller Lime quarry	secs. 15-16, 27N, 9E	Snohomish	rockery	Alpine Rockeries Inc.	Mining	Lenticular beds of folded and faulted, Late Jurassic or Early Cretaceous fossiliferous limestone interbedded with graywacke, argillite, and volcanic rocks
153	Newberry Hill peat	sec. 26, 24N, 1W	Kitsap	peat moss	Asbury's Topsoil	Mining	Bog contains peat, humus, *Sphagnum* moss, and clay, to which sandy loam is added for a topsoil product
154	Sec. 31 pit	sec. 31, 24N, 6E	King	shale	Mutual Materials Co.	Mining	Shale and sandstone of the Eocene Puget Group
155	Pinnacle–Cedar Mountain	sec. 29, 23N, 6E	King	sandstone, expandable shale	Alberg and Associates, Inc.	Permitting	Upper Eocene Renton Formation of the Puget Group
156	Spruce claim	secs. 29, 30, 24N, 11E	King	crystals	Robert Jackson	Mining, guided mineral-collecting field trips	Quartz and pyrite crystals in large, open voids along faulted mega-breccia in the northern phase granodiorite and tonalite (25 Ma) of the Snoqualmie batholith
157	Marenakos Rock Center	various	various	decorative stone	Marenakos	Mining	Granitic talus and round rock, rhyolite, and columnar basalt
158	Elk pit	sec. 34, 22N, 7E	King	shale	Mutual Materials Co.	Mining	Illite- and kaolinite-bearing shales of the Eocene Puget Group
159	Ravensdale pit	sec. 1, 21N, 6E	King	silica	Reserve Silica Corp.	Mining, washing	Sandstone of the Eocene Puget Group
160	John Henry No. 1	sec. 12, 21N, 6E	King	clay	Pacific Coast Coal Co.	Mining	Upper middle Eocene silty clay near the base of the Puget Group comprising a 30-ft-thick zone above the Franklin No. 9 coal seam
161	Mine 11	sec. 11, 21N, 6E	King	decorative stone	Palmer Coking Coal Co.	Drawing from stockpile	Cinders accidentally produced when stockpiles of inferior-quality coal and slag (shale, sandstone, clay) underwent spontaneous combustion and smoldered for years at temperatures exceeding 2,000°F, thereby producing 'nature's brick'

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
162	Franklin Rock quarry	sec. 18, 21N, 7E	King	decorative stone	Palmer Coking Coal Co.	Mining	Andesite
163	Enumclaw quarry	sec. 1, 20N, 6E	King	rockery	Enumclaw Quarry Inc.	Mining	Andesite flows as interbeds in volcanic breccia and sandstone
164	410 quarry	sec. 20, 20N, 7E	King	rockery	410 Quarry Inc.	Mining	Miocene andesite flows
165	Superior quarry	sec. 1, 19N, 7E	King	silica	Ash Grove Cement Co.	Mining, milling	Silica cap in hydrothermally altered Miocene andesites on a caldera margin
166	Buckley quarry	sec. 7, 19N, 7E	Pierce	rockery	Washington Rock Quarries Inc.	Mining	Miocene andesite
167	Wilkeson quarry	sec. 27, 19N, 6E	Pierce	rockery; dimension stone	Rockeries Inc.; Marenakos	Mining	Fluvial sandstone (Wilkeson sandstone) of the Carbonado Formation in the Puget Group
168	Kapowsin quarry	sec. 8, 17N, 5E	Pierce	rockery	Washington Rock Quarries Inc.	Mining	Oligocene–Miocene intrusive andesite
169	Clay City pit	sec. 25, 17N, 4E	Pierce	clay	Mutual Materials Co.	Using stockpiled clay, shutdown adjacent Clay City brick plant	Oligocene–Miocene kaolin-bearing, altered andesite
170	Lynch Creek quarry	sec. 13, 16N, 4E	Pierce	rockery	Randles Sand and Gravel Inc.	Mining	Eocene–Oligocene andesite flows
171	Bucoda pit	sec. 14, 15N, 2W	Thurston	clay	Mutual Materials Co.	Mining	Glacial clay of the Pliocene–Pleistocene Logan Hill Formation overlying silty clay of the Eocene Skookumchuck Formation
172	Hercules quarry	sec. 37, 16N, 1W	Thurston	decorative stone	Northwest Stone Inc.	Mining	Middle to upper Eocene marine sedimentary rocks (Tenino sandstone) assigned to the top of the McIntosh Formation
173	Johnson Creek	sec. 24, 16N, 1W	Thurston	rockery	Sea Tac Rock Co.	Mining	Andesite of the Eocene Northcraft Formation
174	Jones quarry	sec. 29, 18N, 2W	Thurston	rockery, decorative stone	Jones Quarry	Mining	Basalt of the Eocene Crescent Formation, informally known as the Black Hills basalt
175	Olympic peat	sec. 7, 18N, 1W	Thurston	peat	Olympic Peat and Soils	Idle?	Peat deposits
176	North Bay peat	sec. 13, 18N, 12E	Grays Harbor	peat moss	Ocean Farms and Soils	Mining	*Sphagnum* moss produced as a component for top-soil product
177	Snow Queen quarry	sec. 36, 14N, 11E	Yakima	decorative stone	Heatherstone Inc.	Mining	Quaternary andesite flows
178	Castle Rock Clay pit	sec. 18, 10N, 1W	Cowlitz	clay	Ash Grove Cement Co.	Mining	Eocene–Oligocene nearshore sedimentary rocks
179	Blockhouse quarry	secs. 5, 8-9, 4N, 15E	Klickitat	decorative stone	D. M. Layman Inc.	Mining	Pliocene–Quaternary scoriaceous basalt (cinder)
180	Red Rock quarry	sec. 27, 4N, 16E	Klickitat	decorative stone	Bishop Red Rock Inc.	Mining	Near-vent scoriaceous Pliocene–Quaternary basalt (cinder)
181	Fisher quarry	sec. 8, 1N, 3E	Clark	decorative stone	Gilbert Western Corp.	Mining	Pliocene–Quaternary andesite flows

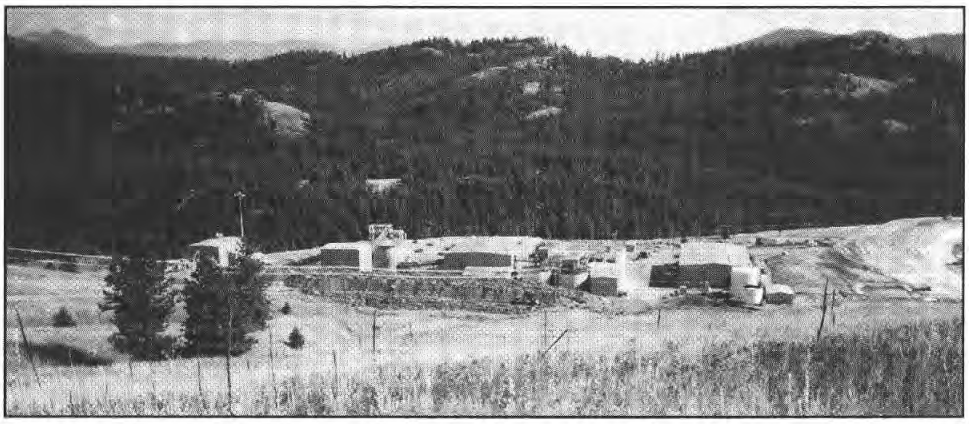

Figure 5. Echo Bay Minerals Co. opened the Kettle River Project mill at Republic in 1989 to process ore from their mines in the area. Through 1994, the mill has processed 2,924,759 tons of ore and recovered 403,671 oz of gold.

names in this text are keyed to the deposits listed in Table 1 and their locations on Figures 4A–D. Metal mines and exploration projects have numbers under 100. The majority of this volunteered information was obtained from an annual survey of mining companies and individuals. Table 1 lists only those companies that returned questionnaires. It is not a complete listing of mineral activities.

As in 1993, many companies and individuals reported maintaining properties, but with little expenditure beyond that required to maintain the property.

Additional details about the geology of the metallic mineral deposits and comparisons of activities in previous years in the state are available in reviews of Washington's mineral industry for 1991 through 1993 by Derkey and Gulick (1992) and Derkey (1993; 1994). Questions about metal mining activities and exploration can be referred to Bob Derkey in the Division's Spokane office.

PRECIOUS METALS

The Cannon mine (no. 50) at Wenatchee, in its final year of operation, maintained its position as Washington's largest gold producer. The operation was a joint venture between Asamera Minerals (U.S.) Inc. (as operator) and Breakwater Resources Ltd. The last blast at the mine was on December 17, and the last ore was hoisted to surface on December 22. During its final year of operation, this epithermal-type deposit produced 125,370 oz of gold and 213,497 oz of silver from 393,461 tons of ore. The head grade of ore shipped to the mill averaged 0.340 oz per ton for gold and 0.631 oz per ton for silver. The increased gold production (relative to 105,477 oz of gold produced in 1993) is attributed to higher grade ore from pillars that had been left as supports and was mined as the company retreated from more distant parts of the mine. Many of the pillars were adjacent to faults that may have been feeders for the mineralizing solutions. From 1985 through 1994, the Cannon mine produced more than 1.25 million oz of gold and 2 million oz of silver from a total of 4,133,101 dry tonnes of ore. (See also review of the history of the Cannon mine, p. 21).

Hecla Mining Co.'s Republic Unit (no. 23) mined 120,165 tons of ore in 1994. The Golden Promise mine (cover photo) was closed on January 2, 1995. The mill operated until mid-February when processing of gold ores was completed. Cleanup of the mill is expected to be completed by early April, when the mill will be mothballed. Head grades were 0.36 oz per ton for gold and 2.89 oz per ton for silver. Gold and silver production were 39,085 oz and 283,326 oz, respectively, in 1994. Despite dwindling ore reserves, the company operated its mill at Republic at full production capacity of 325 tons per day in 1994. Hecla continues to explore on its extensive holdings in the Republic area.

Seattle Mine Partnership/Sunshine Valley Minerals, Inc. produced gold ore from several faces in the Seattle mine (no. 22) at Republic. Their ore was processed at the Bow mill in Greenwood, BC, and the concentrate was sent to the Cominco smelter at Trail, BC.

Echo Bay Minerals Co.'s Kettle River Project at Republic produced 66,782 oz of gold and approximately 10,500 oz of silver in 1994 from 523,400 tons of ore processed in its mill near Republic (Fig. 5). The head grade was 0.149 oz of gold per ton, and recovery was 85.6 percent.

Ore for Echo Bay Minerals operations was mined from the exhalative/replacement-type Key, Overlook, and Lamefoot deposits. The Lamefoot deposit (no. 18) was the new star in gold mining in Washington in 1994. Mining there began in early December of 1994, following receipt of permits to mine in late November. This deposit is expected to be the mainstay of Kettle River project operations for several years. Proven and probable ore reserves are 1,640,300 tons at 0.190 oz of gold per ton (312,000 oz of contained gold). An additional possible ore reserve includes 1,327,600 tons at 0.176 oz of gold per ton (234,000 oz of contained gold). The company will be updating these reserve values in March of 1995.

Open-pit mining of the Key deposits (no. 17) was completed in 1993. Underground mining of a small reserve from the Key deposit west pit (Fig. 6) began in August and was completed in November of 1994. This reserve produced a total of 40,000 tons of ore at a grade of 0.179 oz per ton gold.

Echo Bay Minerals reopened the Overlook mine (no. 16) in 1994 and produced ore for their mill near the mine. Plans are to complete mining of the remaining reserves at the Overlook in 1995.

On February 1, Echo Bay initiated site preparation at the K-2 deposit (no. 15) on an exploratory drift to confirm reserves calculated from drilling. The announced (possible) reserve at this epithermal-type deposit in Eocene rocks of the Republic graben is 631,000 tons of 0.20 oz per ton gold.

The only other known gold production in Washington was from the Lone Jack mine (no. 46), where mining is seasonal due to the high elevation of the deposit. About 1,000 tons of ore were shipped to a smelter in East Helena, MT.

The Crown Jewel deposit (no. 29), a Battle Mountain Gold (operator)/ Crown Resources joint venture, continued its efforts to obtain permits to mine the deposit. A draft environmental impact statement is expected at the end of 1995; this begins a period of review that can lead to preparation of a final environmental impact statement and issuance of permits to mine. Battle Mountain anticipates beginning construction for the mining operation in the spring of 1996; they expect mining

could start about 1 year after construction begins. Announced reserves at the Crown Jewel deposit are 8.7 million tons of ore at a grade of 0.186 oz of gold per ton, or more than 1.6 million oz of gold. For the state of Washington, the gold estimated to be contained in the Crown Jewel deposit is second in amount only to that mined at the combined deposits of the Republic Unit of Hecla Mining Co.

Exploration and property maintenance continued at numerous sites for epithermal deposits, predominantly in Tertiary rocks of the Republic and Chiwaukum grabens. In addition to exploration by Hecla Mining Co. at its Republic holdings (no. 20), and Echo Bay Minerals Co. at their K-2 (no. 15) deposit, maintenance and exploration activities continued at the South Penn (no. 24), Manhattan Mountain (no. 25), Washington Silver (no. 26), Ida (no. 27), and Republic area state leases (no. 19), all properties in or near the Republic graben; at the Mathews (no. 51) in the Chiwaukum graben; at Agency Butte (no. 31) on the Colville Indian Reservation; and at the Wind River deposit (no. 58) in southwestern Washington.

Figure 6. In July 1994, Echo Bay Minerals Co. was preparing to go underground from the highwall of the Key west pit near Republic. The rocks above the planned portal location are being rock bolted for safety. Echo Bay mined the remaining reserve of 40,000 tons in the Key west deposit in 1994.

Copper Lakes (no. 21) was the only project/property reporting exploration for replacement/exhalative-type mineralization in the Republic graben.

Several companies worked on deposits at the north end of the Republic graben in or near rocks of the Shasket Creek alkalic complex. Owners/lessors were maintaining or attempting to sell their properties in that area: the Morning Star (no. 11), the Irish (no. 12), the Gold Mountain (no. 13), and the Lone Star (no. 14) deposits. The nearby Lone Ranch property (no. 10) is being explored as a gold-bearing, exhalative-type deposit in sedimentary rocks.

The Crystal (no. 28) and Molson gold (no. 30) were the only properties reported to be active or maintained that have potential for skarn-type gold mineralization near the Crown Jewel deposit.

A subdued exploration program was carried out at the Parmenter Creek (no. 33) and Strawberry Creek (no. 32) gold prospects on the Colville Indian Reservation.

BASE METALS

Resource Finance Inc. completed 1,500 ft of additional underground drifting at the Pend Oreille mine (no. 1) near Metaline Falls. The work will permit establishing additional drilling stations to test the potential for minable zinc deposits from zinc-rich ores of the 'Yellowhead horizon'. The company will decide whether or not to mine following completion of this drilling.

The status of the Van Stone mine (no. 5) in northern Stevens County was unclear following the acquisition of Equinox Resources Ltd. by Hecla Mining Co. in 1993. The mine, which had been producing zinc and lead concentrates in 1992 and early 1993, was not part of the acquisition, and it now is owned by Pan American Minerals Corp. The company is attempting to sell the mine and mill.

In addition to exploration for Mississippi Valley-type mineralization at Lead Hill (nos. 2,3) and at the Iroquois (no. 4), the Staghorn Mountain area (no. 6) was explored for base metals in rocks with potential for sedimentary exhalative mineralization.

Volcanogenic massive sulfide (VMS) deposit exploration decreased in 1994 following Rio Algom Exploration Inc.'s decision to drop the Lockwood deposit (no. 53) lease. Although it appears to be a large exhalative system, the complex nature of the Lockwood deposit combined with sparse exposures in the area made evaluation of the deposit difficult. More exploration in the area could lead to discovery of additional deposits, which are relatively common in similar rocks in British Columbia.

Exploratory work on other potential VMS-type deposits in Washington (nos. 36, 62) was limited to maintaining of property.

Some porphyry-type deposits, best known for their copper and molybdenum resource potential, were explored for associated gold and silver mineralization in recent years. However, in 1994, there was no reported activity on porphyry deposits in Washington. The only known expenditures were payments to maintain properties, including the Silver Star property (no. 59) and the Kelsey deposit (no. 39).

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The Industrial Mineral Industry of Washington in 1994

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The U.S. Bureau of Mines estimates that the total value of nonfuel mineral production (including gold, silver, zinc, lead, and the nonmetallics) rose approximately 9 percent over the 1993 level, from $505 million to $556 million. Nonmetallic commodities, including magnesium metal derived from dolomite but excluding precious and base metals, accounted for about 85 percent of the total value of nonfuel mineral production for Washington in 1994—$471 million. In descending order of production value, the state had substantive operations in sand and gravel, magnesium metal production, crushed stone, portland and masonry cement, lime, diatomite, silica sand, olivine, gemstones, clays, peat, dimension stone, and gypsite during the past year. A comprehensive list of industrial mineral operations (excluding aggregate producers unless they produced decorative stone or rockery) is presented in Table 1, nos. 101-181 (p. 11–15) and Figs. 4A–D (p. 4–7).

Washington's industrial mineral industries experienced few changes during 1994. One new clay operation is completing the permitting process. Several companies changed ownership, and several companies are conducting reviews of property holdings. If commodity economics are viable, new production activities in several nonmetallic commodities may occur in the future.

Aggregates

Aggregates continue to be the preeminent industrial mineral commodity in terms of value, volume, and numbers of producers. Because there are so many producers, accurate production statistics are difficult to derive. Private estimates of aggregate production suggest that 1994 was somewhat flat and particularly so in the Pacific Northwest and California. According to a survey reported in *Pit and Quarry* magazine (Drake, 1994), aggregate production throughout the west increased 5 percent in 1994. In contrast, the U.S. Bureau of Mines estimated that aggregate production in Washington increased about 12 percent. Whether the increase was modest or substantial, much of the health of the crushed stone and sand and gravel industries is tied to the Seattle economy, which has been stagnant. Light commercial and residential construction is down as a result of overbuilding, rising interest rates, and some antigrowth sentiment. Producers might see a modest 1 percent increase in production levels in 1995 if anticipated highway funding comes through (Turley and Prokopy, 1994).

Efforts to permit significant new sources of round rock aggregate (sand and gravel) were ongoing during 1994. A permit for plant construction and a multi-party settlement agreement on a barge loading facility have been secured for the Lone Star Northwest project at Dupont on Puget Sound south of Tacoma. This will replace Lone Star's nearby Steilacoom pit, which will be exhausted in 3 to 4 years. A final Environmental Impact Statement (EIS) is being prepared for Manke Lumber Co.'s Johns Prairie sand and gravel and barge loading facility project at Shelton in Mason County. Both these projects will be capable of barge-borne transportation. Associated Sand and Gravel continues efforts to replace dwindling reserves at Everett with a large deposit of both round rock and crushed stone in an 825-acre site at Granite Falls northeast of Everett. The final EIS has been prepared; however, traffic issues with the city of Granite Falls have yet to be resolved.

Magnesium

Magnesium metal produced from dolomite at Northwest Alloys Inc. plant at Addy (no. 112) was the second most valuable nonfuel mineral commodity produced in Washington during 1994, second only to sand and gravel. Northwest Alloys, a subsidiary of the Aluminum Corp. of America (ALCOA), is one of three U.S. companies that produced primary magnesium metal last year. Washington's plant is the only facility that produces the metal from dolomite using a thermal smelting process. Dow Chemical Co.'s plant in Freeport, Texas, and the Magnesium Corp. of America's (MAGCORP) plant at the Great Salt Lake in Utah both extract magnesium, from sea water and brines, respectively, using an electrolytic process.

Producers enjoyed a large increase in the free market price of magnesium metal, from $2,300/ton at the beginning of 1994 to $2,950 by mid-November. Much of this increase was due to reduced availability after Dow shut down a large portion of their plant; this voluntary move significantly reduced their capacity (by about 20,000 tons). Another 15,000+ tons of Chinese, Russian, and Ukrainian metal became unavailable when the U.S. Commerce Department imposed tariffs of as much as 108.26 percent for prior 'dumping' practices (selling metal below cost). As a result, Northwest Alloys was able to sell their entire production capacity of about 35,000 tons and may look to restarting a sixth furnace of the nine available. By addressing costs and improving efficiencies, Northwest Alloys was able to achieve the same output with five furnaces running in 1994 as it was able to produce with all nine in operation during 1991.

Carbonates

Western Washington continued to receive imported raw limestone for production of portland cement and lime from three sources on Texada Island, BC. Production of raw carbonates in Washington was virtually unchanged. A few western Washington quarries (nos. 135, 136, 152) produced mainly large limestone boulders for rockery, jetty stone, flood control, etc.

In eastern Washington, dolomite was produced for agricultural products, terrazzo, exposed aggregate, metallurgical flux, and filler (nos. 107, 110, 113, 118, 124, 125). Nanome Aggregates (no. 108) reported that sales were off about 7 percent, much of which could be attributed to the loss of jobs

where large amounts of exposed aggregates are used, typically construction of new federal buildings. Production was in full swing at Columbia River Carbonates quarry near Wauconda (no. 121), and their rock-loading facility at the Janis railroad siding, south of Tonasket, was significantly upgraded.

Olivine

UNIMIN, a Belgian company with U.S. headquarters in New Canaan, CT, purchased AIMCOR's olivine refractory products plant at Hamilton (no. 140) in April of 1994. UNIMIN continues to purchase crushed dunite from Olivine Corp. (no. 139); from it they mill a variety of casting sands and other refractory products.

Olivine Corp. continues to capitalize on its pioneering work in the construction of olivine-lined wood-waste incinerators. Installations of these burners throughout the international lumber-manufacturing community now include 20 units in Australia, 20 in Malaysia, 2 in the Philippines (both designed to burn municipal waste), 1 in Chile, and during 1994, the first in South Africa. The heat-resistant panels that line these units are composed of olivine aggregates in high-temperature cement; this allows the burners to reduce sawdust at high temperatures for cleaner burning. Improved air-quality standards in many parts of the world have necessitated replacement of steel teepee burners, which operate at cooler temperatures in an attempt to reduce the attrition of the steel.

Washington and North Carolina are the only olivine-producing states in the nation. Unlike the east coast markets served by the North Carolina olivine, the western markets for Washington olivine have not experienced encroachment by imports of Norwegian olivine.

Clays

Clay production in Washington was primarily used in brick, tile, and portland cement production (nos. 103, 104, 144, 158, 160, 169, 171, 178). A new specialty clay may enter production during 1995. Final permits are being secured by Basic Resources Corp. of Ephrata to open a clay pit in Douglas County from which they will produce a calcium bentonite clay. The operation, known as the Volcanic mine (no. 126), is approximately 3 mi east of Moses Coulee in the Columbia Basin. Initially, Basic Resources will be serving absorbent and water-sealing markets and may furnish a low-cost binder used to pelletize hay. They are ideally located to fill a potential need for large amounts of clay to line and seal irrigation canals, many of which leak. Calcium bentonite does not swell, in contrast to the more common sodium bentonites used in drilling muds. The ion-exchange capacity of the calcium bentonites, wherein calcium is the major exchangeable cation, can promote their use in a variety of specialized applications.

Basic Resources is amending their reclamation plan to enhance habitat for the pygmy rabbit, a threatened species in Washington. This burrower species cannot currently penetrate the caliche layers associated with the clay section. The reclaimed land and revegetation scheme may provide new habitat for the rabbit.

Decorative and Dimensional Stone

The decorative stone industry in Washington continues to diversify and once again has the capability to produce dimension stone (Fig. 1). Architectural replacement work is generating much of the initial demand for dimension stone, typically pieces of Wilkeson or Tenino sandstone, from which many grand old buildings were constructed. Sandstone accounts for only 3 percent of the domestic dimension stone output, which is dominated by granite and limestone, but it was a significant component of Washington's historic production. Approximately two-thirds of the dimension stone used in the United States is imported from Italy, Spain, Canada, Taiwan, India, Turkey, Norway, Brazil, and elsewhere. Much of this finished stone is produced at a fraction of our labor costs.

Figure 1. Sean Marley cutting a block of Tenino sandstone from the Hercules quarry near Tenino (no. 172). This 9-ft-diameter saw at the Marenakos Stone Center in Issaquah is the largest stone saw in Washington and Oregon. The sandstone has 'buff' and 'blue' color variants. This block is upside down relative to its original stratigraphic orientation. (Photo by David Knoblach, Marenakos Stone Center.)

Washington rough stone production of andesite, basalt, granite, sandstone, limestone, quartzite, argillite, and marble was marketed in a variety of ashlar, rubble, flagstone, fieldstone, crushed stone, landscape, and rockery products throughout the state. Washington's rough stone suppliers have now begun to receive imported, palletized rough stone from China and elsewhere. Many domestic producers are attempting to have tariffs placed on imported rough and dimension stone; tariffs now range from 0 to 7.5 percent.

Barite

Mountain Minerals Co. Ltd. sought to augment their barite production in British Columbia with additional materials dur-

ing 1994. They evaluated several Washington barite properties, including one in southern Stevens County (no. 106). Trader Resources, a subsidiary of Royal Oak Mines, purchased Mountain Minerals during 1994, and a thorough evaluation of all their barite property holdings is ongoing. One of these, the Flagstaff Mountain deposit (no. 116) is being examined as a strong candidate for reactivation.

Talc

A review of talc deposits throughout the Northwest has been undertaken by Pacific Talc Inc. of Kirkland, including examinations of some Washington deposits. The company, primarily brokers of mineral fillers, is negotiating with western U.S. filler producers to supply kaolin and talc, and they may add an in-house processing capacity for talc.

A deposit of soapstone that is suitable for sculpture is being developed west of Lake Wenatchee (no. 132). Carving-grade material has been obtained in this general area for many years by individuals who cut the alpine talus blocks to manageable dimensions with chain saws.

References Cited

Drake, Bob, 1994, Records set and broken: Pit & Quarry, December issue, p. 26-30.

Turley, William; Prokopy, Steven, 1994, Aggregate production to continue upward tend in 1995: Rock Products, December issue, p. 30-40. ■

The Nature of the Northwest Information Center in Portland Offers Many Resources

The Nature of the Northwest Information Center can provide numerous books, maps, brochures, and other publications about natural, cultural, and outdoor recreational resources in Oregon and Washington.

The center offers all available publications of the Oregon Department of Geology and Mineral Industries, a complete selection of USGS topographic maps, all USDA Forest Service maps for Oregon and Washington, selected publications from the Washington Division of Geology and Earth Resources, Oregon Department of Forestry maps, BLM maps for Oregon, Oregon Department of Water Resources drainage basin maps, and some commercial hiking maps.

The center, managed by Don Haines, is operated jointly by the Oregon Department of Geology and Mineral Industries and the USDA Forest Service. The partnership results in convenient, one-stop-shopping for customers.

The center is near Interstate Highways 5 and 84 and the 7th Avenue stop of MAX; it is three blocks east of the Convention Center and three blocks south of the Lloyd Center. The staff can respond to mail, fax, and phone inquiries. Hours are 8:00 am–5:00 pm on weekdays. The address is 800 NE Oregon Street, # 5, Portland, OR 97232-2162; phone 503-872-2750, fax 503-731-4066.

Mining, Exploration, and the Environment '95

Pacific Northwest Mining and Metals Conference
May 1–7, 1995
Hyatt Regency Hotel, Bellevue, Washington

Welcoming Reception, May 2

Technical Sessions, May 3–5

Exploration and the environment
Extractive metallurgy
Diamonds—Deposits and exploration
Exploration geochemistry
Acid mine drainage
Mechanical mining
Exotic minerals and new technologies
New instrumental geochemical techniques
Environmental geochemistry
Superfund and the mining industry
Exploration strategies for the years ahead
International focus—Indonesia
Mine waste remediation
Permitting—A global perspective
International focus—Russia and the Far East
Heap leach pad and tailings pond design
International focus—South America
New discoveries—Case histories
Regional abandoned mine lands

Field Trips, May 1–2 and 5–7

Upper Snoqualmie ground-water basin
Geologic hazards in the Seattle area
Geology and ore deposits of the Tertiary Cascade Range, southern Washington
Industrial minerals in the cement industry
Quartz Creek plutons and copper mineralization, Snoqualmie batholith, Cascade Range, Washington

Short Courses, May 1–2

Diamond exploration—New lithogeochemical exploration techniques
Alkalic mineral systems
Bioremediation

Presented by the North Pacific Section of the Society for Mining, Metallurgy, and Exploration (SME-AIME) and the Association of Exploration Geochemists (AEG).

Registration is $95 for SME-AIME and AEG members and $210 for nonmembers. There will be an additional late charge after April 7.

The Bellevue Hyatt Regency (900 Bellevue Way NE, Bellevue, WA 98004) has set aside a block of rooms for the convention. The special rates are $92 (single) and $102 (double). Reservations can be made by calling the hotel at 206-462-1234.

For more information, write to Mining, Exploration, and the Environment '95, c/o GeoConstrux, 6401 106th Ave NE, Kirkland, WA 98033.

A Brief History of the Cannon Mine

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Washington Division of Geology and Earth Resources
904 W. Riverside, Room 209
Spokane, WA 99201-1011

The Cannon mine (Fig. 1) has been the central focus of mining in the Wenatchee gold belt (Gill, 1994). Its history began in 1885 when a prospector named V. Carkeek staked two claims, less than a mile south of the area later occupied by the Cannon mine on exposures over what became known as the 'D' reef. Carkeek's discovery became known by various mine names (Gold King, Golden King, Wenatchee, Squillchuck), and prior to 1949, there was sporadic production—240 tons worth $1,600 in 1894; 170 tons in 1910; 20,000 tons in 1938–1939; and 6,216 tons from 1944–1946 (Huntting, 1956). Total recorded production prior to 1949 is more than 26,600 tons of ore of unknown grade or gold recovery.

In 1949, the Lovitt Mining Co. gained control of the property and developed the first successful operation in the area, the Lovitt or L-D mine. From 1949 until 1967, Lovitt mined 1,036,572 tons of ore and recovered 410,482 oz of gold and 625,849 oz of silver.

Asamera Minerals (U.S.) Inc. and Goldbelt Mines, Inc., entered into a joint venture agreement in 1981 to explore the property. (Breakwater Resources Ltd. gained control of Goldbelt in 1982.) Cannon mine development and mill construction began in 1984, and operations commenced in July of 1985. Between 1985 and 1994, the Cannon mine produced 1,249,241 oz of gold and 2,075,512 oz of silver (based on estimated recovery during final cleanup of 3,000 oz of gold and 4,000 oz of silver) from a total of 4,133,101 dry tonnes of ore (Table 1). Final production figures will not be available until smelter returns have been received, probably by May 1995.

The Lovitt (L-D) mine and Cannon mine together produced 1,661,723 oz of gold and 2,704,361 oz of silver. If ore grades similar to those of the Lovitt and Cannon mines, 0.30 oz per ton gold and 0.60 oz per ton silver, are used for pre-1949 production, an additional 8,000 oz of gold and 16,000 oz of silver can be attributed to these deposits.

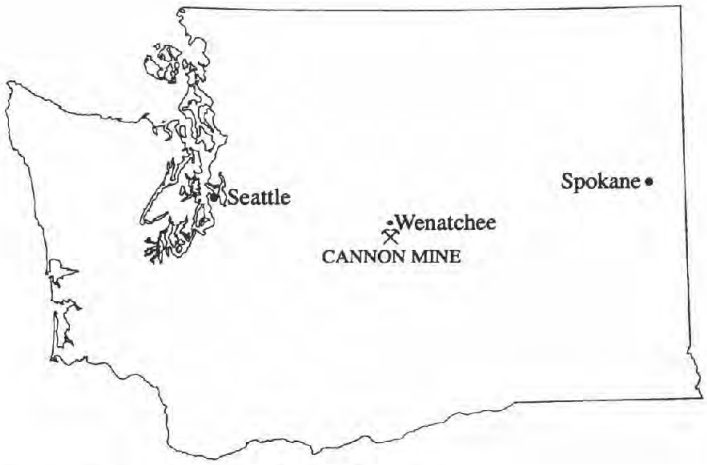

Figure 1. Location of the Cannon mine.

Table 1. Production summary of the Cannon mine, 1985–1994. (Production figures through 1993 from Cameron, 1994; 1994 production figures furnished by Asamera Minerals (U.S.) Inc.)

Year	Dry tonnes milled	Gold shipped (oz)	Silver shipped (oz)
1985	136,539	26,481	37,637
1986	414,695	123,651	189,839
1987	450,694	138,881	195,054
1988	484,653	151,633	263,027
1989	482,089	150,421	302,730
1990	480,318	149,327	252,120
1991	488,763	147,697	235,822
1992	449,138	127,303	205,546
1993	352,751	105,477	176,240
1994	393,461	125,370	213,497
1995	*	3,000	4,000
Totals	4,133,101	1,249,241	2,075,512

* No production is expected in 1995; however, gold and silver will be recovered during dismantling and cleanup of the mill.

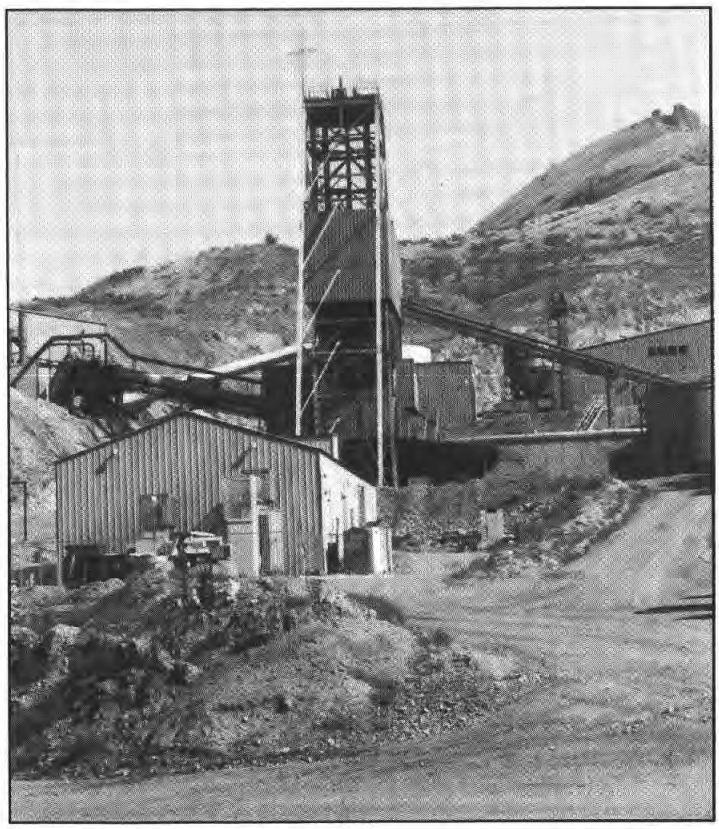

Figure 2. Headframe for the Cannon mine. Most of the ore came to surface in two skips that were attached to a 1.25-in.-thick woven steel cable and raised and lowered by an electric motor.

In terms of its annual production, the Cannon mine was one of the largest underground gold mines in the U.S. It included more than 6 mi of underground tunnels and reached a depth of about 1,100 ft below the surface—or nearly to sea level. Most of the ore from the Asamera–Breakwater joint venture was brought to the surface from a single shaft (Fig. 2), which was 850 ft deep, concrete lined, and 18 ft in diameter. Ore was hoisted by two 7-ton-capacity buckets (called skips) using a 500-horsepower electric motor.

Once at the surface (Fig. 3), ore was crushed and sent to an ore bin prior to delivery to a rod mill (Fig. 4). A ball mill finished grinding the ore to the consistency of face powder. The finely ground material was then sent to flotation cells (Fig. 5) where the gold-bearing minerals were coated with potassium amyl xanthate in water; causing them to float (Fig. 6) when vigorously agitated. The gold- and silver-bearing concentrate was then dried (Fig. 7) and shipped to various smelters in the U.S. or Japan, where the gold was recovered. Each ton of concentrate contained about 6 oz each of gold and silver. No cyanide was used in producing the gold or silver.

Now that the mine is closed, the mill (Figs. 2–4) is being dismantled and sent to Snow Lake, Manitoba, where it will be reassembled for a milling operation.

Exploration continues along the Wenatchee gold belt for additional ore bodies like that at the Cannon mine. The belt is known to extend for at least 9.5 mi (Gill, 1994). However, the mineralization is deep, and exploration is therefore costly.

References Cited

Cameron, D. E., 1994. The Cannon gold mine and its surface outcrop, Wenatchee, Washington. *In* Margolis, Jacob, editor, Epithermal Gold Mineralization, Wenatchee and Liberty districts, Central Washington: Society of Economic Geologists Guidebook Series, v. 20, p. 35-54.

Gill, R. D., 1994, Recent exploration along the Wenatchee gold belt, Wenatchee, Washington. *In* Margolis, Jacob, editor, Epithermal Gold Mineralization, Wenatchee and Liberty districts, Central Washington: Society of Economic Geologists Guidebook Series, v. 20, p. 58-65.

Huntting, M. T., 1956, Inventory of Washington minerals; Part II, Metallic minerals: Washington Division of Mines and Geology Bulletin 37, 2 v. ■

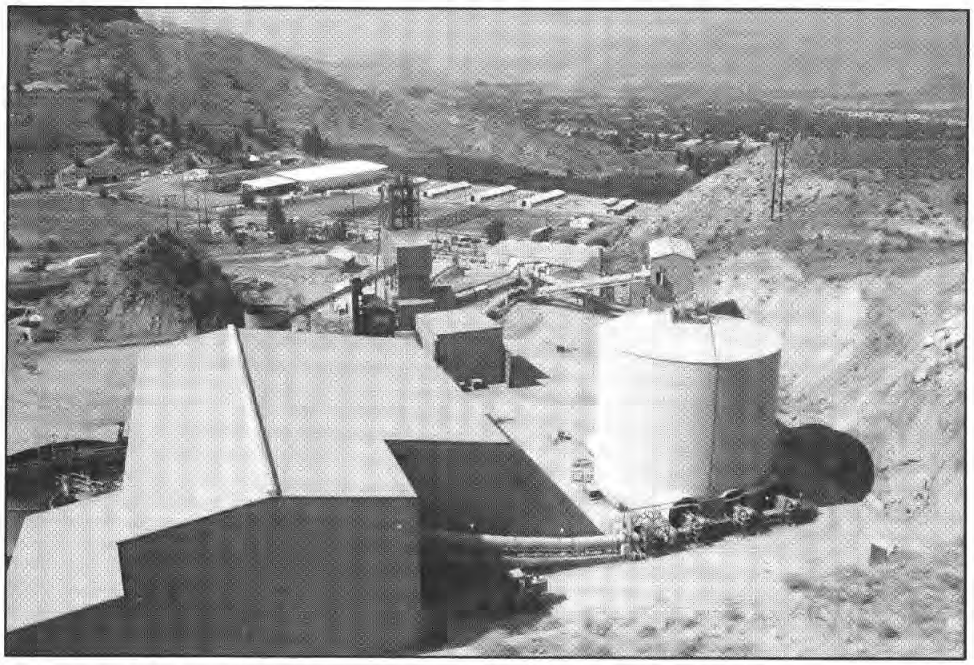

Figure 3. Overview of Cannon mine milling operation. The headframe is in the center of this view. Once the ore reached the surface, it was crushed and moved by belts (center to right center) to an ore storage bin (lower right).

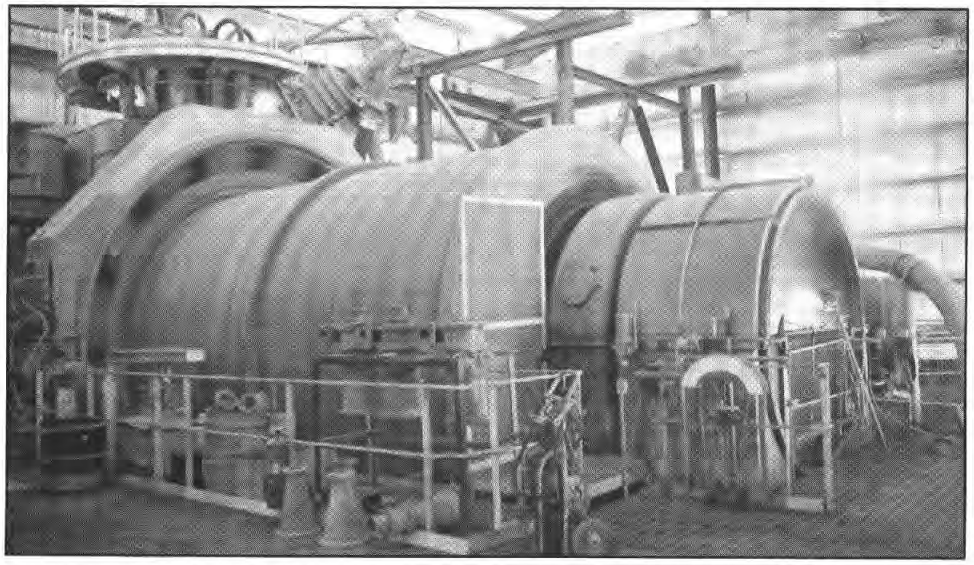

Figure 4. Ore was finely crushed by this rod mill in the mill building (lower left of Fig. 3).

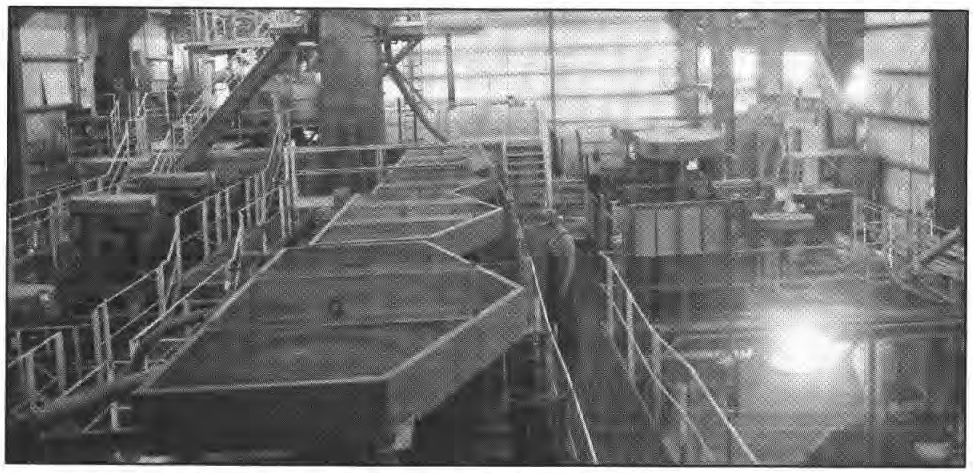

Figure 5. Ground ore was sent to flotation cells (left) where the ore minerals were separated from the waste rock.

The description of the mine operation is summarized from fact sheets (Cannon mine fact sheet, 1 p.; Welcome to the Cannon mine tour, 1 p.; and Exploration and history of the Wenatchee district, 3 p.) provided by Cannon mine staff and supplemented by other source materials.

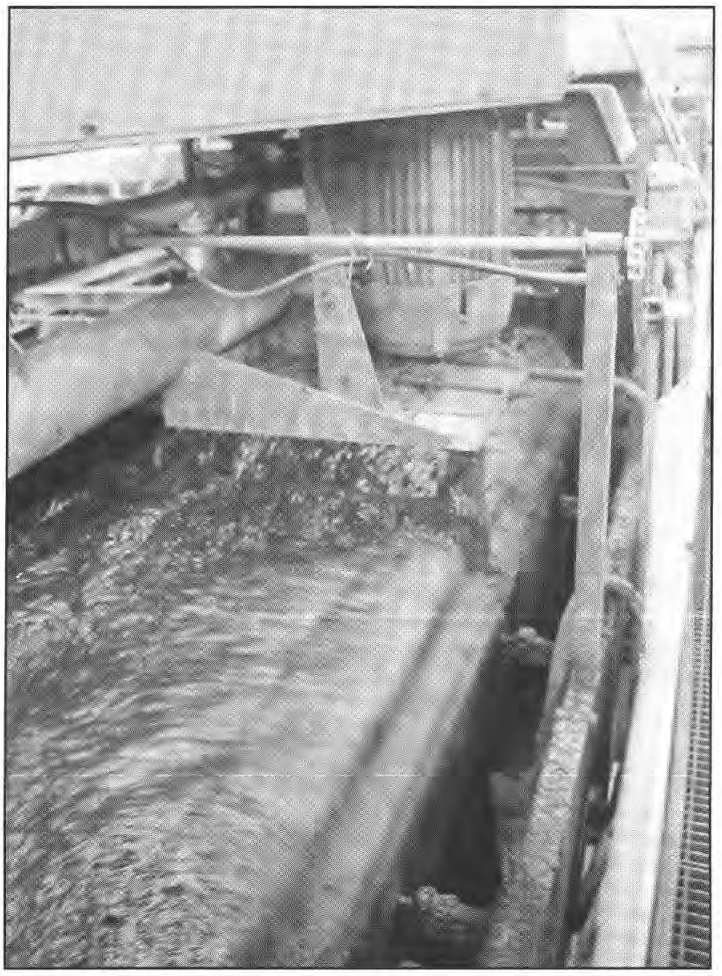

Figure 6. An organic chemical was added to the mixture of finely ground ore and water; the chemical coated the ore minerals. After vigorous agitation, these minerals floated in a kind of froth and were swept off to produce the ore concentrate.

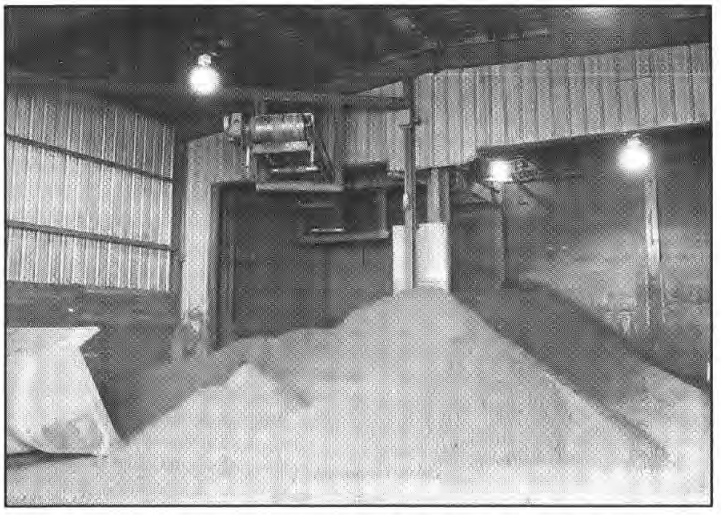

Figure 7. The dried concentrated ore minerals piled in this view were shipped to a smelter where the gold and silver were recovered. Each ton of concentrate contained 5–7 oz gold and 5–7 oz silver (Cannon mine staff).

Republic Field Seminar

Wes Wehr, whose articles about plants and insects of the Eocene deposits at Republic have appeared in *Washington Geology*, is conducting a field seminar about these fossils August 31–September 3 in Republic. Enrollment is limited. For information, call Wes at 206-543-0495.

Northwest Paleontological Association

The Northwest Paleontological Association has scheduled its 1994 meetings on the second Saturday of May, July, September, and November at 1:00 pm in the Burke Room of Burke Museum on the University of Washington campus. Most meetings feature a presentation by a paleontologist, and members and guests commonly get behind-the-scenes tours of the museum. For more information about the association, call Bill Smith, 360-697-1859.

Burke Museum Field Trips

A fossil-collecting trip to the Cowlitz Formation led by Liz Nesbitt is planned for Saturday, June 3. You will get to bring home your own 40-million-year-old clams and snails from two collecting stops in the Longview area.

A geological tour across the Cascades will be led by Tony Irving on Saturday, June 24. It will make several stops between Cle Elum and and Vantage to examine the results of past volcanic activity—from dramatic basalt columns to a petrified forest.

Tour leaders are UW geologists who have taught courses and led field trips for UW Continuing Education. Cost is $40 for members and $50 for nonmembers. Both trips will run from 8:00 am–6:00 pm. Bring your own sack lunch; transportation will be provided. For more information and to register, call 206-543-4491.

Information for Mineral Collectors

For Washington residents interested in 'rockhounding', the organizations listed here can provide information about local gem and mineral clubs.

Washington State Mineral Council
Bob O'Brien, President
605 Virginia Street
Sedro-Woolley, WA 98284

Friends of Mineralogy, Inc.
Pacific Northwest Chapter
John Cornish, President
40 Cedar Glen Lane
Port Angeles, WA 98362

Northwest Micro Mineral Study Group
Donald G. Howard, President
356 SE 44th Ave
Portland, OR 97215

Northwest Federation of Mineralogical Societies
Bill Smith, President
13332 Ridgelane Drive
Silverdale, WA 98383

In addition, your local library may have copies of *Lapidary Journal*. Rock clubs were listed in the April 1994 issue.

History of the Metaline Mining District and the Pend Oreille Mine, Pend Oreille County, Washington

Raymond Lasmanis, State Geologist
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HISTORY

The Metaline mining district is one of the oldest in the state, predating statehood. In his first annual report (for 1890), State Geologist George A. Bethune described the Metaline district as containing an "immense amount of metal...certainly destined to rank as a leading mineral producer." He mentions the high-grade galena ore found in the "lime formation" at the Bonnie Blue Belle mine (Bethune, 1891).

Pend Oreille Mine

Development of the Metaline district can be traced to two Danes—Lewis P. Larsen and Jens Jensen. During 1904, they began prospecting the area around Metaline Falls and initiated development of the Lehigh Cement Co. plant and quarries. They followed this with opening several lead-zinc showings (Fig. 1).

By 1906, minor production was recorded, and the Pend Oreille Mines & Metals Co. was formed, with Larsen as president and Jensen as secretary-treasurer. By 1917, mining and milling of ore was under way in earnest at the Josephine mine (Fig. 2). Charles A. R. Lambly joined the company as general manager of Metaline Falls operations.

The company operated the Josephine mine and the Pend Oreille mine from 1917 until 1974, when Bunker Hill Co. acquired the operations. Mining giants Larsen and Jensen had spent a lifetime keeping mining going at Metaline Falls. In later years, Wray D. Farmin, a former director, assumed the presidency of Pend Oreille Mines & Metals Co. Other well-known directors were H. T. Davenport, J. H. McFadyen, G. A. Pehrson, and A. W. Witherspoon.

The lead-zinc ores of the Metaline district are of low grade and contain only minor amounts of silver. Continued expansion of mining and milling operations must be attributed to the promotional skills of Larsen and the use of trackless mining methods (Fig. 3). In an interview for *Mining Truth* on March 1, 1928, Larsen was quoted as saying: "Diamond drilling results were such as to justify them in the belief that they were developing a lead-zinc area that will yield a tonnage comparable to that of the Sullivan mine of the Consolidated Company of Kimberly, B.C." A souvenir of an October 13, 1928, Northwest Mining Association excursion to Metaline Falls reads: "Put Metaline on the map – 10,000 tons a day or bust – now watch her go" (Zeigler, 1948).

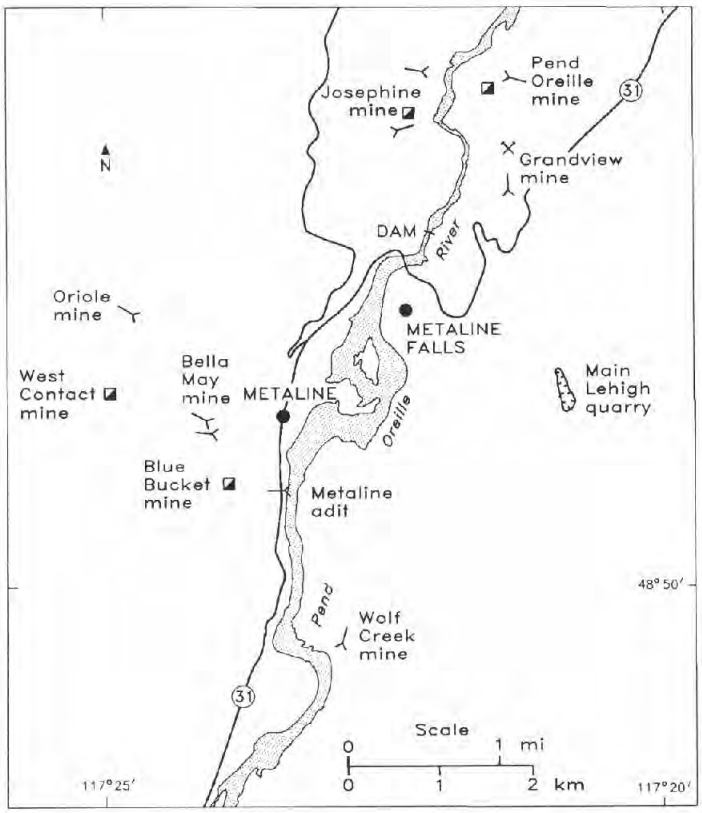

Figure 1. Location of historic and current mines in the area of the Pend Oreille mine in northeastern Washington.

Figure 2. Zinc carbonate stope, Josephine mine. Photo by Olaf P. Jenkins, June 22, 1924.

During World War II (WWII), critical metal shortages brought the U.S. Bureau of Mines to the area to prove up reserves. In 2 years the Bureau completed more than 1.25 million ft of drilling, greatly increasing the reserves. By 1942, indicated reserves totaled 9 million tons of about 5–7 percent combined lead-zinc ore (Fulkerson and Kingston, 1958).

The Bunker Hill Co. operated the Pend Oreille mine and the 2,400 tons per day (t.p.d.) mill until September of 1977 (Fig. 4). Mine closure came about as a result of a strike in June of that year at the electrolytic plant adjacent to Bunker's smelter in Idaho. Ownership of the Pend Oreille mine and mill then went to Pintlar Corp., a wholly owned subsidiary of Gulf Resources & Chemical Corp.

In 1988, Pintlar optioned the property to Resource Finance Corp. (RFC). Since then, with financing from Metall Mining Corp., RFC has completed an extensive development program—dewatering the mine, drilling, underground drifting, as well as engineering and feasibility studies. In August 1994, the company gave mining reserves in the Yellowhead zone at 3.5 million tons grading 9.1 percent zinc and 1.3 percent lead. Additional drilling and the driving of a 2,900-ft decline were under way in January of 1995. Development of the Pend Oreille mine is under the direction of the mine manager, Loui Forget.

Figure 3. Trackless mining with a loader and 12-ton truck in the Pend Oreille mine. Photo by Libby & Son, courtesy of Pend Oreille Mines & Metals Co., 1969.

Grandview and Bella May (Metaline) Mines

During the second decade of this century, other properties in the district were brought into production on a modest scale. At the Oriole mine, a small mill was erected in 1918, but it did not operate for long. In 1919, a 25-ton concentrator was built at the Bella May mine (Fig. 5). At the Wolf Creek mine, George Gage designed and built a smelter, but it failed to operate (Fig. 6). At the Grandview mine, a 250-t.p.d. mill, constructed by Grandview Mines, Inc., operated from 1928 to 1930, milling 15,000 tons of ore. At that time, vice president of Grandview was T. S. Lane, and secretary-treasurer was James S. Ramage, both of Spokane.

Howard I. Young of American Zinc, Lead & Smelting Co. of St. Louis soon recognized an opportunity to expand mining operations into Washington state. During 1935, the Bella May properties (owned by Riverview Mining Co., A. H. Kroll, president) were sold to Metaline Mining & Leasing Co., while American Zinc leased the Grandview mine and mill. Arrangements were made to have American Zinc, in exchange for stock, provide the financing for Metaline Mining to develop the Bella May and process the ore in the expanded Grandview mill. Officers of Metaline Mining & Leasing Co. were H. I. Young, president, D. I. Hayes, vice president, and W. N. Payne, secretary-treasurer. In charge of mine development and mill expansion for American Zinc was R. E. Calhoun of Metaline Falls. As with the Pend Oreille operations, metals needs of WWII provided the impetus to develop the Grandview and Bella May mines.

Development at the Bella May was impressive—driving of a 4,800-ft access adit to the Bella May, Blue Bucket, and West Contact ore bodies. The mine became known as the Metaline mine when the adit was used to produce ore for the Grandview mill from all three bodies. The Metaline mine last produced in 1950, and the Grandview mine and mill shut down on September 5, 1964.

Figure 4. Pend Oreille mill, November 1983.

Table 1. Metaline District, Washington, mine production, 1906–1977

Mine	Ore (tons)	Lead (tons)	Zinc (tons)
Pend Oreille	14,796,305	166,985	345,761
Grandview	3,995,745	46,179	120,411
Metaline	431,480	5,173	18,472
Others	53,271	582	840
TOTAL	19,276,801	218,919	485,484

Table 2. Metaline District, Washington, average grade of ore produced

Mine	Lead (%)	Zinc (%)
Pend Oreille	1.13	2.34
Grandview	1.16	3.01
Metaline	1.20	4.28
Others	1.09	1.58
District Average	1.14	2.52

Table 3. Production from the Pend Oreille (Josephine) mine, Washington

Year	Ore (tons)	Gold (oz)	Silver (oz)	Copper (lb)	Lead (lb)	Zinc (lb)
1917	14,953		97		36,876	1,171,296
1918	55				1,202	38,873
1925	25		48		24,585	
1926	17		22		14,730	
1927	32,577[1]	6	2,134	1,075	37,788	868,018
1929	320	8	1,172	436	6,510	47,234
1930	6,000		870	240	407,650	665,280
1931	80,968		4,595	2,670	2,514,977	9,947,495
1932	33,423		2,589	3,360	1,349,713	4,489,334
1933	48,479		3,260	5,062	1,443,783	6,738,169
1934	28,322		1,151	2,575	473,649	3,852,419
1936	76,060		3,317	6,011	1,540,847	8,777,220
1937	98,500		10,081		5,137,858	7,462,200
1938	214,120		14,584		7,413,000	18,598,000
1939	241,624		11,603		6,472,000	18,555,558
1940	232,587		8,587		4,152,700	18,792,000
1941	219,835		7,948		3,731,449	15,958,000
1942	234,215		9,622		5,091,141	14,508,700
1943	183,042		3,848		4,524,200	9,815,000
1944	157,638		7,172		4,070,593	7,959,000
1945	119,696		4,400		2,425,000	5,445,000
1946	122,106		3,050		1,496,200	6,252,700
1947	116,695		4,733	4,300	3,235,000	6,270,000
1948	133,755		7,377		5,825,500	5,462,188
1949	186,955		9,365	16,475	6,547,000	8,438,750
1950	186,197		9,001	15,347	6,126,500	8,774,470
1951	273,580	30	16,041	13,721	5,937,458	12,402,138

PRODUCTION

Production for the Metaline district from 1906 to 1977 is given in Table 1. The Pend Oreille mine was by far the largest producer. The average grade of the 19.3 million tons of ore mined in the district was 1.14 percent lead and 2.25 percent zinc (Table 2).

Annual Pend Oreille mine production is given in Table 3. Increased production rates beginning in 1938 reflect the needs of WWII and the Korean and Viet Nam conflicts.

By-products were copper, silver, cadmium, and traces of gold. Silver is carried in the galena concentrate (2.3 oz per ton), and the sphalerite concentrate assays 0.2 percent cadmium. Copper, in the form of chalcopyrite and tetrahedrite, seems to report with the sphalerite concentrate. Geochemical analyses of pyrite concentrate indicate the presence of minor amounts of tennantite (Bending, 1983).

ORE GENESIS AND CONTROL

The first published paper to describe the ore genesis of the district was by Bancroft (1914). He attributed the lead-zinc ores to hot siliceous solutions emanating from granite and noted that the ores resemble those of Joplin, Missouri. This genetic model was repeated by Jenkins[1] (1924) and by Eby (1928), who further postulated that the intrusive bodies underlay the district. The word 'jasperoid' was seen in the literature for both Metaline and Joplin ores. Structural complexity of the district was also being recognized (Fig. 7).

In 1930, Oscar H. Hershey presented two key elements of ore control that are still valid. Hershey recognized that the Josephine breccia ores were related to the contact with the overlying black shale (later named the Ledbetter Slate) and that there was a deeper ore zone, which had been penetrated by two deep drill holes. He called the lower pyritic zinc deposit the 'Washington horizon'. This lower ore zone is now known as the Yellowhead and was first described in detail by Morton (1974). Hershey did not discuss ore genesis, but he noted that the Metaline ores were similar to lead deposits in the Flat River district of southeast Missouri.

The concept that the Metaline ores were formed by replacement of limestone by hot solutions from granite persisted through 1965. Bell (1934) noted that the Josephine breccia ores (of granitic origin) were cut by later mineralization, which was concentrated by ground water—a new idea. Hougland (1936) produced the first geologic map of the district, but he still attributed the ore to ascending thermal waters of igneous origin.

Park and Cannon (1943) and Dings and Whitebread (1965) state that the ores are genetically related to the Kaniksu batholith. Their papers provide a detailed physical description of the ore bodies and mineralogy. The term 'zebra rock' is used to describe a type of banded ore that Dings and Whitebread

[1] Olaf P. Jenkins was on the staff of the Washington Division of Geology in the 1920s and served as California State Geologist from 1947 to 1958.

Year	Ore (tons)	Gold (oz)	Silver (oz)	Copper (lb)	Lead (lb)	Zinc (lb)
1952	336,205	22	20,882	24,220	9,721,198	15,604,647
1953	500,042	17	23,719	34,056	11,400,566	21,715,290
1954	482,055	3	19,000	8,200	14,946,000	12,890,600
1955	503,391	9	22,752	33,700	13,372,500	15,101,500
1956	587,891		24,206	30,200	15,884,400	14,689,200
1957	757,197		30,973	47,000	17,891,800	21,983,400
1958	607,695		26,363	32,000	11,847,300	23,176,400
1959	619,779		30,152	42,000	15,359,300	20,725,200
1960	727,759		16,611	46,800	15,512,000	28,248,200
1961	742,934		38,425	54,200	12,751,800	25,538,200
1962	619,946		24,994	53,000	9,327,200	30,273,600
1963	651,992		28,257	51,900	9,800,300	32,002,700
1964	697,113		27,096	50,200	8,660,700	32,530,400
1965	640,604		23,689	44,000	8,822,000	26,402,000
1966	594,654		21,478	38,000	7,846,000	23,818,000
1967	292,628		9,831	20,000	3,576,000	10,838,000
1968	197,826	4	15,061	14,100	9,888,100	9,280,900
1969	215,702		16,971	11,200	15,187,300	8,529,900
1970	223,729	34	13,671	10,700	9,532,600	9,056,500
1971	252,492	105	12,358	20,400	10,302,300	11,548,500
1972	217,383		6,851	14,006	5,131,922	12,965,197
1973	212,289		6,662	11,155	4,422,314	12,751,366
1974	232,895		3,774	NA*	2,594,816	13,597,818
1975	306,184	30	9,437	17,553	3,679,432	20,240,607
1976	380,581	33	11,343	21,247	4,074,841	25,584,982
1977[2]	153,595	11	5,289	9,773	2,399,617	11,139,330
Total	14,796,305	312	636,512	810,882	333,970,215	691,521,479

[1] Includes 9,537 tons of old tailings *NA = not available

[2] Mine closed by strike at Bunker Hill electrolytic plant, June 1, 1977

(1965) attributed to hydrothermal activity, but district mine geologists ascribed 'zebra rock' textures to algal/stromatolitic origin (James L. Browne, written commun., 1995). Like Bell (1934), the mine geologists attribute late-stage sphalerite to supergene action. However, they do not mention the Yellowhead ore.

From 1914 through 1965 all writers compared the Metaline ores to those of Joplin (Missouri), southeast Missouri, and Silesia (most of which is now included in Poland) and still assign ore origin to hydrothermal solutions. In Mississippi Valley-type (MVT) analogue deposits, however, intrusives are not associated with ore formation.

In a series of papers from 1967 to 1970, R. A. Anderson and G. G. Addie of the Pend Oreille Mines & Metals Co. rejected the granite-source hypothesis and stated that these deposits are MVT deposits and have the same genesis. In an unpublished paper, Anderson (1967) speculated that Josephine lead-zinc ores were precipitated syngenetically at the time of reef growth and that only the coarse late-stage fracture-filling mineralization is epigenetic, derived from a deeper hydrothermal source or remobilized from earlier mineralization.

Anderson also recognized the significance of facies changes, pyrobitumen, and the Yellowhead zone, located 300 m below the Josephine breccia ore zone. McConnel and Anderson (1968) further expanded on their concept of the contemporaneous sedimentary–diagenetic origin of the zinc-rich jasperoid ores of the Josephine deposit, and in the same volume, Cox (1968) stated that the deposits were indeed MVT. Additional papers describing the Metaline and other deposits of the Kootenay arc as MVT were presented by Ohle and Addie during the 1970 Society of Economic Geologists Northwest Field Conference.

Morton (1974) gave the first detailed description of the Yellowhead ore zone. He ascribed the origin of the pyrite-rich zinc mineralization to either commingling of ascending metalliferous connate brines with oxygenated meteoric water in karst solution breccias, or direct precipitation of ore from downward percolating meteoric water.

Bending (1983) detailed ore genesis on the basis of geochemistry, fluid inclusion studies, microthermometry, and cathodoluminesence. Bending stated that mineralizing solutions originated from basinal brines and that both Josephine-type and Yellowhead-type mineralization formed at between 95°C and 155°C. The Josephine deposit is cut by later fracture-controlled mineralization consisting of quartz with sulfides and silver and copper contents higher than those of earlier formed veins. Formation of this later stage was at 200°–260°C. Bending believed that the metals for the late stage were expelled from overlying and lateral shale units. He concluded that the Metaline deposits are comparable to MVT deposits and that Jurassic and Cretaceous igneous events in the region post-date the formation of the deposits.

Great strides have been made in recent years in unscrambling the depositional and stratigraphic setting of the Metaline Formation, host of the ore bodies. Results were reported by Bush and others (1992). Recent drilling has demonstrated that the three units Dings and Whitebread (1965) used to describe the Metaline Formation are no longer valid. The 1992 studies showed that the Cambrian–Ordovician Metaline Formation was deposited on a steepened ramp adjacent to a basin and that the Josephine breccia should be considered a lithofacies. Syndepositional faulting influenced the stratigraphic relations of facies in the Metaline Formation.

Morton (1992) elaborated on ore genesis in light of the stratigraphic framework. He reconfirmed that the Josephine and Yellowhead ores are syngenetic and had a common low-temperature source—metalliferous brines expelled from adja-

cent basins. Morton differed with Bending in suggesting that the late-stage veins resulted from an influx of high-temperature fluids from a deep igneous source or represent remobilization of earlier sulfides and quartz. Morton also suggested that, because of syndepositional faulting, late-stage mineralization has some affinities with Irish-type base-metal deposits.

SUMMARY

The Metaline District demonstrates a century of progress in mining methods and metallurgy and understanding of stratigraphy and ore genesis. The 19.3 million tons of ore that was mined and processed are a tribute to the ingenuity and perseverance of mining giants from the Pacific Northwest.

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Figure 5. Hand jig at the Bella May mine. Photo by Olaf P. Jenkins, June 29, 1924.

Figure 6. Unsuccessful smelter at the Wolf Creek mine. Photo by Olaf P. Jenkins, June 28, 1924.

Figure 7. Virgil Barnes indicating the lower plane of a thrust fault in Metaline limestone. Photo by Olaf P. Jenkins, June 21, 1924.

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This paper was presented at the 100th annual Northwest Mining Association Convention, Spokane, WA, Nov. 29–Dec. 2, 1994.

More about Museum Displays

Readers have offered additional information about the following mineral, fossil, and mining displays:

- *The museum at Holden Village*, northwest side of Lake Chelan, has a large collection of photos, mineral specimens, and artifacts of the mining operations. The museum is open without charge.
- *The Whitman College Geology Department* in Walla Walla exhibits also include imagery of the United States from space, a display about the 1980 eruption of Mount St. Helens, and a seismic station. The large nautiloid and echinoderm with spines are no longer on display.
- *The Lewis County Historical Museum*, at the Old Railroad Depot at 599 NW Front Way in Chehalis, has an exhibit of the Mount St. Helens eruption that includes: ash from five localities and some pumice samples; 48 specimens of concretions, petrified wood, fossils, and minerals; and historic pictures of the local coal industry. A video of Mount St. Helens is also part of the museum collection. The museum is open Tuesday through Saturday, 9:00 am–5:00 pm, Sunday, 1:00–5:00 pm; closed holidays. Admission is $2 for adults. For more information, call 360-748-0831.
- Visitors to Portland might like to visit the *Oregon Museum of Science and Industry* (OMSI), 1945 SE Water Ave. The large earth-science hall features before-and-after topographic models of Mount St. Helens showing areas of devastation; topographic models of the 1980 mudflows down the North Fork Toutle River and subsequent erosion; a display about how the lava dome is being rebuilt; and rocks samples from Mount St. Helens and other localities. Other models describe shear, collision, and spreading zones in the Earth's crust. An interactive video displays plate movements, earthquakes, and hot spots. The museum also has an earthquake-simulation room, a display about aspects of global warming, a quiz about cities of the world that are subject to relatively great geologic and weather-related hazards, a wave tank, and a watershed lab room with a stream erosion table. Between Labor Day and Memorial Day, the museum is open 9:30 am–5:30 pm, Saturday through Wednesday; 9:30 am–9:00 pm, Thursday and Friday. From Memorial Day to Labor Day hours are 9:30 am–7:00 pm, Saturday through Wednesday, and 9:30 am–9:00 pm, Thursday and Friday. It is closed on Christmas Day. Adult admission is $7 for the basic exhibits. For more information, call 503-797-4000. ■

New Book on Banded Agates

Banded Agates—Origins and Inclusions, a 32-page book by R. K. Pabian and A. Zarins, was recently added to the Division's library collection. The breadth of the book's coverage is indicated by the list of contents. Among the topics discussed are tectonic and stratigraphic settings, geochemistry, how and why bands form, and pre-banding inclusions. The 57 illustrations are in full color. The book was published in 1994 as Educational Circular 12 by the Conservation and Survey Division of the University of Nebraska–Lincoln. Mineral collectors are invited to read the copy at the Division's library.

Cyanide Heap Leaching—The Process, Environmental Problems, and Regulation in Washington

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INTRODUCTION

Heap leaching is a metallurgical process for extracting metals by trickling cyanide solutions through crushed ore that has been stacked on the ground (Fig. 1). The process is used primarily for extracting gold and silver from low-grade oxidized ores where large flat areas are available for outdoor pads. Cyanide heap-leach operations are currently used primarily in the arid western states, particularly at gold mines in Nevada (Fig. 2).

While the concept of extracting metals using cyanide is fairly old, cyanide heap-leach technology has developed significantly over the past 15 years. Use of cyanide heap leaching has steadily increased due to its low cost for recovering gold and silver.

Northern Nevada was the site of the first small-scale commercial cyanide heap-leach operation by the Carlin Gold Mining Co. in the late 1960s (Hiskey, 1985). The first large-scale operation, in the early 1970s, was also in Nevada (Dorey and others, 1988).

Only three cyanide heap leaches have operated in Washington. None is currently active, and all were less than 2 acres. However, the impact of these operations has been greater than their size would indicate. Each of these operations is briefly described in this article. Large-scale cyanide heap-leach operations have not been attempted in Washington.

CYANIDE AND THE MINING INDUSTRY

Cyanide Chemistry

The cyanide anion is a simple compound consisting only of carbon and nitrogen (CN^-). It is a fundamental building block of many organic compounds.

Many industrial uses for cyanide have been discovered, principally in the chemical, metal, and mining industries. Naturally occurring elevated levels of CN^- are also found in plants, such as corn, lima beans, and sweet potatoes, as well as in the seeds of fruit, such as apples, cherries, and plums. A host of diverse products, such as pesticides, fertilizers, drugs, plastics, dyes, and pigments, require cyanide in their manufacture (Stanton and others, 1986). It is also an important ingredient in processes for electroplating, case hardening of steel, metal cleaning, metals leaching, and ore flotation.

Cyanide readily forms stable salts with sodium, calcium, and potassium. Sodium cyanide (NaCN), the most common salt used in mineral processing, is usually transported as a solid to the mine site, where it is dissolved for use in processing. In solution, NaCN dissociates to sodium (Na^+) and cyanide (CN^-). When cyanide reacts with water, it forms hydrocyanic acid (HCN).

HCN readily evaporates, and HCN gas is less dense than air, flammable, and toxic. Cyanide can be kept in the liquid state by controlling the concentration, temperature, and pH of

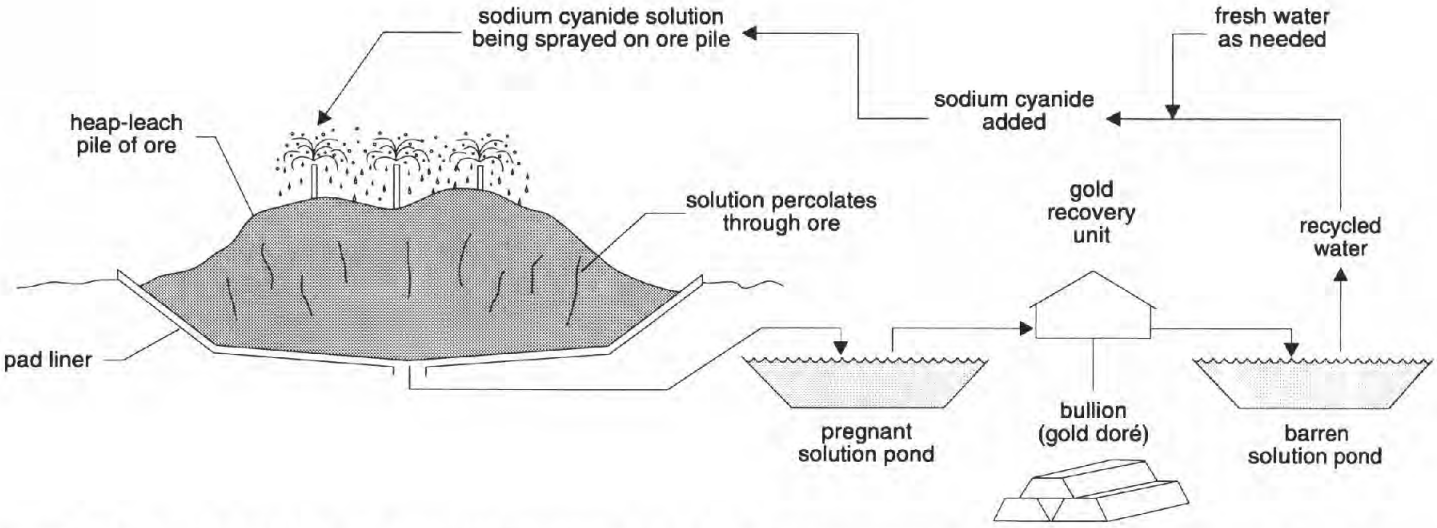


Figure 1. Main steps of a heap-leach operation that produces gold doré or bullion (semirefined gold and silver with some impurities). (Redrawn from an illustration by Alan Czarnowsky, TerraMatrix.)

the solution. In general, high temperature, high solution concentration, and low pH (more acidic) promote the generation of gaseous HCN (Fig. 3).

Removal of Metals with Cyanide

Cyanide is able to complex (bond) with gold and silver, a characteristic that makes it possible to dissolve and remove these metals from ore. However, cyanide can also form complexes with mercury, zinc, copper, iron, nickel, and lead. If ores also contain these metals, extracting gold requires more concentrated cyanide, which in turn creates waste waters that are difficult to treat (Smith and Mudder, 1991).

Chemists describe the removal of gold (Au), as well as silver (Ag), by cyanide in this overall reaction:

$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH$$

In general, fairly weak cyanide solutions can be used to extract gold and silver because the chemical tendency to complex with these metals is strong. In the absence of other metals, a 100 milligrams/liter (mg/l) solution of NaCN (that is, about 50 mg/l free cyanide) can provide the maximum rate and extent of dissolution (Smith and Mudder, 1991). Free cyanide is defined as the sum of molecular hydrogen cyanide (HCN) and cyanide anion (CN^-).

The solution of gold complexed with cyanide is called a 'pregnant' solution. Gold is recovered from this solution by the zinc precipitation process or by the activated carbon adsorption process.

The *zinc precipitation process* is an electrochemical reaction in which electrons are released as the metallic zinc powder reacts with free cyanide ions in the absence of oxygen, converting the gold ions that are complexed with cyanide to elemental gold.

The *activated carbon adsorption process* introduces no additional metals into the gold recovery process. Stripping the adsorbed gold from carbon is typically accomplished using a solution containing 0.1% NaCN and 1% sodium hydroxide (NaOH) at elevated temperatures. The gold is generally recovered from the NaCN/NaOH solution by electrowinning (the recovery of metals from solution by electrolysis), allowing a portion of the cyanide to be recycled (Muhtadi, 1988). The use of activated carbon can decrease the concentrations of undesirable metals (particularly mercury) in solution, making wastewater treatment more efficient (Smith and Mudder, 1991). As a consequence, many mine operations have begun using the activated carbon adsorption process.

Cyanide Extraction Methods

Heap leach and tank cyanidation are the two most common methods of gold extraction using cyanide that are currently employed by the mining industry. This paper deals only with the heap-leach process, but there are similarities between the two methods.

Heap-leach extraction is used for lower grade ore. The ore is stacked in the open on an impervious pad, and a cyanide solution is trickled through the pile. Prior to being stacked on the pad, the ore must be prepared. Ore preparation can range from no treatment, to crushing only, to crushing and combining smaller particles of ore into groups of particles (termed agglomeration). Agglomeration is accomplished with lime or cement to form pellets that increase the permeability of the heap.

Oxidized ores are most amenable to heap leaching. Most oxidized ore has been subjected to the action of surface waters carrying oxygen, carbon dioxide, etc. Oxidation alters the original sulfide minerals (in which a metal is bonded to sulfur) to oxides (in which a metal is bonded to oxygen.) For ores that are not oxidized, one strategy for oxidizing the ore is autoclaving or pressure cooking the sulfides.

Tank cyanidation is used for higher grade ores. For tank cyanidation, the ore must be finely ground prior to treatment. Gold recovery is much higher from fine ore than from coarse fragments. Cyanidation takes place in an enclosed tank located indoors or outdoors.

Figure 2. The Gold Bar mine in Nevada owned by Atlas Gold Mining, Inc. Shown in the photo are: (1) the open-pit mine, (2) heap-leach pads and pad area, (3) barren ponds and pregnant ponds, (4) cyanide neutralization facilities, (5) building facilities and crushers, and (6) waste rock. (Photo courtesy of Atlas Gold Mining, Inc.)

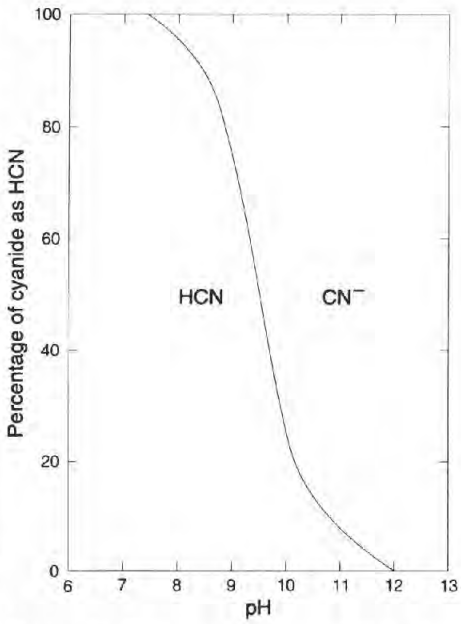


Figure 3. Relation of HCN and CN^- to pH.

It is widely used in the mining industry—the Echo Bay Mining and Hecla Mining Co. operations at Republic, Washington, use tank cyanidation to recover gold and silver.

THE HEAP-LEACH PROCESS

For a cyanide heap leach, the ore is piled in truncated pyramids, typically in 20- to 30-ft high lifts (layers) (Fig. 4) that may cover as much as several hundred acres. A dilute NaCN solution is then applied to the top of the ore pile by drip or spray-irrigation techniques (Fig. 5). Typical application rates range from 5 to 75 gal/ft^2 of surface per day. Solution strengths are approximately 400–800 mg/l NaCN with a pH of about 10.3. As the NaCN solution passes through the stockpiled ore, gold and other metals are leached from the rock.

The pregnant solution containing the gold flows out from under the pile along an impervious pad or liner (Fig. 6) to a lined pregnant solution pond (Fig. 7). The pregnant solution is then pumped to a gold recovery plant, where either the activated carbon adsorption or the zinc precipitation method is used to extract gold.

Once the gold is stripped from the liquid, the barren cyanide solution is recycled to the leach piles. Depending on the chemistry of the barren solution, more cyanide may be added and the pH may be adjusted. The piles are leached until all of the gold that can be economically extracted by the method is removed. Heap leaching typically recovers only 60 to 80 percent of the gold and silver in the ore.

In well-operated mines, heaps and solution ponds are then neutralized by natural processes, washing with water, or treating with chemicals that destroy cyanide. The neutralization process can generate nitrites, nitrates, and inorganic carbon.

The heaps are either reclaimed in place or the neutralized spent ore is placed back in the pit (if suitable conditions are present and the pad can be unloaded without damage) (Fig. 8).

Heap-Leach Components

The main components of a heap-leach operation (Fig. 1) are:

- mine or source of ore,
- ore preparation,
- heap pile (ore),
- pad,
- liner,
- cyanide solution application system (sprinklers or drip irrigation),
- pregnant solution pond,
- gold recovery circuit, and
- barren solution pond.

The three main components of a heap-leach operation that have the potential to create significant adverse environmental impacts are the:

- mine area (not unique to the heap-leach process),
- waste-rock dumps, where overburden is placed during mining (also not unique to the heap-leach process), and
- ore-processing area with a leach pad and pond system (unique to the heap-leach process).

Heap and Pad Construction

Choices of heap locations are generally constrained by haul distance, land availability, and topography. The foundation for the heap must be engineered to withstand loading—it must be stable and not settle.

Three basic methods of heap and pad construction are used:

Permanent multiple-lift expanding heap. Spent ore remains on the pad after leaching is completed. New layers, referred to as lifts, are continually built on top of the spent ore (Figs. 2, 4), resulting in a truncated pyramid appearance.

Reusable pads. Spent ore is removed from the pad and disposed of. More ore is then placed on the pad, and the process is repeated

Valley leach. A valley is used as the leaching area. An earthen dam built at the lower end of the valley holds both the ore and the leachate (Dorey and others, 1988). The heap and the pad are designed to be stable structures. This method is most commonly used in mountainous terrain. Ore is continuously placed on the heap as in the permanent multiple-lift expanding heap method. The liner must resist the tendency to creep down the valley (Dorey and others, 1992).

Liners

The pad liner is a critical component for a safe heap-leach operation. The liner collects and contains the leach solutions (Figs. 6 and 9) and acts as a platform on which the heap is built. Historically, liners (soils, clays, and geomembranes) have leaked, but recent advances have made liners more reliable. However, design criteria must be based on the assumption that leaks will occur and that leak detection and recovery systems are necessary.

Figure 4. Hecla Mining Co.'s Yellow Pine, Idaho, heap-leach facility. Lifts are approximately 20 ft high, resulting in an 80-ft high heap. After each layer of the heap is leached, a new layer is placed on top and leaching continues.

Soil for liners can consist of onsite or local borrow materials (if they have the correct clay content), bentonite, or mixtures of both. Important considerations in choosing soil for liners are its availability and composition. Imperfections such as roots must be removed during pad construction. The soil must have an appropriate clay content, low permeability, plasticity, and chemical stability when in contact with a cyanide solution.

The thickness and method of liner compaction at the site are also important engineering considerations. Most clay liners are designed to achieve a permeability in the range of 10^{-6} to 10^{-7} cm/s (1.0–0.1 ft/yr). To attain low-permeability containment, clay liners must be properly compacted with appropriate equipment while protecting against cracking from drying and (or) shrinkage (Hutchinson and Ellison, 1992). In general, increasing the clay content of soil decreases the permeability. However, clay mineralogy can also affect permeability. Expandable clays (smectite and illite-smectite group clays) are less permeable than other clays (kaolinite or illite). Additionally, if the clay is not thoroughly mixed, conditioned, and carefully placed, the liner permeability is unlikely to be uniformly low. Construction quality assurance/quality control (QA/QC) should be part of any liner installation.

Mine location can influence the choice of liners. Some sites lack adequate natural materials such as clay, sand, and gravel to construct liner components. If natural material is not available, a synthetic liner system must be used. Typically, multiple liners are required, with the bottom layer consisting of clay.

Technological advances in the manufacture of synthetic materials during the past decade have resulted in the use of geomembranes for all components of the liner system (Ellison and others, 1992). Geomembranes are made of polyvinyl chloride (PVC), hypalon, high-density polyethylene (HDPE), very low density polyethylene (VLDPE), Chevron Industrial Membrane (CIM), chlorinated polyethylene (CPE), and asphalt/hydraulic asphaltic concrete (HAC) (Dorey and others, 1988). The most commonly used geomembrane is HDPE. Geomembranes must not react with reagents used in heap-leach processing. Other important considerations in choosing geomembranes are thickness, strength, durability, cost, cover material needed for cushioning, method of placement, and method of sealing and quality of seams between the sections of the liner.

Liner design is a site-specific choice. A wide variety of combinations is available (Fig. 9). The term 'triple liner' (double composite liners of the U.S. Environmental Protection Agency; Strachan and van Zyl, 1988) generally means two geomembranes separated by a drainage layer and underlain by a clay liner.

Figure 5. Sprinkler system applying cyanide solution to a heap-leach pad at the Gold Bar mine in Nevada. Sprinklers oxygenate the solution more effectively than drip irrigation systems. Drip systems, however, have less evaporative loss. (Photo courtesy of Atlas Gold Mining, Inc.)

Figure 6. Preparation of a heap-leach pad and liner at the Coeur Thunder mine (owned by Couer d'Alene Mining Co.) in central Idaho in 1985. An impermeable geomembrane is laid down on a slightly inclined surface of compacted low-permeability glacial till before ore is stacked. Lined ditches contain and collect solutions. (Photo courtesy of Bruce Schuld, Idaho Department of Environmental Quality.)

Past failures of geomembrane liners have been attributed to poor welding of the seams or joints in the geomembrane or to puncturing. Puncturing can be avoided by properly cushioning the geomembrane. New techniques for welding seams have improved seam reliability. Installing a cover layer to cushion and protect the geomembrane has also been key in successful operations. Most failures can be prevented by strict adherence to QA/QC during pad construction.

Solution Application and Collection Systems

At most facilities, cyanide solutions are pumped onto the heap through a sprinkler or drip system. The chemical reaction that dissolves the metals with cyanide requires oxygen. Sprinklers can make more oxygen available by mixing the solution with air. In most instances, however, sufficient oxygen is available in the heap itself. The pregnant solution is collected by a system of perforated drain pipes and trenches that divert the liquid to the pregnant solution pond.

Solution Storage Ponds

The pregnant solution pond holds highly toxic solutions that contain the dissolved gold. The barren solution pond holds the solutions that have been stripped of gold. Pond liners must ensure that no leakage occurs. Commonly, the ponds are placed side by side to confine large volumes of solutions to one area and to reduce costs of pumping (Fig. 1). The volumes of both storage ponds must be designed to contain the heap-leach solutions as well as precipitation from storm events expected at the mine site.

Water Balance

Every mine operator and regulator must be concerned about the water balance, or the volume of water for processing ore together with precipitation and evaporative loss. Water balance is a critical design element for heap-leach operations because processing occurs outdoors and pads and ponds may cover many acres.

Because of water balance, climate becomes an important consideration when designing a heap-leach facility. For example, many potential sites for a heap-leach process in Washington are extremely wet. Failure to properly calculate water balance could result in the heap becoming overly expensive to operate or failing to function as excess water dilutes the cyanide solution. Pads and ponds must be designed to contain all solutions from the heap-leach process and all precipitation that falls on the heap. Overtopping of ponds could release toxic metallocyanide solutions to surface and ground water.

ENVIRONMENTAL ISSUES

Cyanide Toxicity

Cyanide is a potent asphyxiant (chemical that stops the respiratory function or displaces oxygen) that acts rapidly in an aquatic environment. Cyanide enters the body by inhalation, ingestion, or absorption through the skin. It spreads throughout the body in the bloodstream. Because the central nervous system of higher animals has the greatest oxygen requirement, it is the most strongly affected by cyanide. Suppressing the central nervous system leads to suspension of all vital functions and death (Smith and Mudder, 1991). However, sublethal doses of cyanide may be ingested without bio-accumulating due to cyanide's high biological reactivity and the body's detoxification mechanisms.

In an aquatic environment, the primary toxic agent is free cyanide, which was defined as the sum of molecular hydrogen cyanide (HCN) and cyanide anion (CN^-). HCN is the most toxic cyanide species. As previously noted, HCN is extremely water soluble. For solutions with pH greater than 10, nearly 90 percent of the free cyanide is in the form of CN^-. Below pH about 8.5, nearly 90 percent of the free cyanide occurs as HCN (Fig. 3). Thus, small pH differences significantly change the toxicity of process solutions.

Other factors also affect cyanide toxicity. Among these are the temperature and oxygen content of the aquatic environment, acclimation of the organism to cyanide (which activates defense mechanisms), life stage, stress factors, size and species of organism exposed, presence of other chemicals (such as ammonia) in the environment, concentrations, or time-dependent tolerance increases.

Figure 7. Pregnant solution pond at the Coeur Thunder mine in 1985. Posts in foreground are about 5 ft high. (Photo courtesy of Bruce Schuld, Idaho Department of Environmental Quality.)

Toxicity of Cyanide-Metal Complexes

Cyanide is used for processing ores because, when present in excess, it readily complexes with and dissolves metals. The toxicity of solutions containing cyanide complexed with metals depends on the concentration of free cyanide formed by dissociation or hydrolysis. Metallocyanides are classified as weak acid dissociable (WAD) if they dissociate at pH 4.5.

One method of analyzing for metallocyanides in aqueous solutions is the WAD method, which uses acids with pH 4.5 to dissociate the metals. Upon dissociation in acidic aqueous solution, WAD cyanide complexes liberate free cyanide, thus increasing the toxicity of the solution. Cyanide complexes with gold, silver, iron, and cobalt are considered stable, although photolysis (chemical decomposition induced by light) will cause iron cyanide complexes to release free cyanide. Turbidity, shading, and depth of the solution will affect photolysis. The WAD method will detect by recovery all the cyanide from zinc and nickel cyanide complexes, about 70 percent from copper complexes, and 30 percent from cadmium cyanide complexes. It does not recover any cyanide from iron- or cobalt-cyanide complexes (Smith and Mudder, 1991).

Cyanide Persistence in Surface Water, Ground Water, and Soils

Cyanide is seldom biologically available in aquatic environments or soils owing to its reactivity—it rapidly complexes with metals to form insoluble compounds. Some free cyanide is lost to the atmosphere through volatilization (evaporation). Under aerobic conditions, soil microbes metabolize cyanide, producing carbon dioxide and ammonia. Under anaerobic conditions in nonsterile soils, bacteria convert cyanide, through denitrification, to gaseous nitrogen compounds that escape to the atmosphere. However, significant amounts of cyanide are neither absorbed nor adsorbed by soils and can leach into the surrounding ground water.

Cyanide has relatively short persistence in surface water under normal conditions because it degrades quickly. It may be present for extended periods in ground water where it cannot readily volatilize. Volatilization is the dominant mechanism for removing free cyanide from concentrated solutions and is most effective at high summer temperatures and in solutions with high dissolved oxygen or carbon dioxide concentrations. All of these conditions may be lacking in ground water.

Cyanide Impacts on Wildlife

Eisler (1991) determined that between 1980 and 1989, nearly 7,000 birds, including many species of waterfowl and songbirds, were found dead at cyanide-extraction leach ponds at gold mines in California, Nevada, and Arizona. Also killed were about 520 mammals, mostly rodents and bats, but coyotes, foxes, skunks, badgers, weasels, rabbits, deer, and beavers as well. Also found dead at these leach ponds were 38 reptiles and 55 amphibians.

Bird sensitivity to cyanide is not related to body size; rather, it seems to be associated with diet. Birds that feed predominantly on flesh, such as vultures, kestrels, and owls, are more sensitive to cyanide than species that feed mainly on plants—with the possible exception of mallards.

The situation is complicated by the condition of birds arriving at the mine ponds. Some consume relatively little fluid, while others, if dehydrated, may consume much more pond water. Pond location, size, visibility, and proximity to other water bodies and migration routes may be also important in influencing mortality rates (Hallock, 1990).

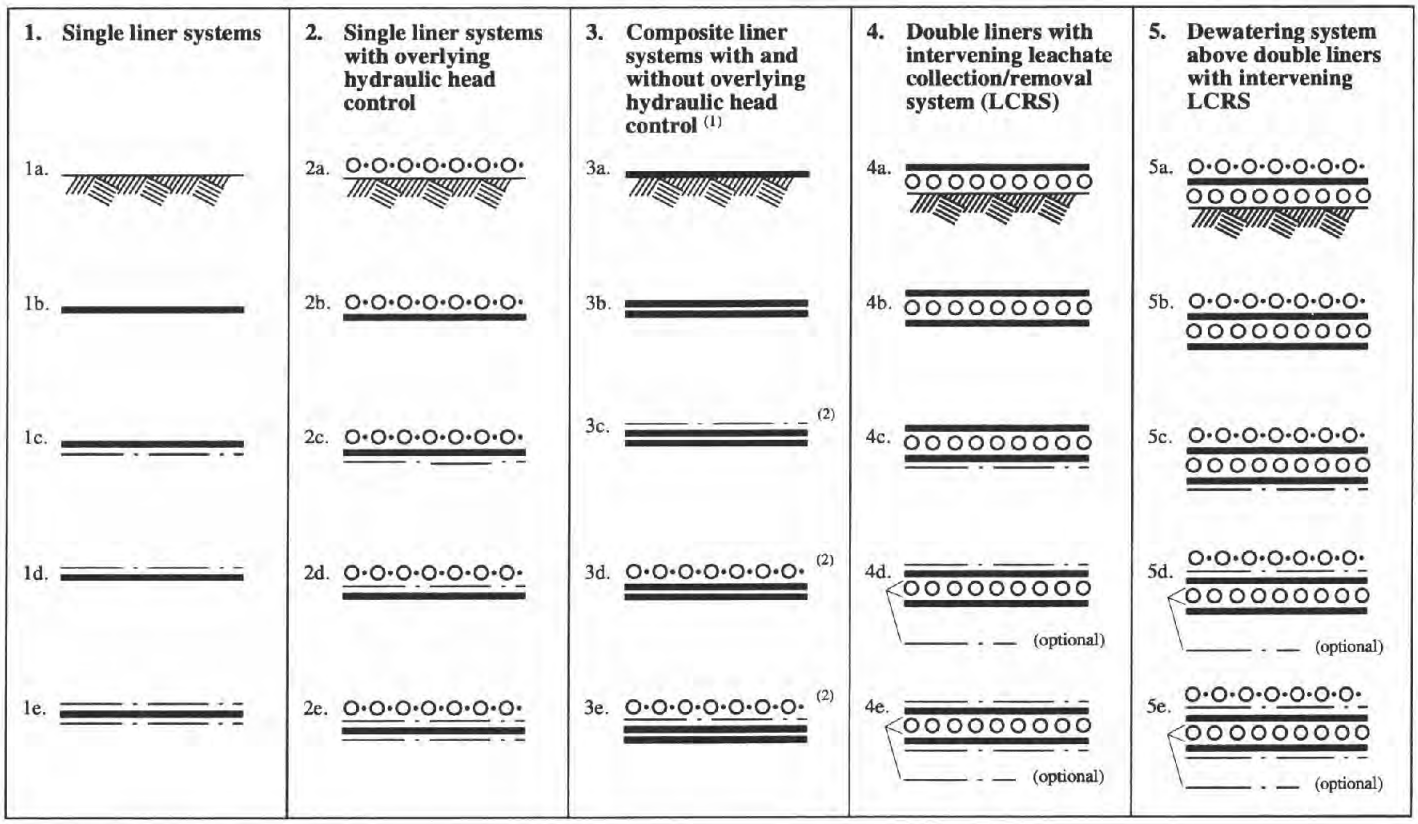
Some birds may die after drinking solutions containing theoretically sublethal concentrations of cyanide. A mechanism that could account for this phenomenon involves WAD cyanide compounds. Cyanide bound to certain metals, particularly copper, is dissociable in weak acids such as those in the stomach. Clark and Hothem (1991) suggest that animals that drink sublethal cyanide solutions may die later when additional cyanide is liberated by stomach acid.

Case histories show that migratory birds constitute the majority of documented wildlife deaths attributed to cyanide at mine sites. According to Hallock (1990) of the U.S. Fish and Wildlife Service (USFWS), "the Migratory Bird Treaty Act makes no provisions for migratory birds killed at ponds containing cyanide. USFWS's position is that killing migratory birds with cyanide at mine ponds is illegal."

For mammals, studies show that cyanide is not bio-accumulative or biomagnified in the food chain, possibly because most animals rapidly detoxify sublethal doses or die after higher doses. In sublethal doses, cyanide exposure does not result in cumulative adverse effects, and sublethal intermittent doses can be tolerated by many terrestrial species for long periods, perhaps indefinitely.

Eisler (1991) reported that fish were the most sensitive animals included in his survey. Adverse impacts on fish included impaired swimming ability, increased vulnerability to predation, disrupted respiration, and altered growth patterns. For example, with salmonids, swimming ability is irreversibly im-

Figure 8. Reclaimed heap-leach pad at the Coeur Thunder mine in 1993, approximately 2 years after mining was completed. Spent ore was unloaded from pads and placed in mined-out pits. Photo shows approximately the same location as that in Figure 6. The recent drought has limited growth here, but grass and pine trees have begun to spread as conditions become more favorable.



Legend:

- Natural low hydraulic conductivity soil or unfractured rock
- Constructed low hydraulic conductivity liner, e.g., geomembrane
- Cushion or load-bearing protection layer
- O·O·O·O· Hydraulic head control layer (dewatering system)
- O O O O O Leachate collection and removal system (LCRS)

(1) The most common composite liner system involves a geomembrane overlying a low hydraulic conductivity soil

(2) These composites also include a geomembrane overlying a low hydraulic conductivity soil or rock

Figure 9. Various combinations of liner systems. (Redrawn from Ellison and others, 1992, fig. 7.1, p. 335. Used by permission of Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida.)

paired in well-aerated water with free cyanide concentrations as low as 10 µg/l. Of all animals studied, aquatic invertebrates were most sensitive to HCN at elevated water temperatures, regardless of dose.

Bird control at containment ponds has relied on two primary techniques: hazing with sound/visual systems and stretch wire. These approaches are not completely successful (Martin, 1992). Netting can be effective in keeping birds away from smaller regularly shaped ponds such as those constructed to contain pregnant solutions (Hallock, 1990). But some birds get tangled in the nets. The best method of reducing wildlife mortality is to properly neutralize cyanide solutions.

FACTORS THAT LEAD TO ENVIRONMENTAL PROBLEMS

Some of the problems that have occurred at sites throughout the western United States can be attributed to:

Leach solution overflow. During heavy rains or rapid snowmelt, some leach solution ponds have proven to be too small to contain the precipitation. The cyanide solution overflows onto the ground or into streams.

Leaks in liners. Liner failures allowed the leach solution to leak through to the ground under the pad or ponds.

Improper closure. The cyanide leach solution is not neutralized to subtoxic levels at mine closure. Improper management of leach solutions containing concentrated metals or operator bankruptcy have resulted in abandonment of unreclaimed sites.

Poor site selection. Mine sites are affected by many factors, such as climate, topography, and the geology and geochemistry of the site. Dealing with these factors in inappropriate ways can bankrupt the mine operator and create environmental problems.

In the now infamous case at Summitville, Colorado, where (among other problems) acid mine drainage and metallocyanides reached the Alamosa River, all of these factors contributed to some extent to the failure of the operation and subsequent adverse environmental impacts (Knight Piésold and Co., 1993; Lyon and others, 1993).

Heap Neutralization

After the economic supply of metal has been leached from the heap, the mine must be decommissioned. An essential component of decommissioning is neutralizing (detoxifying) the heap. Each heap has a unique set of characteristics, and choice of neutralization method will be influenced by many factors. Some of the methods available for detoxifying cyanide are:

- natural degradation,
- fresh-water rinse,
- alkaline chlorination,
- use of hydrogen peroxide,
- use of sulfur dioxide and air,
- acidification, volatilization, and recovery (AVR), and
- biological processing.

More information about neutralization is given by Smith and Struhsacker (1988), Denton and others (1992), Smith and Mudder (1991), and the U.S. Bureau of Land Management (1992).

RECLAMATION

In Washington, after a heap has been neutralized, the site must be thoroughly reclaimed (Revised Code of Washington (RCW) 78.44). Reclamation of mines is discussed in Norman and Lingley (1992) and Norman (1992). The same basic principles and strategies apply to reclamation of heap-leach operations. The important activities in planning and executing reclamation are saving and replacing topsoil, creating natural and stable landforms, and establishing vegetation.

In the past, industry practice was to use spent ore from the pad to backfill a mined-out pit or to reclaim the heap in place. Dumping spent ore into a pit seldom results in landforms that are stable or properly shaped. The Coeur d'Alene Mining Co. has used spent ore to create stable landforms that appear natural at Coeur Thunder mine in Idaho (Norman, 1993) (Fig. 8).

If the heap is to be reclaimed in place, the heap slopes must be pushed down to a stable, natural appearing configuration. Experience has shown that slopes no steeper than 3 horizontal to 1 vertical on which topsoil is replaced offer the best environment for revegetation.

CYANIDE HEAP-LEACH OPERATIONS IN WASHINGTON

Two of the three heap-leach operations in Washington (Fig. 10) are the Silver Mountain mine and the Minnie mine (Fig. 11). They were abandoned and are, or will be, undergoing cleanup at the expense of the taxpayer.

The Silver Mountain operation was an underground mine located on private land that used heap-leach processing from 1980 to 1981. A 20-mil plastic liner was placed on the ground and covered with an ore heap measuring 100 ft x 105 ft x 14 ft and containing approximately 5,300 tons of ore. Over the life of the mine, an estimated 4,400 lb of NaCN was mixed with water and sprayed over the heap. Overflow from the leachate collection pond contaminated the soils adjacent to the heap; liner failure was also suspected. Cyanide and other contaminants from the leach pile were found in ground-water monitoring wells installed by U.S. Environmental Protection Agency (EPA). The site was added to the National Priority List of Superfund Sites in 1984.

The Minnie mine operated from 1984 to 1985 on federal land. The pad consisted of a 30-mil geomembrane placed on a compacted soil base. The operators were issued a temporary state Waste Discharge Permit by the Department of Ecology (DOE) before operations commenced. Approximately 6,000 tons of ore were placed on the 120 ft x 120 ft pad. Ore was crushed and agglomerated with cement prior to stacking.

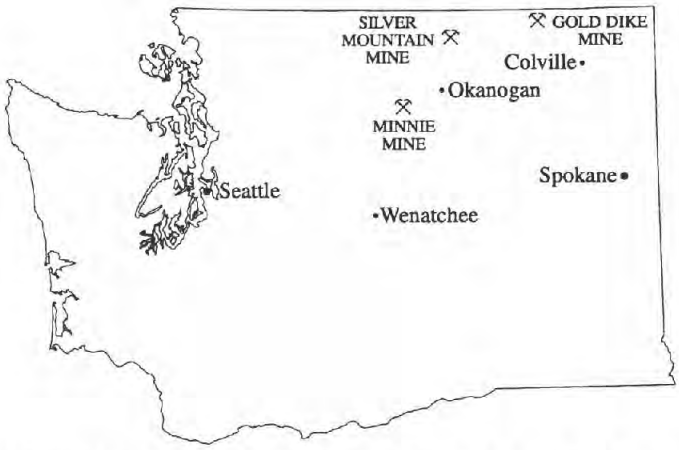


Figure 10. Locations of the three Washington mines with cyanide heap-leach operations.

Sprinklers delivered cyanide solutions. Spent ore was washed with water and also neutralized using alkaline chlorination. The operators failed to neutralize either the ponds or the heap and declared bankruptcy. The U.S. Forest Service collected a bond of $7,200 and an additional $8,000 in compensation and began site cleanup and neutralization in 1991. During reclamation by the Forest Service, stripping neutralized layers off the pad assisted neutralization by exposing lower material to air, light, and treatment solutions. Final closure/cleanup costs will exceed $225,000, far more than the original bond estimate, because of requirements not envisioned by the Forest Service. The unforeseen remediation costs involved mainly the offsite disposal of treated pond fluids and sludges and the associated studies, reports, and engineering designs required under both the Model Toxic Control Act (MTCA) and the federal Comprehensive Environmental Response and Compensation Act (CERCLA). The site will be capped in 1995 and monitored for the long term (Rod Lentz, U.S. Forest Service, written commun., 1994).

N. A. Degerstrom, Inc., operated the Gold Dike mine on private and federal land in Ferry County as a pilot heap-leach project in 1989 but subsequently suspended operations. However, Degerstrom still has a valid Reclamation Permit for the site. The $215,000 performance security for the site is held by the Department of Natural Resources (DNR). The project is unlikely to proceed because of the poor economics of the deposit. Termination of the Reclamation Permit has been discussed with the operator.

MINING REGULATIONS

In Washington, no one body of law deals with the cyanide heap-leach mining process. Rather, portions of existing laws are interpreted by agencies to apply. Regulation of mining begins with identification and mitigation of adverse environmental impacts during the preparation of an Environmental Impact Statement (EIS) pursuant to the State Environmental Policy Act (SEPA) (RCW 43.21C). DOE is designated as the SEPA lead agency for metal mining and milling (RCW 78.56). No permits may be issued until the EIS is accepted by the SEPA Responsible Official. Permit requirements are based on criteria and processes set forth in law, rule, or ordinance.

SEPA substantive authority may be applied on a site-specific basis.

The most important state laws generally applicable to mining are the SEPA, the Metal Mining and Milling Act (RCW 78.56), the Surface Mine Reclamation Act (RCW 78.44) (although underground mining and its surface effects are currently excluded from regulation), the Water Pollution Control Act (RCW 90.48), and the Clean Air Act (RCW 70.94).

Virtually all mitigation requirements must be applied on a site-specific basis because cyanide heap leaching is only one of many metallurgical methods for processing ore. The geology and hydrology of sites differ; generic review standards therefore cannot be applied.

Historically, heap-leach processing in Washington has escaped thorough regulation under waste-management law. Operators of heap-leach projects have asserted that all their leach solutions are continuously collected and recirculated into the ore. In this scenario, the leach solution does not meet the definition of 'waste'. Therefore, regulations for dangerous waste do not apply until the end of the project when the leach solution is collected for final disposal.

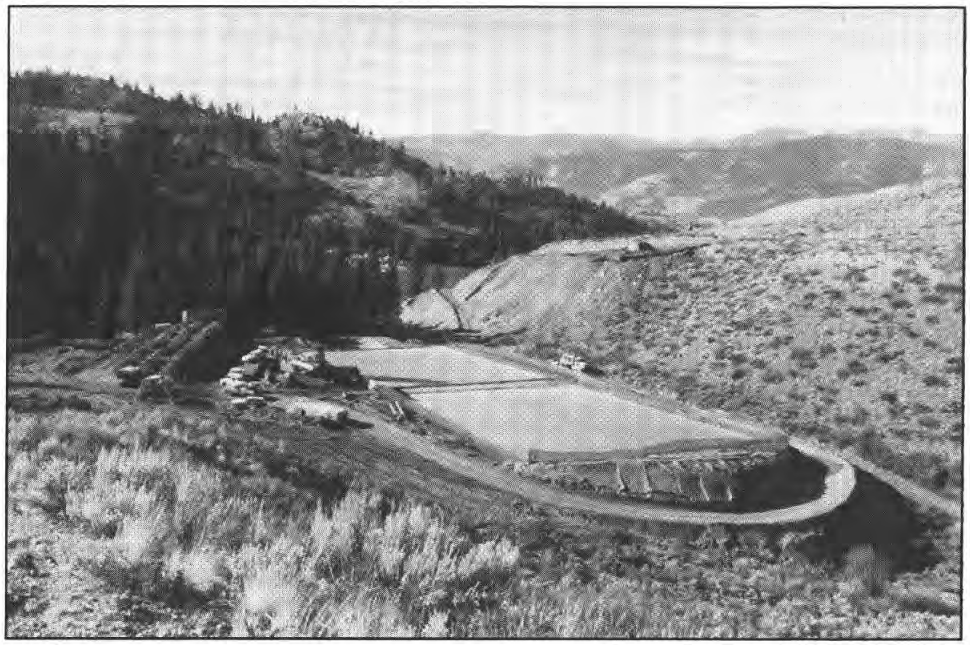


Figure 11. Initial construction of heap-leach pads (the two flat areas in center of photo) and pregnant and barren solution ponds (barely visible in the shadows above the pads) in 1984 at the Minnie mine (Fig. 10). Each pond could hold about 80,000 gal. The ponds used a double geomembrane liner system with leak detection placed on a compacted soil base. The pad liners consisted of single layer 30-mil geomembrane placed on a compacted soil base. Ore was stacked 16 ft high on the only 120 ft x 120 ft pad that was actually used (top). (Photo by Rod Lentz, U.S. Forest Service, Okanogan National Forest.)

Any heap-leach operation on federal land must also meet the requirements of the National Environmental Policy Act (NEPA) (42 United States Code section 4321). NEPA sets forth both environmental policies and the means for carrying out these policies. All federal agencies making decisions about permits or licenses are required to comply with the NEPA. NEPA requirements are similar to those of the SEPA. The SEPA/NEPA lead agency and review processes have been shared cooperatively between a federal agency and DOE. Regulatory responsibilities of federal, state, and local agencies are detailed in Norman (1994) and Smith (1993).

Water Quality

Among the most significant potential impacts from mining and milling are those related to water quality. For discharges to surface waters of Washington, certain provisions of Title 40, Code of Federal Regulations (CFR), Part 440—Ore Mining and Dressing, Point Source Category, Subpart J—Copper, Lead, Zinc, Gold, Silver, and Molybdenum Ores Subcategory apply to mining. This regulation sets maximum daily and average monthly Effluent Limit Guidelines (ELGs) for copper, lead, zinc, cadmium, mercury, pH, and total suspended solids for new open-pit and underground mines, regardless of whether heap-leach techniques are applied. ELGs are included in the federal National Pollutant Discharge Elimination System (NPDES) permit issued and administered by the DOE for discharges to surface water.

The federal EPA considers mine drainage to include any waters that originate or drain from crushers, spent ore piles, ore stockpiles, waste rock and overburden piles, or dams or dikes and onsite haul roads constructed from waste rock or spent ore. The EPA also considers water draining from a pit or underground working, whether pumped or drained by gravity, and water from a seep or french drain associated with the mine to be mine drainage. Precipitation on any of these mine elements that results in a discharge to surface water is also considered mine drainage and is subject to ELGs.

If ore is milled, 40 CFR 440 sets a 'zero discharge' standard for process wastewater from mills that use cyanidation processes, tailings facilities, and (or) heap-leach piles. In Washington, the NPDES permit is issued according to the requirements of Chapter 173-220 Washington Administrative Code (WAC). In addition to the ELGs in 40 CFR 440, discharges to surface waters of the state are subject to the surface-water quality standards in Chapter 173-201A WAC.

Several other Washington state regulations address water quality. Discharges to the ground are covered by a state Waste Discharge Permit in accordance with Chapter 173-216 WAC. Typically, this permit is combined with the NPDES permit for discharges to surface water. Discharges of storm water or process water to the ground are subject to the ground-water quality standards in Chapter 173-200 WAC; these include antidegradation requirements intended to preserve the beneficial use of ground water. This chapter also defines a process for evaluating the ground-water impacts of a facility. Chapter 173-240 WAC requires submittal of an engineering report, an operations and maintenance manual, and a facility plan for review and approval by the DOE before discharge permits can be issued.

Water Resources

The permit and water rights application procedures for mining projects are subject to the same considerations as for other proposed uses of water. Considerations and studies are defined by the DOE's Water Resources Program. Before water is appropriated, or changes to an appropriation are made, applicants must be able to answer 'yes' to four basic questions:

- Is a beneficial use of the water proposed?
- Can the water use be carried on without detriment to the public interest?
- Is water available for the proposed project uses?
- Can water be appropriated without impairing existing rights?

Air Quality

Metallic mineral processing plants, including heap-leach processing, must register as sources of air pollutants with the state's DOE or the regional air pollution authority. One air-quality permit, the Notice of Construction, is now required for new or modified heap-leach operations. A Prevention of Significant Deterioration Applicability form is used to determine whether a second air-quality permit, the Prevention of Significant Deterioration (PSD) permit, is required. For heap-leach processing, the PSD permit is required if emissions of a criterion pollutant (excluding fugitive emissions) exceed 250 tons per year.

Dangerous and Hazardous Waste

The dangerous and hazardous waste regulations apply to any industry that uses toxic substances and generates dangerous wastes. Cyanide heap-leach operations may be included in one of two ways:

1. *As dangerous and hazardous waste management facilities.* This includes facilities that treat, dispose of, or store dangerous wastes for longer than 90 days. They must be permitted prior to beginning operations. The permitting process for these facilities requires detailed review of a great deal of technical information submitted by the applicant. For some proposals, there is a lengthy permit-writing period that includes public involvement at various stages.

A permit application is required (Chapter 173-303-800 WAC), and a Notice of Intent (Chapter 173-303-281 WAC) must be filed. The purpose of the Notice of Intent is to notify the DOE, the local community, and the public that siting a dangerous waste facility is being considered. The Notice of Intent also provides general information about the proposed facility, its owner/operator, and the types of wastes that will be managed. It describes compliance with siting criteria (Chapter 173-303-282 WAC) established to serve as an initial filter during consideration of sites for Dangerous and Hazardous Waste Management Facilities.

2. *As dangerous and hazardous waste generators.* In Washington, when dangerous-waste quantities exceed specific threshold levels, the generators become subject to waste designation, reporting, storage, labeling, spill notification, and transport requirements. The waste generators do not have to obtain permits if they store dangerous waste in containers and tanks for less than 90 days. They may not treat or dispose of their stored dangerous wastes. They must obtain a state/EPA identification number if they intend to transport their waste to a permitted Dangerous Waste Management Facility, and they must annually report the quantities and types of wastes generated to the DOE.

Generators that produce more than 2,640 lb of dangerous waste per year must also prepare a pollution prevention plan (Chapter 173-307 WAC). This planning requires a comprehensive analysis of toxic substance use and methods of waste generation so as to identify and analyze strategies to reduce toxic releases and the amount of waste generated. Implementation of those strategies is voluntary.

Determining how the dangerous waste regulations will apply to a specific proposed business, such as cyanide heap-leach operations, can be accomplished only through the review of the types of industrial processes used, the specific waste-handling practices proposed, and the types and quantities of wastes that will be generated.

Surface Mine Reclamation Act

DNR administers the Surface Mine Reclamation Act, a law that requires a permit for each surface mine that results in more than 3 acres of disturbed ground or has a highwall that is both higher than 30 ft and steeper than 45 degrees (Chapter 78.44 RCW, Chapter 332-18 WAC). The purpose of the Surface Mine Reclamation Act is to assure that every surface mine in the state is thoroughly reclaimed. A high-quality reclamation plan is required for each mine. (See Norman, 1993; Norman and Lingley, 1992.) Important aspects of the Act are:

- segmental reclamation (where possible),
- preservation of topsoil,
- slope restoration such that highwalls are rounded in plan and section,
- stable slopes/cliffs in consolidated materials,
- final topography that includes sinuous contours, chutes and buttresses, spurs, and rolling mounds and hills, all of which blend with adjacent topography to a reasonable extent, and
- effective revegetation with diverse ground-cover plants and trees.

The state surface-mine reclamation permit issued by DNR applies to most surface mines in Washington. DNR does not regulate reclamation of underground mines or the related surface disturbances. DNR has not regulated on federal lands prior to the Crown Jewel Project (Okanogan County) proposed by Battle Mountain Gold Corp.

Metal Mining and Milling Act

The Metal Mining and Milling Act (RCW 78.56) addresses conditions for constructing, operating, reclaiming, and closing metal mines and milling operations. The Act applies to new or expanded base- or precious-metal open-pit and underground mining operations. Milling is defined as the process of grinding or crushing ore and extracting base or precious metals by chemical solution, electrowinning, or flotation processes.

Open-pit and underground mining methods and the waste rock that is generated are not unique to cyanide heap-leach facilities. The one component that sets heap-leach processing apart from conventional mining and milling is the processing area that includes the leach pad and various ponds.

While the Act addresses other components of mining methods and waste rock placement, it does not include language that could be specifically applied to some aspects of heap-leach operations. Sections of the Act set conditions for permitting, siting, and operating, but some of these requirements cannot be applied to an active heap-leach operation. The Act addresses waste rock and tailings in Section 10, but it does not identify spent ore generated by a heap-leach facility. Spent ore could be regulated in the same manner as tailings. The chemistry and reclamation of waste rock will differ from site to site, but the Act specifies a process intended to identify and address conditions that have potential adverse environmental impacts. Section 10 (1 (a)(i)) limits the concentration of toxic materials in the tailings facility to assure protection of wildlife and human health. Since solution ponds and heaps are part of a processing operation, tailings facility toxicity requirements do not readily apply. In particular, solutions that are sprinkled or dripped onto ore do not meet this standard of protection. When leaching has been completed, successful detoxification of the heap through one or more of the methods listed in a previous section of this article would result in compliance with this requirement, although the required standard of protection is vague. For these reasons, the minimum design criteria for tailings impoundments (Section 10) may not be adequate for heap-leach operations.

Siting criteria (Section 9) for tailings impoundments include requirements that are conceptually appropriate to heap-leach operations because they are similar to conventional mining and milling operations. Siting a heap-leach pad and pond system should be based on the same site characteristics required for a tailings facility. The process for determining and maintaining performance security (bonds) (Section 11) for activities covered by the Act is equally applicable to heap-leach operations.

Some other aspects of the Metal Mining and Milling Act are:

- Agencies with regulatory authority are required to inspect mining and milling facilities four times a year.
- The DOE will hold all state performance securities for each site.
- Criteria for designing tailings impoundments and siting, including site geology, liner design, and leak detection and collection, are established.
- A waste-rock management plan must be developed by the operator and approved by the DOE and DNR.
- Citizens can observe and verify water sampling by either the mine operator or the DOE.
- Agencies are required to conduct post-closure monitoring.
- Citizens are allowed to file lawsuits.

FUTURE APPROACHES TO REGULATION OF CYANIDE HEAP LEACHING IN WASHINGTON

In its 1994 session, the Washington State Legislature passed a moratorium on cyanide heap-leach until June 30, 1996, and directed DNR and DOE to gather more information about the use of the technique and to review the adequacy of the laws.

The authors recently prepared a report for the legislature in which the following recommendations for improving oversight of heap-leach mines were made:

- *Use the Metal Mining and Milling Act to regulate heap-leach operations.*

  This Act appears to be the best readily available vehicle for regulating these operations. Impacts that were inadequately regulated by the waste management laws appear to be covered by the Act. Because the Act specifies that operations using chemicals in their processing are regulated, all cyanide heap-leach mines are included and must prepare an EIS. The DOE is the SEPA lead agency for the EIS. Any new cyanide heap-leach operation would trigger a site-specific investigation as part of the EIS. Public involvement is an integral part of the SEPA process.

- *Give legislative intent but not detailed descriptions of procedures or standards.*

  Any changes to existing statutes should provide legislative intent but not detailed descriptions of procedures or standards. Regulation of heap-leach processing is compatible with the Metal Mining and Milling Act combined with guidance documents jointly prepared and accepted by DOE and DNR.

- *Develop heap-leach performance standards and guidelines.*

  Developing rigid design criteria that would be applied statewide is not practical because of the wide range of geologic, hydrologic, and climatic conditions in Washington. However, it may be appropriate to develop heap-leach performance standards and guidelines. Several states (such as Colorado [Doerfer, 1992] and Nevada) have opted to develop heap-leach guidelines instead of detailed regulation.

  The Metal Mining and Milling Act encourages development of site-specific requirements. This is consistent with conclusions reached by the EPA (NUS Corp. and U.S. Environmental Protection Agency, 1988) with regard to the development of draft criteria for designing Municipal Solid Waste Landfill containment systems. EPA studies showed that a site-specific, risk-based approach would be most appropriate in these circumstances. In reaching its conclusion, the EPA specifically recognized the importance of climate and geologic factors, including impacts to ground water, at each site (Ellison and others 1992).

  In response to the direction given in the Act, DOE is preparing guidelines for designing tailings facilities. A similar approach could be used for designing heap-leaching operations. Guidelines serve several purposes:

  - When engineering design criteria for critical components are established, then site-specific conditions are easy to develop.
  - Areas of acute environmental concern and expectations for mitigation are identified early in the review process.
  - The result of establishing guidelines will be a more efficient and streamlined environmental review and permitting process.

■ *Other recommendations include:*

- Regulate reclamation of new underground mines and their related surface disturbance under RCW 78.44.
- Eliminate size threshold for reclamation of metal mines in RCW 78.44.
- Establish an adequate funding source for developing guidelines and regulations.

Acknowledgments

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Oil and Gas Permits Issued for Activity in Washington, 1993–1994

During 1993 and 1994, no significant petroleum exploration occurred in Washington. Testing activities on the Ferndale No. 2 coalbed-methane well have been temporarily suspended. Washington Natural Gas plans to expand the Jackson Prairie Gas Storage Project by drilling two wells in 1995. Hunt Oil Company has been granted an extension for Permit 445 to drill a deep wildcat well in Lewis County. FSL, from south line; FEL, from east line; FWL, from west line.

Company	Permit no.	Unique no.	Well name	Legal description	Ground elevation	Total depth (estimated)	Date issued	Status
Washington Natural Gas – Jackson Prairie Gas Storage	439	041-00166	R. Gunther #3 Storage Unit #910	2,918′ FSL, 1,099′ FEL, sec 8, T12N, R1W, Lewis County	535′	(3,500′)		Canceled
Washington Natural Gas – Jackson Prairie Gas Storage	440	041-00167	Longview Fibre #17 Storage Unit #912	201′ FEL, 736′ FSL, sec 17, T12N, R1W, Lewis County	522′	(3,500′)		Canceled
Washington Natural Gas – Jackson Prairie Gas Storage	441	041-00168	J. Alexander #1 Storage Unit #911	1,158′ FSL, 1,093′ FWL, sec 9, T12N, R1W, Lewis County	530′	(3,500′)		Canceled
Palo Petroleum Inc. and Texaco Exploration and Production Inc.	442	033-00049	Palo–Texaco Black Diamond #6-1	2,300′ FSL, 400′ FWL, sec 6, T21, R7E, King County	860′	(4,000′)	08-04-92	Canceled
Palo Petroleum Inc. and Texaco Exploration and Production Inc.	443	033-00050	Palo–Texaco Black Diamond #11-1	660′ FSL, 1605′ FEL, sec 11, T21N, R6E, King County	700′	(4,000′)	08-04-92	Canceled
Rival Resources Inc.	444	073-00098	Ferndale #2	1,320′ FEL, 1,320′ FSL, sec 25, T39N, R2E, Whatcom County	100′	(1,850′)	11-19-92	Suspended
Hunt Oil Co.	445	041-00169	HOC Clevinger #1	2,279′ FWL, 2,333′ FSL, sec 1, T12N, R4E, Lewis County	1,125′	(15,000′)	5-13-94	
Washington Natural Gas – Jackson Prairie Gas Storage	446	041-00170	Longview Fibre #17 Storage Unit #911	1,750′ FEL, 1,000′ FSL, sec 17, T12N, R1W, Lewis County	530′	(3,050′)	11-23-94	
Washington Natural Gas – Jackson Prairie Gas Storage	447	041-00171	Manke #1 Storage Unit #910	710′ FEL, 115′ FSL, sec 21, T12N, R1W, Lewis County	410′	(3,000′)	11-23-94	

Resolution of the National Governors Association, January 1995

NR-17. GEOLOGIC MAPPING

17.1 Preamble

Geologic maps are a principal source of critical earth-related information required by federal, state, and local government agencies and the private sector. They are essential for numerous assessments, evaluations, and decisions related to the economic development and maintenance of the environment of the nation. These maps provide vital information needed for land-use planning. In particular, they are indispensable for locating disposal sites for municipal, hazardous, and radioactive wastes; locating and protecting surface water and groundwater resources; locating and developing mineral and energy resources; reducing the risks from earthquakes, landslides, and ground failure hazards; predicting hazards from volcanoes and from stream and shoreline erosion; siting critical emergency facilities; routing highways and public utility lines; and investigating basic earth science matters.

17.2 Recommendations

Geologic map coverage of the nation, however, is critically out of date and insufficient to meet the demands of private, industrial, and government agency users. The nation's Governors strongly support national legislation to build the nation's geologic map database through a program to be implemented in equity partnership between the states (through their geological surveys or other designated agencies) and the federal government. The program must be sufficiently funded at both the federal and state levels to permit achieving complete geologic map coverage for the nation at an appropriated level of detail within a reasonably short period of time.

Time limited (effective Winter Meeting 1995–Winter Meeting 1997).

Adopted August 1991 (formerly Policy D-16).

Washington's Coal Industry—1994

Henry W. Schasse and David K. Norman
Washington Division of Geology and Earth Resources
PO Box 47007, Olympia, WA 98504-7007

In 1994, Washington had two producing coal mines: the Centralia Mine in north-central Lewis County and the John Henry No. 1 Mine in south-central King County. Production was up slightly from last year by about 129,000 short tons.

The John Henry No. 1 Coal Mine produced 233,086 clean short tons of bituminous coal in 1994, up 5 percent from its 1993 production. The mine is operated by the Pacific Coast Coal Co. (PCCC), a joint American and Japanese venture. PCCC exported 61 percent of its 1994 coal sales to South Korea to be used as steam coal. Thirty-eight percent of its 1994 sales was supplied to the industrial sector of Washington State; this value is up from 27 percent a year ago. The remainder was sold to the Centralia Steam Plant for blending and to residential customers for space heating.

In 1994, PCCC mined coal from two pits at the John Henry Mine, located about 2 mi northeast of the town of Black Diamond. Most of the coal mined comes from Pit No. 1 (Fig. 2), where the Franklin Nos. 7, 8, 9, and 10 coalbeds are mined. A small amount was mined from Pit No. 2, where only the Franklin No. 12 coalbed is mined. The Franklin coalbeds occur stratigraphically near the base of the undivided Eocene Puget Group in nonmarine deltaic sedimentary rocks. PCCC is now mining the higher levels of the anticlinal structure that occurs in the mine, to the west of the deepest part of Pit No. 1 (where mining has been completed and backfilling is taking place). When we visited the mine in early January of 1995, PCCC was mining the Franklin Nos. 7, 8, and 9 coalbeds along the northwest limb of the anticlinal structure, near its crest. As PCCC mines the Franklin Nos. 9 and 10 coalbeds, it also mines an intervening clay bed, which it sells to a customer who blends it with high-alumina clay for use in making portland cement in Seattle.

The Centralia Coal Mine, operated by the Centralia Mining Co., a division of PacifiCorp, is the state's largest coal producer. The mine is located 5 mi northeast of the city of Centralia in Lewis County. The mine completed its 24th year by producing 4,634,883 clean short tons of subbituminous coal; this is 117,000 tons more than in 1993.

The mine's average annual production for the past 5 years has been 4.8 million tons and 4.2 million tons over its lifetime. The coal is supplied to the Centralia Steam Plant, the mine's sole customer, located about a mile from the mine. Coal production for 1994 came from seven coalbeds mined at three pits. Beds mined in 1994 were the Big Dirty (and its two splits), Little Dirty (and

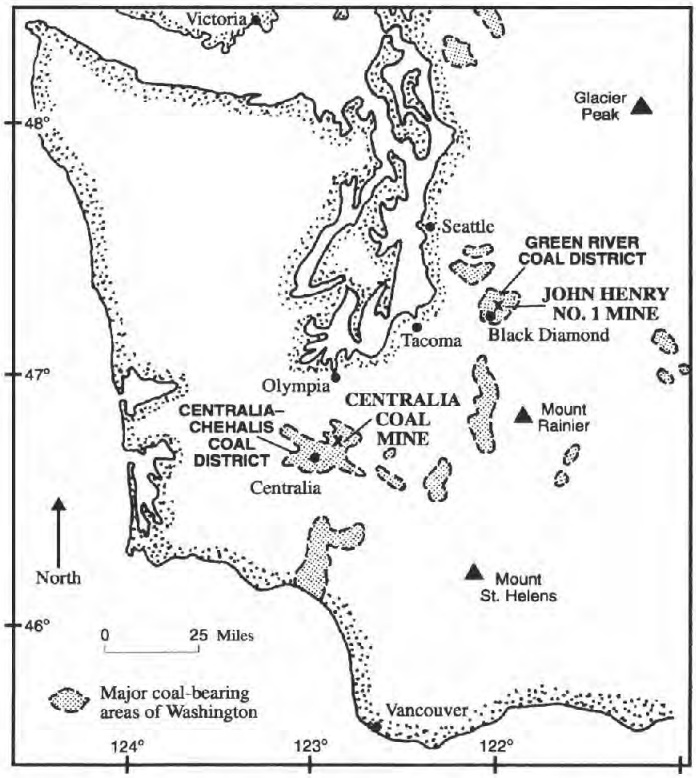

Figure 1. Coal-producing areas and districts, western Washington.

Figure 2. John Henry No. 1 Coal Mine, Pit No. 1, January 1995. View shows the northwest limb of the anticlinal structure, where mining has been completed. Currently coal is being mined just out of view (at the bottom of the photograph) from the Franklin Nos. 7, 8, and 9 coalbeds. Two coalbeds higher in the stratigraphic section appear in the light-colored sediments in the highwall; the beds dip to the northwest (view to the north). The coal is hauled to a beneficiation plant located ⅓ mi from the pit.

two splits of this coalbed), Smith, Lower Thompson, Upper Thompson, Tono No. 1, and Tono No. 2. These coalbeds are part of the Skookumchuck Formation, composed of nearshore marine and nonmarine sedimentary rocks. The Skookumchuck is a member of the Eocene Puget Group.

COAL MINE RECLAMATION

Reclamation at Washington's coal mines is regulated by the Department of the Interior's Office of Surface Mining (OSM). The John Henry mine is permitted for 420 acres and has disturbed 270 acres. Reclamation is ongoing, and the operators are currently backfilling the north end of Pit No. 1 (Fig. 3).

In 1991, OSM gave the Centralia Mining Co. the prestigious Director's Award for best reclamation, given to only one mine nationwide each year. In 1993, the mine won an OSM award for best wildlife habitat management.

The Centralia Coal Mine is permitted for 14,500 acres, has disturbed approximately 6,100 acres, and has successfully reclaimed 1,900 acres. Approximately 350 acres mined before enactment of the Surface Mining Control Act of 1977 were successfully reclaimed under the authority of the Department of Natural Resources.

Post-mining land use at the Centralia Coal Mine emphasizes vegetation diversity to support a wide variety of wildlife. Five wildlife habitats, characterized by dominant species, are present: upland coniferous forest (Fig. 4) (primarily Douglas-fir), upland hardwood forest (primarily western red cedar and red alder), bottomland riparian zone, sedge-meadow/pasturelands, and wetlands and ponds (Fig. 5). Diversity and transitions of vegetation among these zones provide cover and breeding, nesting, and forage habitat year-round for waterfowl, shorebirds, raptors, and small and large mammals. ■

Figure 3. Backfilling of Pacific Coast Coal Co. Pit No. 1, John Henry mine. Note the lake at the bottom of this view. On the left side of this photograph is the north limb of the anticline where mining stopped. (Photo by Glenn Waugh, Office of Surface Mining.)

Figure 4. *(center)* Reforestation at the Centralia Coal Mine. Shown are 5-year-old Douglas-fir on a reclaimed spoil area. In the foreground is newly graded spoil ready for topsoil application and revegetation. (Photo by Roy Garrison, Centralia Mining Co.)

Figure 5. *(right)* As part of reclamation at the Centralia Coal Mine, wetlands with diverse vegetation are created to provide habitat and wildlife forage. Wetlands at this mine are an integral part of the larger ecosystem being reclaimed. (Photo by Roy Garrison, Centralia Mining Co.)

Current Faculty and Student Geological Research at Washington Universities and Colleges

Compiled by Rebecca Christie, DGER; Meghan Miller, Central Washington University; Candy Oswald, Eastern Washington University; Linda Critchlow, University of Puget Sound; Nancy Neyens, University of Washington; Sue Elder, Washington State University; Chris Sutton, Western Washington University; Bob Carson, Whitman College; and Newell Campbell, Yakima Valley College.

Taken from material submitted by press time. Names in parentheses with the faculty projects are students; with student projects, they are faculty collaborators unless otherwise noted. Affiliations other than with the pertinent school are bracketed. Some projects involve areas outside of Washington.

CENTRAL WASHINGTON UNIVERSITY

Present-day kinematics and the evolution of transpeninsular slip in northern Baja California—*T. H. Dixon, E. D. Humphreys, M. M. Miller*

Holocene lacustrine records of decade- to century-scale variations in monsoon precipitation, northwestern India—*L. L. Ely*

GIS technology transfer to local governments—*Jim Hinthorne*

Satellite-based observations of the transition from an oceanic rift to continental transform, northern Baja California, Mexico—*M. M. Miller, R. C. Crippen, J. Lee, F. Suarez*

Active deformation in the Mojave Desert region and the Walker Lane belt: A Global Positioning System experiment—*M. M. Miller, M. P. Golombek, R. K. Dokka*

The role of extension during the evolution of a transform plate boundary, northeastern Baja California, Mexico—*M. M. Miller, J. Lee*

Application of high resolution topography and remote sensing imagery to the kinematics of fold-and-thrust belts—*C. M. Rubin*

Interactive petrographic instrumentation in geology—*M. M. Miller, C. M. Rubin, J. Hinthorne, R. D. Bentley*

Active crustal shortening along the southern margin of the central Transverse Ranges, California: A paleoseismic study—*C. M. Rubin, K. Sieh [CalTech]*

Paleoseismic studies of the Mojave shear zone: Slip rates and recurrence interval on the Emerson and Camp Rock faults—*C. M. Rubin, K. Sieh [CalTech]*

Field studies in geology and biology: Sparking pre-freshman interest—*Nick Zentner, Liz Zentner*

EASTERN WASHINGTON UNIVERSITY

Faculty Research

Mineralogy of the Golden Horn batholith, North Cascades, Washington—*Russell C. Boggs*

Structural states of feldspars as an indicator of sedimentary provenance—*Russell C. Boggs*

Mineralogy of the Sawtooth batholith, Idaho—*Russell C. Boggs*

Formulation of a finite-difference model of the Spokane Valley–Rathdrum Prairie aquifer system, Washington and Idaho—*John P. Buchanan*

Radon gas distribution in cave systems in the Pacific Northwest—*John P. Buchanan*

Hydrogeologic study of the West Plains area, Spokane County, Washington—*John P. Buchanan*

Hydrogeologic investigation of West Medical Lake, Spokane County, Washington—*John P. Buchanan*

Radon soil gas mapping of Spokane County, Washington—*John P. Buchanan*

Permian bryozoans of the Productus Creek Group, South Island, New Zealand—*Ernest H. Gilmour*

Biostratigraphic studies of Pennsylvanian and Permian bryozoans in North America and Pakistan—*Ernest H. Gilmour*

Permian bryozoans of the carbonate units of the Mission Argillite, northeastern Washington—*Ernest H. Gilmour*

Inductively coupled plasma mass spectrometry in environmental research and mineral exploration—*Mohammed Ikramuddin*

Chemical analysis of water, wastewater, soil, and sediments using EPA methods and EPA quality assurance/quality control protocol—*Mohammed Ikramuddin*

Distribution and transport of inorganic contaminants in ground water and soil—*Mohammed Ikramuddin*

Trace-element geochemistry of water, soil, and stream sediments affected by mining activities—*Mohammed Ikramuddin*

Distribution of metals in the Spokane aquifer, Washington—*Mohammed Ikramuddin*

Development of new analytical methods by ICP-mass spectrometry, inductively coupled plasma-emission spectrometry, and Zeeman graphite furnace atomic absorption—*Mohammed Ikramuddin*

Hydrogeochemical and biogeochemical methods of exploration for gold and silver—*Mohammed Ikramuddin*

Use of thallium, cesium, and boron as guides to mineral deposits—*Mohammed Ikramuddin*

Geochemistry of gold-silver deposits—*Mohammed Ikramuddin*

Isotopic composition of lead in contaminated sediments and soil—*Mohammed Ikramuddin*

Chemical analysis of ultrapure electronic materials—*Mohammed Ikramuddin*

Glacial and catastrophic flood history of eastern Washington—*Eugene P. Kiver*

Quaternary map of northeastern Washington east of the Okanogan River—*Eugene P. Kiver*

Geology of national parks—*Eugene P. Kiver*

Paleozoic continental margin sedimentation in the western U.S.—*Linda B. McCollum*

Pattern of extinction and replacement at the Lower–Middle Cambrian boundary in the Great Basin—*Linda B. McCollum*

Conodont biostratigraphy of the Late Cambrian and Early Ordovician within the Getchel Gold trend, Nevada—*Linda B. McCollum*

Geologic mapping in the Osgood Mountains, Nevada—*Linda B. McCollum*

Transcurrent faulting and suspect terranes in the Great Basin—*Linda B. McCollum*

Alkaline igneous rocks and related precious metal deposits—*Felix E. Mutschler*

Space-time tectonic and magmatic maps of the Cordillera—*Felix E. Mutschler*

Compilation of a computer database of whole-rock chemical analyses of igneous rocks—*Felix E. Mutschler*

Use of remanent magnetization direction to correlate air-fall ash deposits from Cascade volcanoes—*William K. Steele*

Magnetostratigraphy of the Clarkia Miocene fossil site—*William K. Steele [with the University of Idaho]*

Student Research

Hydrogeology and water budget analysis of West Medical Lake, Spokane County, Washington—*Nasir Aziz*

Impact of mining on trace element geochemistry and lead isotopic composition of soil from the Coeur d'Alene area, Idaho—*Nikolaos Condoyannis*

Hydrogeologic characterization of the West Plains area, Spokane County, Washington—*William B. Deobald*

Description and interpretation of late Quaternary sediments in the Rocky Reach of the Columbia River Valley, Douglas County, Washington—*Stanley C. Gough*

Granite molybdenite systems of the North American Cordillera—*Curt A. Hughes*

Soil-gas radon mapping of the Spokane 1:100,000 scale quadrangle, Washington—*Eric A. Johnson*

Distribution of major and trace metals in ground water of the Spokane aquifer, northeastern Washington—*Zheng Yi*

UNIVERSITY OF PUGET SOUND

Faculty Research

Literature review of older batholithic rocks of eastern Washington—*Ken Clark*

Structural geology and igneous petrology and stratigraphy of the Pacific Northwest and the evolution of the Coast Range basaltic province—*Ken Clark*

Ongoing projects on Central American volcanoes—*Al Eggers*

Seismicity and structure of the Puget Lowland—*Al Eggers*

Use of x-ray fluorescence in chemical analysis of rocks and minerals—*Al Eggers*

Volcanology, emphasizing recent Mount Rainier tephras and geochemical evolution of Rainier magma systems—*Al Eggers*

Geomorphology and Quaternary geology of the Puget Lowland (Puget lobe) and Colorado Rockies—*Barry Goldstein*

River-valley evolution of northern New Mexico—*Barry Goldstein*

Triassic stratigraphy, sedimentology, and paleontology of northern New Mexico—*Barry Goldstein*

Electron microscopy of diatoms and radiolarians from Northwest localities—*Stewart Lowther*

Mesozoic paleobotany—*Stewart Lowther*

Petrography and micro-analysis of Mesozoic and Cenozoic sandstones and igneous rocks—*Stewart Lowther*

Ultrastructure of modern and fossil pollen—*Stewart Lowther*

Magnetostratigraphy of the Cascade volcanoes and Cenozoic mafic dikes—*Mike Valentine*

Paleomagnetism and/or structural geology on the Olympic Peninsula and to the south—*Mike Valentine*

UNIVERSITY OF WASHINGTON

Faculty Research

Late Quaternary climate and vegetation history of Beringia (Alaska and northeastern Siberia)—*Patricia M. Anderson, Linda B. Brubaker*

Unified model of mountain drainage basin geomorphology for watersheds with areas of hundreds of square kilometers—*Lee Benda, Dan Miller, Thomas Dunne*

Linking phase relations, thermal budgets, and deformation in the generation and mobilization of dehydration melts, Ivrea Zone, Italy—*George Bergantz, (Scott Barboza)*

Origin of compositional zoning and the mechanics of assembly of plutonic complexes, Sierra Nevada, California—*George Bergantz, (Steve Macias)*

Southern end of the Straight Creek fault, Easton 1:24,000 and adjacent quadrangles—*Eric Cheney*

Stratigraphy and structure of Quesnellia in Okanogan and Ferry Counties—*Eric Cheney*

Hydrology, sediment transport, and geomorphology in the Amazon River basin, Brazil and Bolivia—*Thomas Dunne (Rolf Aalto, Elizabeth Safran)*

Thermal processes in the active layer: Defining boundary conditions and quantifying heat transfer processes, western Spitsbergen, Norway—*Bernard Hallet*

Crustal evolution and tectonic history of southern Mexico and central America—*Uwe Herrmann, Bruce K. Nelson*

Chemical and isotopic study of upper mantle and lower crustal xenolith suites from Montana and Wyoming—*Tony Irving, Scott Kuehner*

Electron microprobe and electron diffraction study of ferric iron sanidine from the Leucite Hills, Wyoming—*Scott Kuehner, Dave Joswiak*

Chemical and thermal implication of fluid-flow in subduction zones; examples from the Franciscan Complex, California and the Tauern window, Austria—*Bruce K. Nelson*

Geochronologic and isotopic investigation of crust formation in far-eastern Russia—*Bruce K. Nelson*

Isotopic and geochemical study of the provenance of sediments in the Methow and Tyaughton basins, northern Washington and southern British Columbia—*Bruce K. Nelson*

Holocene ^{13}C, climate and carbon cycling: Carbon isotopes in lake sediments and macrofossils from Heal Lake, British Columbia—*Minze Stuiver (Paula J. Reimer)*

Younger Dryas(?) climatic reversal in the western United States—*Terry Swanson, Stephen Porter*

Trace element diffusion in apatite from the Idaho batholith: Implications for the interpretation of zoning in 'inherited' apatites—*Jeff Tepper [Valdosta State University], Scott Kuehner*

Chemical characterization and interpretation of the vaterite–aragonite phase transition in salmonid otoliths—*Eric Volk, Scott Kuehner*

Integration of compositional and textural information in the interpretation of the pressure-temperature-fluid history of rocks from a sedimentary through granulite facies sequence—*Donna Whitney [University of North Carolina], Scott Kuehner*

Graduate Student Research

The physical characteristics, physics, and geomorphic consequences of wood debris jams in fluvial networks in the Queets River basin, Olympic National Park—*Tim B. Abbe*

Petrologic, stratigraphic and geochemical studies of the tholeiitic to alkalic transition of Hawaiian basalts on East Molokai and Waianai volcanoes—*Nuni Anders*

Late-Pleistocene and Holocene glacial records preserved in alpine lakes in the Pacific Northwest—*Douglas H. Clark (Alan R. Gillespie*

Petrology and stratigraphy of the upper Banded Zone, Stillwater Complex, Montana—*Catherine Cullicott*

Trace element variability in skeletal tissues of domesticated pigs (*Sus scrofa*) raised on controlled diets—*Diana M. Greenlee (Scott Kuehner)*

Understanding post-depositional alteration of trace-element concentrations in archaeological human bones—*Diana M. Greenlee (Scott Kuehner)*

Climatic change at the last glacial/interglacial transition on Mount Rainier volcano, Washington: A study of the glacial landforms to delineate timing and extent of the glacier advances—*Jan T. Heine*

Microstructural adaptation to gnawing stresses in the incisor enamel of rodents—*Howard F. Heller (John Rensberger)*

An examination of past velocities of rock glaciers to help determine the origins of rock glaciers—*Sarah Konrad (Steve Porter)*

Thermal link between the atmosphere and permafrost—*Jaakko Putkonen*

Post-erosional basalt petrogenesis on the island of Kauai, Hawaii, and implications for melt production and melt–solid interaction in the mantle—*Peter Reiners*

Chromium geochemistry at a contaminated site: Laboratory, field, and computational study of reactions between acid-waste solutions rich in hexavalent chromium and calcareous desert soils—*Carol Stein*

Metal oxide and hydroxide formation: Coprecipitation of chromium(III) and aluminum(III) and development of ordered phases in gels—*Carol Stein*

Uptake of Cr(VI) in gypsum and the $CaSO_4.2H_2O$—$CaCrO_4.2H_2O$ solid solution series—*Carol Stein*

Lead in sandblasting grit and environmental consequences for Puget Sound—*Carol Stein (Bruce Nelson)*

Migration of metals from plating waste: Field and laboratory study of near-shore sediments from a disposal site on Puget Sound—*Carol Stein*

Microbial reduction of hexavalent chromium—*Carol Stein*

Microbial alteration of mineral surfaces—*Carol Stein*

Microbial degradation of contaminants in marine sediments: A site capping study—*Carol Stein (J. Deming)*

Glaciation and neotectonic deformation on the western Olympic Peninsula, Washington—*Glenn Thackray*

Neotectonic deformation on the Olympic coast, Washington: Implications for tectonic processes and earthquake hazards—*Glenn Thackray (Stephen Porter)*

Origin and activity of the Hell Creek 'fault', southwestern British Columbia—*Stephen Thompson*

Landslides, rock mass strength, and topographic relief limits for the Chuckanut Formation and Quaternary glacial sediments—*Kevin M. Schmidt*

Experimental debris flow initiation: Controlled artificial watering experiments on a hollow in the Oregon Coast Range—*Kevin M. Schmidt*

WASHINGTON STATE UNIVERSITY

Faculty Research

Nonlinear and competitive nonionic organic pollutant sorption in natural clay-rich aquitards—*Richelle M. Allen-King (Christene Albanese)*

Vertical spacial variability of nonlinear perchloroethene sorption in a sandy aquifer—*Richelle M. Allen-King*

Flow correlation in Columbia River Basalt Group of southeast Washington—*Peter Hooper*

Geology of the Lewiston Basin and the Lewiston structure in southeastern Washington—*Peter Hooper*

Investigation of fluid sources and the effects of water/rock interaction in a fossil hydrothermal plume, Rico, Colorado—*Peter B. Larson*

Skarn deposits in the South Pacific (including Australia, Irian Jaya, and Papua New Guinea)—*Larry Meinert*

3-D fold morphology, using examples of buckled vein systems from the Kootenay arc—*A. J. Watkinson*

Tectonic and strain models of the Kootenay arc, northeastern Washington—*A. J. Watkinson*

Carboniferous crinoid faunas of the western U.S.: New Early and Middle Carboniferous crinoids of Montana, Nevada, and Utah and new Late Carboniferous crinoids of New Mexico—*G. D. Webster*

Compilation of the Paleozoic crinoid literature with an index of illustrated or described species worldwide—*G. D. Webster*

Early and Late Carboniferous boundaries based on conodonts from stratigraphic sections in the western U.S.—*G. D. Webster*

Graduate Student Research

Major and trace element variation in the Cretaceous Spirit pluton, northeast Washington—*Leslie Ann Driver (Peter B. Larson)*

Correlation between PCE sorption, hydraulic conductivity, and sediment facies variability in an unconsolidated aquifer—*Richard Halket (Richelle M. Allen-King, David Gaylord)*

Residence time of labile carbon in the vadose zone—*Diana J. Holford (C. Kent Keller)*

Occurrence and fate of nitrate in pore water and ground water in loess—*Todd K. Kafka (C. Kent Keller)*

Geology of the intersection of the Hite and Olympic lineament fault zones near Walla Walla, southeast Washington—*Steve Kuehn*

Geology of the Key East gold deposit, Ferry County, Washington—*Christopher H. Lowe (Peter B. Larson)*

Extent and character of oxygen isotope exchange and major element metasomatism in the Rico, Hermosa, and Cutler Formations, Rico, Colorado—*Tom Meuzelaar (Peter B. Larson)*

Origin of the Colville batholith and associated volcanic rocks, northeast Washington—*George Morris*

Differentiating the rocks of the Rossland Group, northeastern Washington—*R. L. Patton (A. J. Watkinson)*

Ground-water residence times in the Columbia River basalts of southeastern Washington: A stable isotope study—*Thomas H. Reppe (C. Kent Keller)*

Petrogenesis of the Eocene Boulder Mountains stock, central Idaho—*Melissa C. Robertson (Peter B. Larson)*

Release of chloride from basalt: The implications for the chloride mass-balance approach to estimating ground-water recharge—*Robert B. Roe (C. Kent Keller)*

Geophysical constraints on the tectonic evolution of the Columbia Plateau—*Stan Sobczyk*

WESTERN WASHINGTON UNIVERSITY

Faculty Research

Paleomagnetic investigations of inclination anomalies in the Aegean Sea—*Myrl Beck*

Paleomagnetic investigations of the Atacama fault region, Chile—*Myrl Beck*

Tectonics of the southern Caribbean—*Myrl Beck*

Geologic history and tectonic evolution of the eastern San Juan Islands: A study of the structure and tectonics of Mesozoic strata—*Dave Engebretson*

Magnetic anomalies and bathymetry of the Central Pacific near the Nova–Canton Trough: A study of tectonic evolution between 160 and 100 Ma—*Dave Engebretson*

Plate kinematics of the Pacific Basin in relation to the Mesozoic-to-present tectonic evolution of the Arctic region—*Dave Engebretson*

Wadi Ziglab Project: A study of recent landslides in northern Jordan—*John Field [University of Toronto archaeological investigation]*

Survey of Washington earth-science teachers to assess their needs in integrating environmental topics into the classroom—*John Field*

Sedimentation and tectonics of the Eocene through Miocene clastic sedimentary rocks of the Crescent terrane, northern Olympic Peninsula—*Chris Suczek*

Origin of gold deposits along the Lone Jack–Boundary–Red Mountain trend, Whatcom County, Washington—*Antoni Wodzicki*

Graduate Student Research

Structure and metamorphosis in the Kwoiek Creek area, British Columbia—*Kris Alvarez*

Global plate reorganization at approximately 5 Ma: A global compilation of relative motion poles and their changes—*Lisa Hogan*

Comparison of spectral values of surface minerals in the Cuprite Mining District, using remote and quantitative FIS data—*Lynne Holland*

Interaction between ground water and river water along the Hanford Reach of the Columbia River, Hanford Nuclear Reservation, Washington—*Paul Humphreys*

The Wallula Fault Zone: A study of the structure and tectonic history of a portion of the Olympic–Wallowa Lineament—*Ingrid Hutter*

Sediment budget for the South Fork Nooksack River, Skagit and Whatcom Counties, Washington—*Jeff Kirtland*

Re-advance of the Cordilleran ice sheet in northwestern Washington and southwestern British Columbia during the Sumas stade—*Dori Kovanen*

Analysis of fluid inclusion leachate: Methods and applications to geothermometry—*Amy Loomis*

The geology and Cu-Zn-Au-Ag mineralization of the Lockwood volcanogenic massive sulfide deposit, Snohomish County, Washington—*Duane Olson*

Recent tectonic activity in the Chuckanut Mountains—*Paul Pittman*

Stratigraphy, provenance, and facies analysis of the Albian– Turonian Virginian Ridge Formation and Winthrop Sandstone, Methow basin, northeastern Cascades, Washington—*Phil Royce*

Tectonic implications of paleomagnetic data from Lago Verde and northern Isla Chiloe, southern Chile—*Brian Steele*

Net shore-drift and artificial structures along the estuarine beaches of Grays Harbor, Willapa Bay, and mouth of the Columbia River, Washington—*B. Patrice Thomas*

The stratigraphy and tectonics of the Hoko River Formation, northern Olympic Peninsula, Washington—*Laura Vaugeois*

WHITMAN COLLEGE

Faculty Research

Berg mounds and gravel bars deposited by the Missoula floods, Walla Walla County, Washington—*Bob Carson (Cindy Bartlett, Ryan Ott)*

Quaternary geology of the Clarks Fork region, Wyoming–Montana and the environmental geology of proposed Crown Butte gold mine—*Bob Carson, Eric Leonard [Colorado College], Dave DeSimone [Williams College], Mary Savina [Carleton College], (Kirby Bean)*

Geomorphology of the Wallowa and Elkhorn Mountains, Oregon: Fluvial, karst, glacial, and periglacial processes—*Bob Carson, (Keith Pohs, Ryan Bixby)*

Origin and emplacement mechanisms for clastic dikes in the Touchet Beds of south-central Washington: Soft-sediment deformation, liquefaction, earthquakes—*Kevin Pogue, (Janel Martin)*

Structure and petrography of granitic rocks of the Indus Syntaxis, northern Pakistan: Shear zones, mylonites, Himalayan deformation, transpression—*Kevin Pogue, (Peter Sak)*

Stratigraphy, sedimentology, and paleontology of the Late Pleistocene–Early Holocene 'Palouse Silt', southeastern Washington—*Patrick K. Spencer, (Jim Riesterer, Sarah Wheeler)*

Contact metamorphism in the northern Wallowa Mountains—*John Winter*

Petrology and structure of the Angmagssalik area, West Greenland—*John Winter, David Bridgwater [Geological Museum, Copenhagen], Hikon Austerheim [Geological Museum, Oslo]*

YAKIMA VALLEY COMMUNITY COLLEGE

Faculty Research

Earthquake assessment of Toppenish and Ahtanum Ridges, including trenching, seismograph installation, trilateration survey, and seismic line—*Newell Campbell [with Yakama Nation Water Resources Branch]*

Geohydrology of the Moxee and Selah Basins, including well cuttings, log analysis, and study of producing zones in Ellensburg Formation—*Newell Campbell* ■

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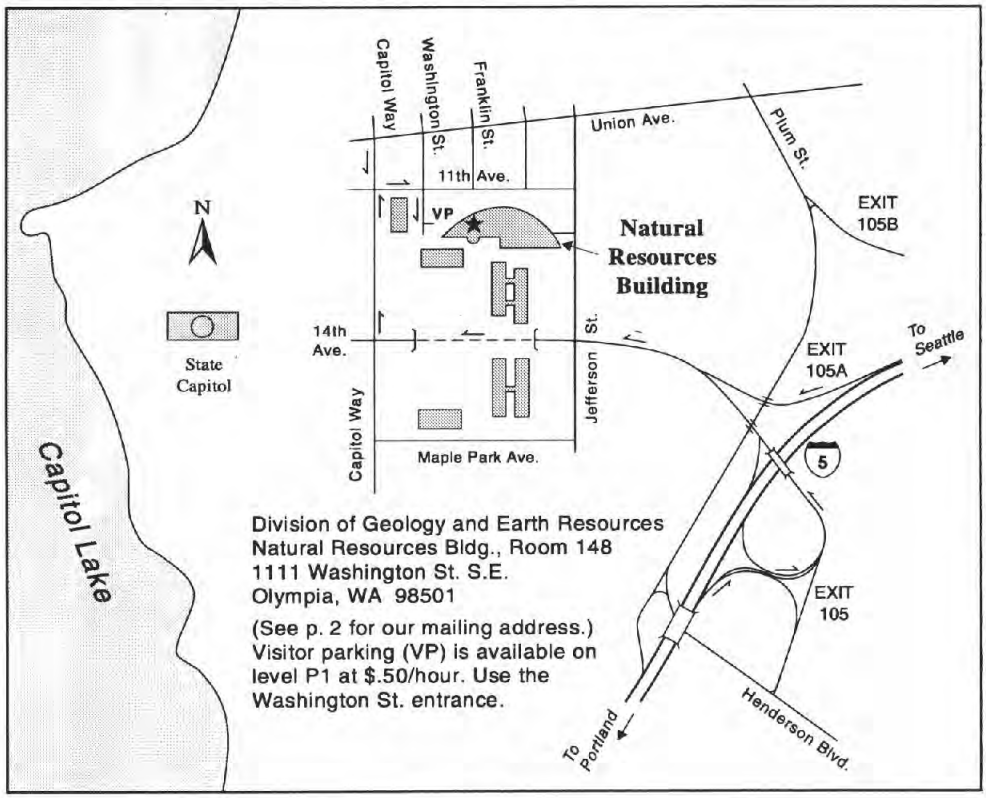

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Erratum

The price of the **Bibliography and index of the geology and mineral resources of Washington, 1993**, Open File Report 94-15, was erroneously listed as $4.25. It should be $2.78 + .22 tax = $3.00.

Our address and phone number are given on p. 2. Orders must be prepaid; make check or money order payable to the Department of Natural Resources. Taxes apply to Washington residents only. Please include $1.00 with each order to cover postage and handling.

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