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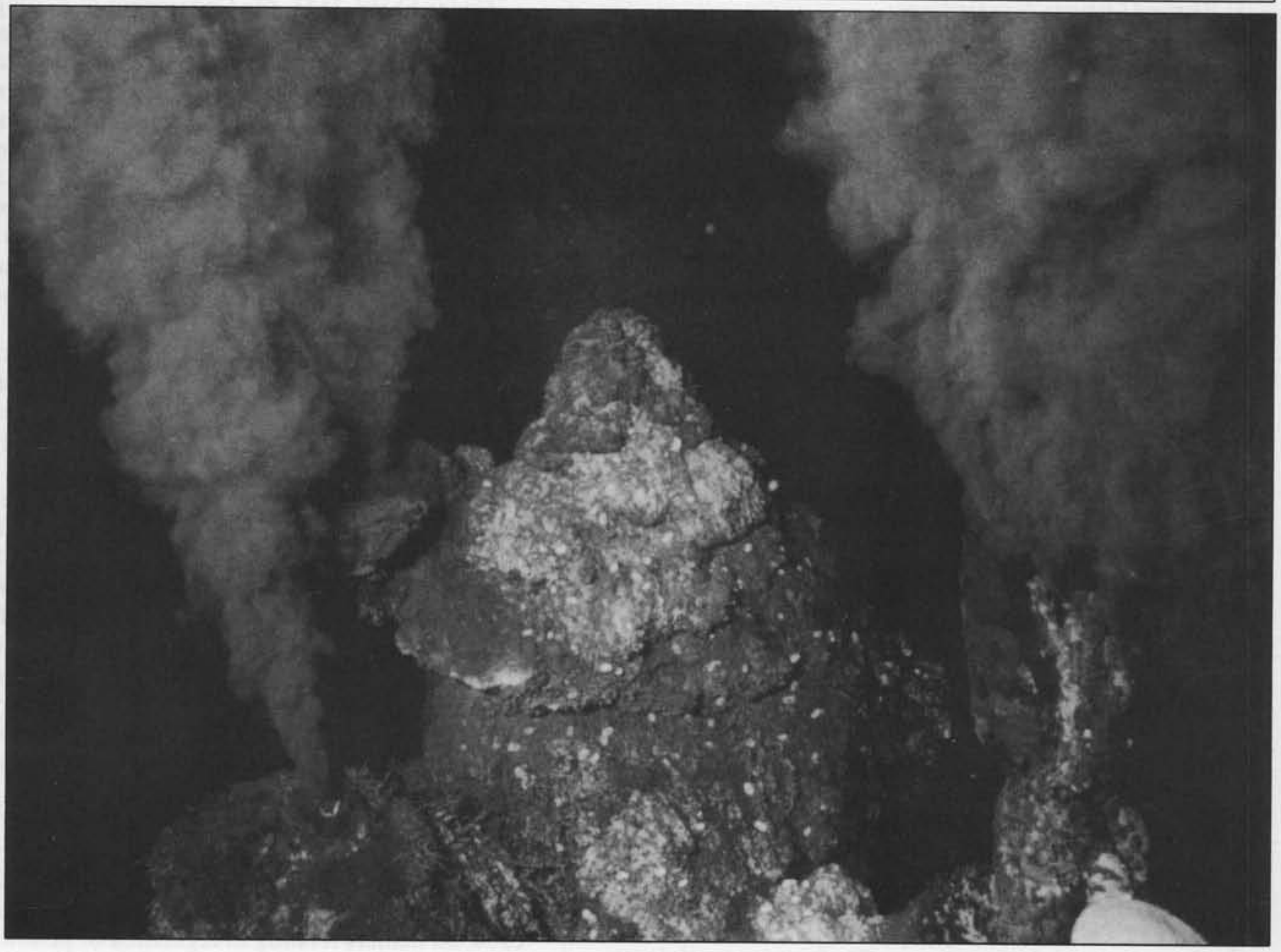

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Natural Resources
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Cover photo: Monolith vent black smokers located on the crest segment at the southern end of the Juan de Fuca Ridge off the coast of Washington photographed from the bow camera of Alvin submersible. The black smokers are represented by the cloudy material in the left and right center and upper portions of the photo. From a slide furnished by R. A. Koski, U.S. Geological Survey.

Developments in Environmental Regulation

by Ray Lasmanis, *State Geologist*

During its 1994 Session, the State Legislature passed bills affecting the environmental regulation of petroleum, geothermal resources, underground gas storage, and metals mining in Washington. Of these bills, Engrossed Substitute House Bill (ESHB) 2521, the Metals Mining and Milling Act, is the most important.

The Metals Mining and Milling Act is based partly on the findings of a task force of industry, environmental, and community voices, as well as those of the Departments of Ecology (DOE) and Natural Resources (DNR). The Act establishes a regulatory scheme for metal mining, which, after July 1, 1994, will overlap current regulations.

Under ESHB 2521, the Department of Ecology is responsible for preparing an environmental impact statement for each proposed metal mining and milling operation, independent of the scope of the project. A lack of appropriate monitoring was identified as a shortcoming of existing regulations. After July 1, 1996, each agency and each regulatory program will inspect Washington's 11 metal mines and (or) mills at least quarterly. The Bill also establishes criteria for tailings impoundment control and siting including site geology, liner design, and leak detection and collection. The Department of Ecology is also directed to implement a procedure for including citizens in water quality monitoring inspections.

The Departments of Natural Resources and Ecology are directed to work together to study the efficacy of existing heap leach regulations and to study funding for the new regulatory scheme. The agencies must report back to the Legislature prior to the next session.

The Legislature also made an effort to reduce bureaucracy by adopting the Acts relating to Regulatory Reform (ESSHB 2510) and to State Boards and Commissions (ESHBa 2676). The former will guide and restrict the ways in which the Department writes formal rules. The Boards and Commissions Act abolishes a number of governmental bodies including the Washington Oil & Gas Conservation Commission. The Commission, which had not convened a meeting in 4 years, lacked requisite expertise to address technical issues such as adjudication of petroleum rights and well spacing for coalbed-methane exploratory bores.

The Legislature chose to assign the duties of the Conservation Commission to the Department of Natural Resources. (Division of Geology and Earth Resources personnel had acted as staff to the Commission for several decades.) After July 1, 1994, all matters relating to regulation of petroleum, geothermal resources, and gas storage will be regulated by the Department of Natural Resources. This should significantly reduce the time involved for regulatory actions and reduce costs of regulation. For issues, such as adjudication, that require an impartial tribunal, the Commissioner of Public Lands will appoint examiners with appropriate expertise and integrity.

Implementing these three acts will involve additional work and responsibility for the Department of Natural Resources. ■

Washington's Mineral Industry—1993

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Gold production in Washington State during 1993 had an estimated value of $480.4 million, according to the U.S. Bureau of Mines (USBM). Production of gold continued to decline last year, down from the peak production of more than 320,000 ounces reached in 1991 (Fig. 1). Lead and zinc production was negligible, but despite the decreases in both precious-metal and base-metal production, the USBM estimate for 1993 total nonfuel mineral value was 2 percent greater than in 1992. The rise was primarily attributed to an increased value for magnesium metal (produced from dolomite) and the increased value for sand and gravel produced last year.

Production of industrial minerals, chiefly construction materials (sand and gravel, crushed stone, portland cement) accounted for 64 percent of the total nonfuel mineral production value (Minarik, 1994). Industrial mineral commodities produced in Wasington (in approximate decreasing order of importance) were: sand and gravel, crushed stone, limestone and dolomite, diatomite, silica sand, olivine, clays, mineral water (not discussed in this article), gemstones, peat, and gypsite.

The emphasis of exploration for metallic minerals in Washington State changed in 1993. Many larger mining companies with well-established exploration programs continued to maintain their programs or even acquired additional properties. Companies that have small exploration programs or limited operating budgets for Washington State scaled back or terminated their programs. All companies, large and small, as well as individuals, dropped or reduced the number of unpatented mining claims on federal land. As a result, the total number of unpatented claims for Washington and Oregon combined fell from approximately 36,000 to 15,000. Although many claims on federal land were dropped, companies and individuals maintained state mineral leases and those properties for which mineral rights are not owned by the federal government.

Other changes in emphasis for mineral exploration in Washington are beginning to emerge. The rush to find another Crown Jewel deposit has subsided, and some companies are developing new exploration models or are broadening their focus. Exploration for volcanogenic massive sulfide mineralization is increasing, particularly in British Columbia, and some companies may begin to extend exploration efforts into Washington State.

Exploration for zinc and lead mineralization in the northeast corner of the state picked up in 1993. Resource Finance Corp. conducted an extensive program of underground development to confirm drill-indicated reserves at the Pend Oreille mine. Two companies also acquired and drilled properties for zinc and lead mineralization.

Employment in the nonfuel mineral industries showed an apparent decrease in 1992 (the latest year for which data are available) relative to 1991. An average of 2,586 people were employed in 1992 compared to 2,813 in 1991. These statistics reflect the average annual employment in Standard Industrial Classification (SIC) codes 10 (metal mining) and 14 (nonmetallic minerals, except fuels) as compiled by the Washington State Employment Security Department. The decrease in employment may only be apparent because acquisitions and mergers may shift workers from one SIC classification code to another, depending on the classification of the acquiring company. In contrast, employment in SIC code 32 (stone, clay, glass, and concrete products) jumped from 7,525 workers in 1991 to 7,887 in 1992 and could account for some of the decreases in the nonfuel mineral categories.

Table 1 summarizes mining and mineral exploration activities in Washington for 1993. The majority of this volunteered information was obtained from an annual survey of mining companies and individuals. Not all questionnaires were returned; therefore Table 1 is not a complete listing of mineral activities. The property or mine numbers are keyed to Figures 2A–D.

Questions about the information in this and the following two articles can be referred to Bob Derkey and Chuck Gulick in the Division's Spokane office. ■

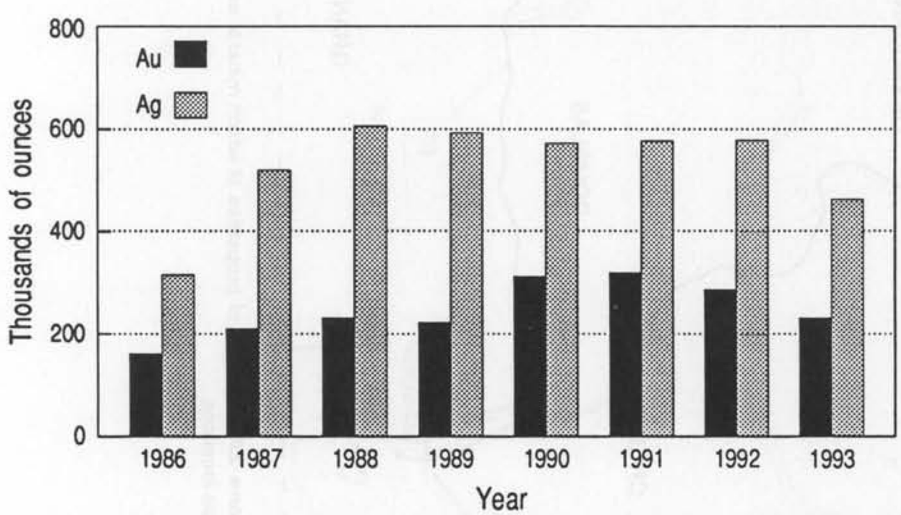

Figure 1. Gold (Au) and silver (Ag) production in Washington, 1986 through 1993.

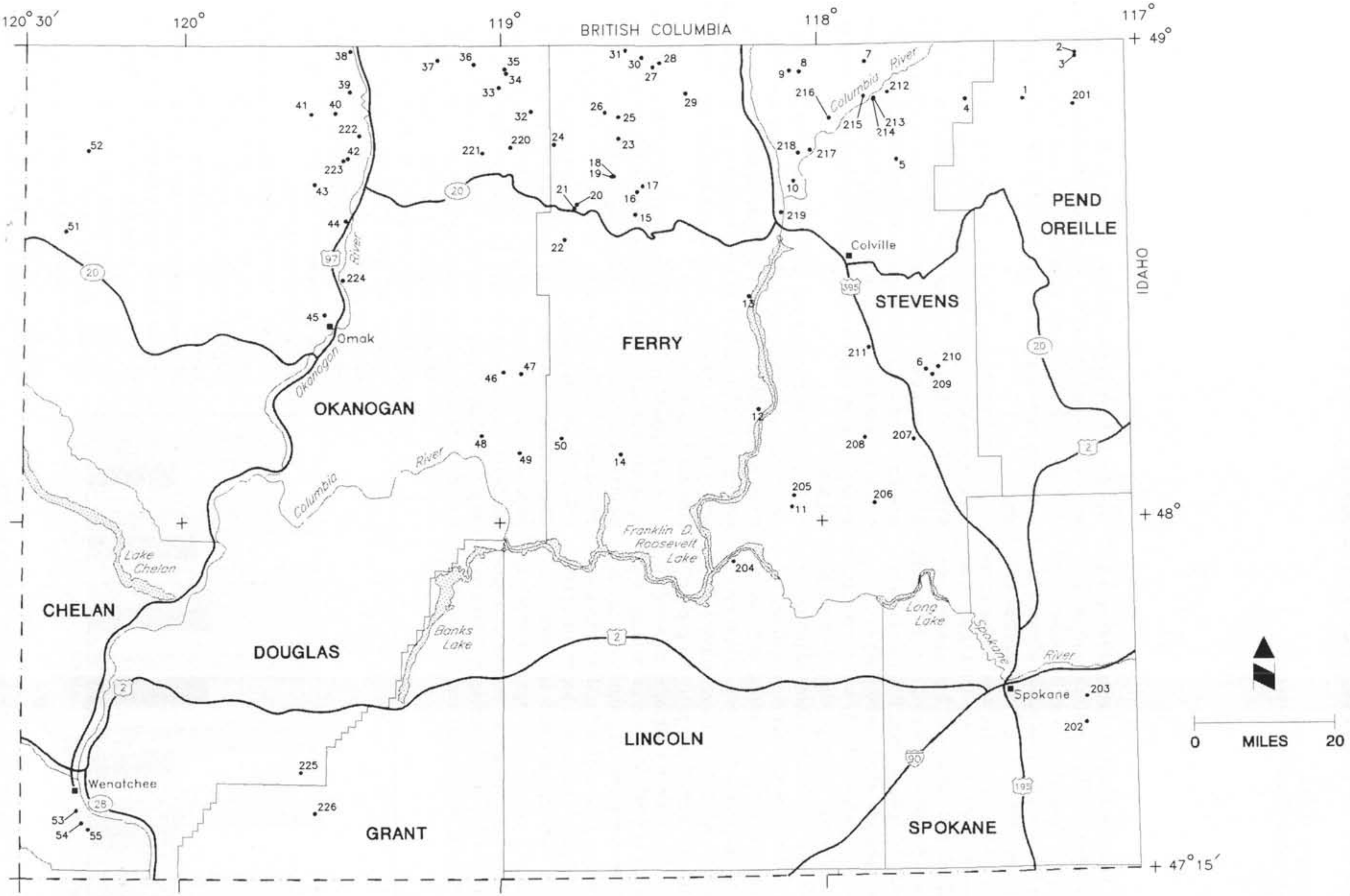

Figure 2A. Location of properties at which mineral exploration, development, or mining took place in 1993 in northeast Washington. See Table 1 for more information about each of these locations.

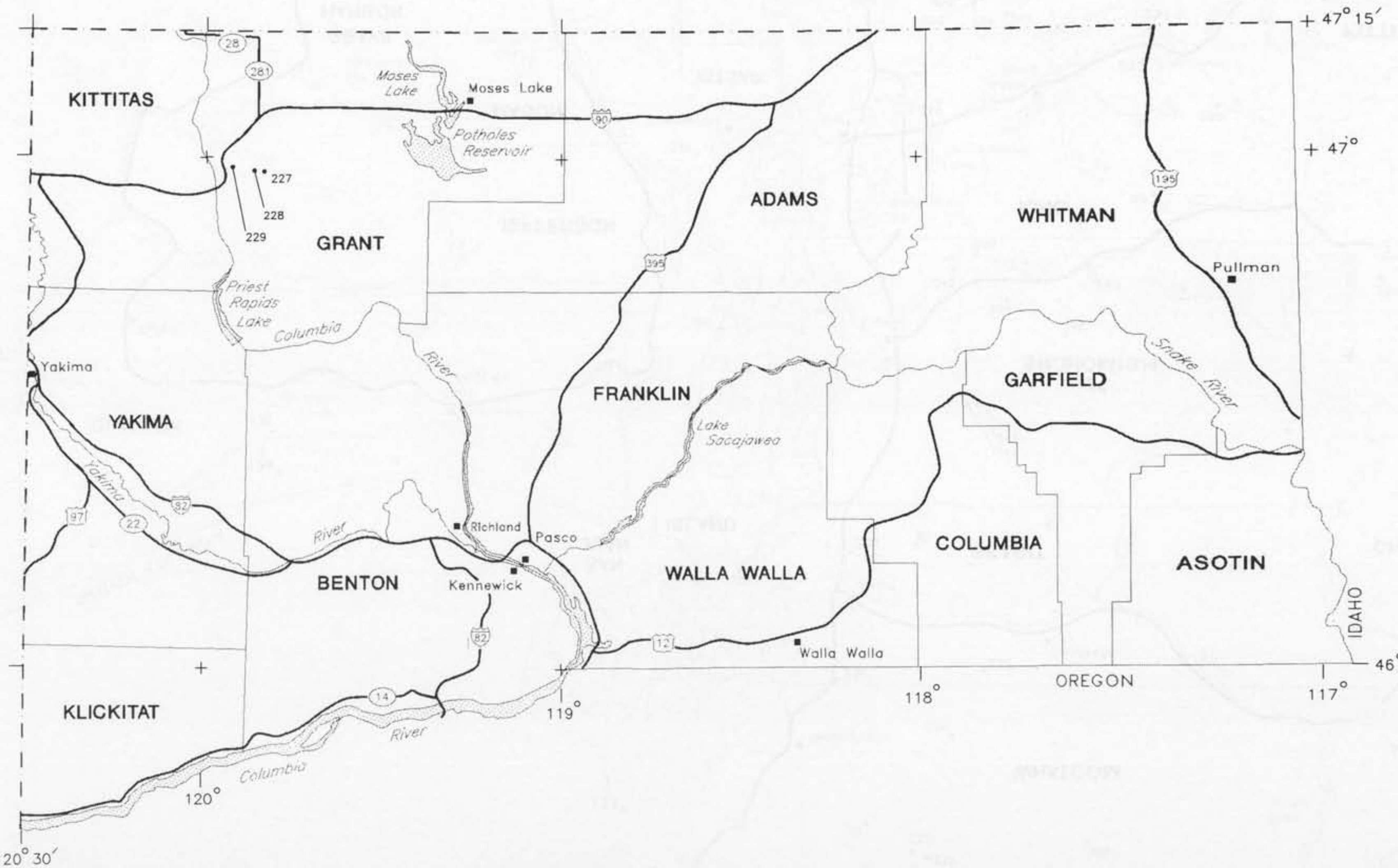

Figure 2B. Location of properties at which mineral exploration, development, or mining took place in 1993 in southeast Washington. See Table 1 for more information about each of these locations.

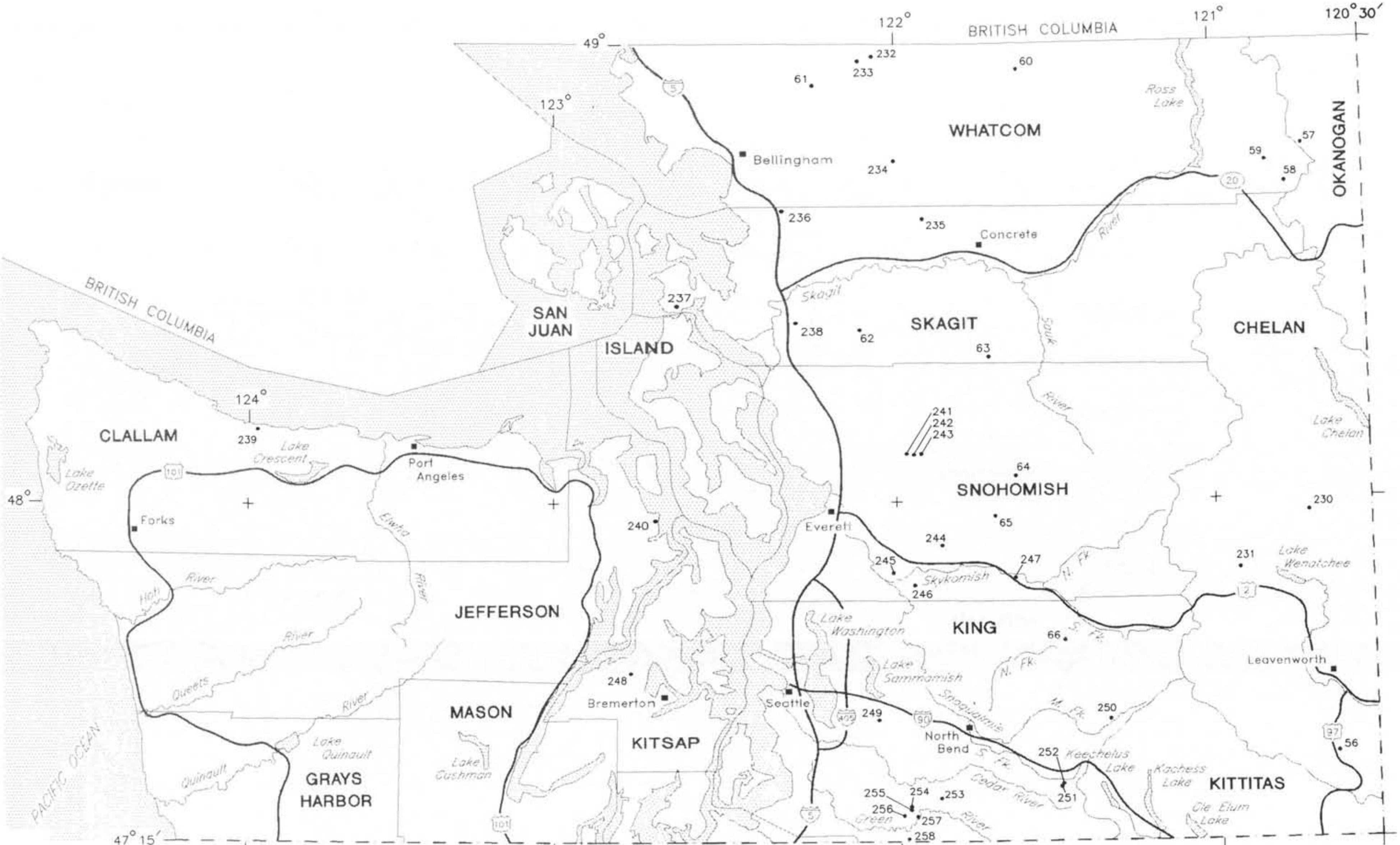

Figure 2C. Location of properties at which mineral exploration, development, or mining took place in 1993 in northwest Washington. See Table 1 for more information about each of these locations.

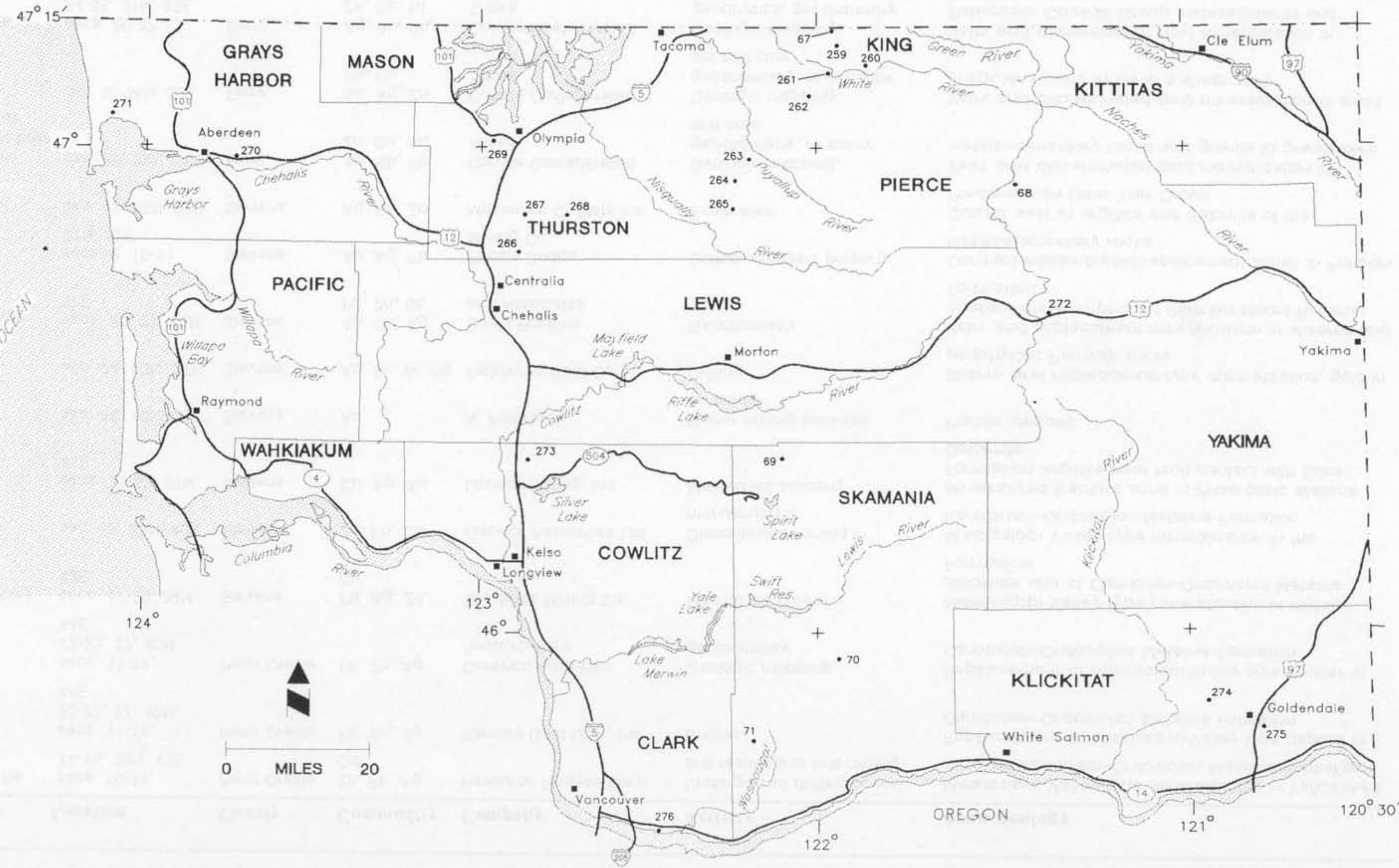

Figure 2D. Location of properties at which mineral exploration, development, or mining took place in 1993 in southwest Washington. See Table 1 for more information about each of these locations.

Table 1. Mining and mineral exploration in Washington, 1993. 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 2A through 2D. Entries 1–71 are base and precious metal properties; entries 201–276 are sites of industrial mineral activity

Loc no.	Property	Location	County	Commodity	Company	Activity	Area geology
1	Pend Oreille mine	secs. 10-11, 14-15, 39N, 43E	Pend Oreille	Zn, Pb, Ag, Cd	Resource Finance Corp.	Underground drifting to test drill results and test mining	Mississippi Valley-type mineralization in Yellowhead zone of Cambrian–Ordovician Metaline Formation
2	Lead Hill	secs. 11-14, 22-23, 27, 40N, 44E	Pend Oreille	Pb, Zn, Ag	Ramrod Gold USA, Inc.	Drilling	Replacement or Mississippi-Valley-type deposit in Cambrian–Ordovician Metaline Formation
3	Lead Hill	secs. 11-14, 22-23, 27, 40N, 44E	Pend Oreille	Pb, Zn, Ag	Cominco American Resources Inc.	Geologic mapping, geochemistry	Replacement or Mississippi-Valley-type deposit in Cambrian–Ordovician Metaline Formation
4	Electric Point	secs. 17-20, 39N, 42E.	Stevens	Pb, Ag, Zn, Cu	The State Mining Co.	Maintained property	Mississippi Valley-type mineralization in middle dolomite unit of Cambrian–Ordovician Metaline Formation
5	Van Stone mine	sec. 33, 38N, 40E	Stevens	Zn, Pb, Cd	Equinox Resources Ltd.	Discontinued mining in mid-January	Mississippi Valley-type mineralization in the Cambrian–Ordovician Metaline Formation
6	Amazon	secs. 31-32, 33N, 41E	Stevens	Cu, Ag, Au	Lovejoy Mining, Inc.	Maintained property	Mineralized fracture zone in Proterozoic Wallace Formation argillite near fault contact with Edna Dolomite
7	Ambrose Mining	sec. 16, 40N, 39E	Stevens	Au	A. Ambrose	Placer mining activities on hold	Placer deposit
8	Big Iron/ McNally	sec. 24, 40N, 37E	Stevens	Au, Fe, W, Ag	Pathfinder Gold Corp.	Drilling	Skarn- and replacement-type mineralization; gold in porphyritic Permian rocks
9	Cleta Group	secs. 22, 27, 40N, 37E	Stevens	Au, Cu, Ag, Pb, Zn, Sb	David Robbins and Associates	Geochemistry	Vein and replacement mineralization in sheared and contact-metamorphosed Permian Mount Roberts Formation
10	Kelly Hill	secs. 2, 10-11, 37N, 37E	Stevens	Au, Ag, Pb	Phelps Dodge Mining Co.	Drilled, dropped property	Contact metamorphic/replacement zones in Permian metasedimentary rocks
11	Deer Trail	sec. 12, 29N, 37E	Stevens	Ag, Pb, Zn	McLennon C. Slate Inc.	Exploration	Quartz vein in argillite and dolomite of the Precambrian Deer Trail Group
12	Longstreet and Silver Leaf mine areas	sec. 36, 32N, 36E	Ferry	Ag, Sb, Pb, Zn, Cu, Au	Colville Confederated Tribes	Geologic mapping, geochemistry, re-assay drill core	Vein and disseminated gold mineralization in metasedimentary rocks and granite to granodiorite
13	Cuban	sec. 2, 34N, 36E	Ferry	Au, Ag, Zn, Pb, Cu	Colville Confederated Tribes	Geologic mapping, geochemistry, re-evaluate old drill core	Vein and disseminated gold mineralization in small, irregular quartz veins in a shear zone
14	Shamrock	secs. 26-27, 34-35, 31N, 33E	Ferry	Ag, Au, Pb, Zn, Cu, Ni	Colville Confederated Tribes	Geologic mapping, geophysics, geochemistry	Vein and disseminated gold mineralization in Paleozoic Covada Group metasediments and Tertiary rhyodacite
15	Ferguson Ranch	sec. 5, 36N, 34E	Ferry	Au	Phelps Dodge Mining Co.	Drilled, dropped property	Replacement/exhalative type gold mineralization in Permian rocks
16	Overlook mine	sec. 18, 37N, 34E	Ferry	Au, Ag, Cu, Fe	Echo Bay Minerals Co.	Some exploratory drilling only	Gold mineralization associated with massive iron replacement/exhalative mineralization and stockwork of veinlets in Permian sedimentary rocks

17	Key Project	sec. 18, 37N, 34E	Ferry	Au, Ag, Cu, Fe	Echo Bay Minerals Co.	Mining completed and ore stockpiled; drilling	Gold mineralization associated with massive iron replacement/exhalative mineralization in Permian sedimentary rocks
18	Lamefoot	secs. 4, 8, 37N, 33E	Ferry	Au, Fe, Ag, Cu	Echo Bay Minerals Co.	Underground development and drilling to evaluate deposit	Gold mineralization associated with massive iron replacement/exhalative mineralization in Permian sedimentary rocks
19	Wardlaw	sec. 4, 37N, 33E	Ferry	Au, Ag	Equinox Resources Ltd.	Maintained property	Gold mineralization in Permian limestone and clastic rocks
20	Republic Unit	secs. 27, 34-35, 37N, 32E	Ferry	Au, Ag	Hecla Mining Co.	Mining, milling; extensive underground exploration and development	Epithermal gold veins in dacite and andesite flows, flow breccias, tuffs, and tuff breccias of Eocene Sanpoil Volcanics
21	Seattle	secs. 33-34, 37N, 32E	Ferry	Au, Ag	Crown Resources Corp.	Dewatering shaft	Epithermal deposit in Eocene Sanpoil Volcanics
22	Golden Harvest	numerous secs., 36N, 32E	Ferry	Au	Santa Fe Pacific Mining Inc./Pathfinder Gold Corp.	Geological mapping, geochemistry, drilling	Skarn and epithermal mineralization in pre-Eocene metavolcanic and Eocene volcanic rocks of the Republic graben
23	Republic–Belcher area	37-39N, 33E	Ferry	Au, Ag	Equinox Resources Ltd.	Maintained property	Gold mineralization in Permian limestone and clastic rocks
24	Manhattan Mountain	secs. 7, 18, 38N, 32E	Ferry, Okanogan	Au, Ag, Cu, Pb, Zn, talc	Westmont Gold Inc.	Maintained a portion of property	Epithermal gold in Eocene volcanic rocks of the Toroda Creek graben
25	Graben properties	numerous secs., 36N, 32E	Ferry	Au	Pathfinder Gold Corp.	Seeking exploration partner	Skarn and epithermal mineralization in pre-Eocene metavolcanic and Eocene volcanic rocks of the Republic graben
26	K-2	sec. 20, 39N, 33E	Ferry	Au, Ag	Echo Bay Minerals Co.	Baseline studies and drilling	Epithermal deposit in Eocene Sanpoil Volcanics
27	Morning Star	sec. 16, 40N, 34E	Ferry	Au, Ag, Cu, W	Echo Bay Exploration Inc.	Geologic mapping, geophysics	Veins at the sheared contact between Permian–Triassic greenstone and serpentinite
28	Irish	sec. 15, 40N, 34E	Ferry	Au	Johnson Explosives	Trenching, geochemistry	Gold mineralization in alkalic rocks of the Jurassic Shasket Creek complex
29	Lone Ranch	unsurveyed, 39N, 35E	Ferry	Au, Ag	Cyprus Minerals Co.	Maintained a portion of property	Gold-enriched sedimentary exhalative deposit in Permian metasedimentary rocks
30	Gold Mountain	secs. 7-8, 40N, 34E	Ferry	Au, Ag, Cu	Gold Express Corp./ N. A. Degerstrom, Inc.	Permitted, mining dependent on gold price	Gold-pyrite mineralization in an alkalic dike of the Jurassic Shasket Creek complex
31	Lone Star	sec. 2, 40N, 33E	Ferry	Au, Cu, Ag	BPG Resources, Inc., *subsidiary of* Britannia Gold	Obtained property, applied for exploration permits	Disseminated and stockwork chalcopyrite and pyrite in Permian–Triassic greenstone, graywacke, argillite, and limestone
32	Ida	secs. 16, 21, 39N, 31E	Okanogan	Au, Ag, Cu	Crown Resources Corp.	Geochemistry	Epithermal veins in Eocene Sanpoil Volcanics and Klondike Mountain Formation of the Toroda Creek graben
33	Crystal	sec. 35, 40N, 30E	Okanogan	Au, Ag, Pb, Zn, Cu	Keystone Gold, Inc.	Drilling	Skarn-type mineralization in Permian Spectacle Formation intruded by Mesozoic rocks
34	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
35	Crown Jewel area	secs. 13-14, 23-26, 40N, 30E	Okanogan	Au, Cu, Ag, Fe	Battle Mountain Gold Corp./Crown Resources Corp.	Exploration in areas adjacent to the Crown Jewel ore body	Gold skarn mineralization in Permian or Triassic metasedimentary rocks adjacent to the Jurassic–Cretaceous(?) Buckhorn Mountain pluton

Table 1. Mining and mineral exploration in Washington, 1993 *(continued)*

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
36	Strawberry Lake	secs. 6-9, 16-21, 29-30, 40N, 30E; sec. 24, 40N, 29E	Okanogan	Au, Ag, Cu	Crown Resources Corp.	Geologic mapping	Gold skarn- and vein-type mineralization in Permian to Triassic metasedimentary and metavolcanic rocks intruded by Mesozoic granitic rocks
37	Molson Gold	numerous secs., 39-40N, 28-29E	Okanogan	Au, Ag	Kennecott Exploration Co./Crown Resources Corp.	Geologic mapping, geophysics	Skarn- and epithermal-type mineralization in Permian to Triassic metasedimentary and metavolcanic rocks intruded by Mesozoic granitic rocks
38	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
39	Blue Lake	sec. 5-6, 39N, 27E	Okanogan	Au, Ag	Wilbur Hallauer	Geologic mapping, geochemistry	Gold enrichment zones in Permian–Triassic limestone
40	Cayuse	sec. 23, 38N, 26E	Okanogan	Au	Northwest Minerals Inc.	Maintained property	Skarn and replacement mineralization in Permian Spectacle Formation
41	Copper World, Palmer Mountain Properties	secs. 20, 29, 39N, 26E	Okanogan	Cu, Au, Ag, W, Zn, Fe	Wilbur Hallauer	Geologic mapping, geochemistry	Volcanogenic massive sulfide mineralization in Permian–Triassic Palmer Mountain Greenstone
42	Lucky Knock	sec. 19, 38N, 27E	Okanogan	Au, Sb	Magill and Associates	Geochemistry	Stibnite veinlets in fractured and silicified limestone of the Permian Spectacle Formation
43	Starr Molybdenum	secs. 8, 16, 37N, 26E	Okanogan	Mo, Cu, W	Wilbur Hallauer	Maintained property	Porphyry-type mineralization in Cretaceous Aeneas Creek quartz monzonite and granodiorite; gold in secondary enriched zone
44	Montgomery	sec. 12, 36N, 26E	Okanogan	Au, Cu, W	McGill and Associates	Geochemistry	Mineralization in contact-metamorphosed Permian–Triassic Kobau Formation
45	Three Buttes	sec. 15, 34N, 26E	Okanogan	Au, Mn	Echo Bay Exploration Inc.	Geologic mapping, geochemistry, geophysics, drilling	Sheeted veins and porphyry-type mineralization in Pogue Mountain quartz monzonite
46	Parmenter Creek	secs. 1, 12, 32N, 30E	Okanogan	Au, Cu, Zn	Colville Confederated Tribes	Geologic mapping, geochemistry	Shear-zone mineralization in metamorphic rocks
47	Wasco Ridge/ Strawberry Ridge	secs. 28-33, 33N, 31E; secs. 4-5, 32N, 31E	Okanogan	Au, Ag	Colville Confederated Tribes/Santa Fe Pacific Mining, Inc.	Geologic mapping, geochemistry, geophysics	Shear-zone mineralization in metamorphic rocks adjacent to Eocene intrusive rocks
48	Squaw Mountain	secs. 16-17, 20-21, 31N, 30E	Okanogan	Au, Ag, Cu, Mo	Colville Confederated Tribes	Geologic mapping, geochemistry	Veinlets and porphyry-type mineralization in granitic rocks
49	Agency Butte	secs. 31-32, 31N, 31E	Okanogan	Au, Ag	Kennecott Exploration Co./Colville Confederated Tribes	Geologic mapping, geochemistry	Epithermal mineralization in Eocene Sanpoil Volcanics
50	Agency Trend	31-33N, 31-32E	Okanogan	Au, Ag	Colville Confederated Tribes	Reconnaissance geologic mapping, geochemistry, data compilation	Epithermal mineralization in Eocene Sanpoil Volcanics and granitic rocks; extensions of mineralization at Agency Butte
51	Mazama	secs. 17, 19-20, 36N, 20E	Okanogan	Au, Cu, Ag	Centurion Mines Corp.	Geologic mapping, geochemistry, maintained property	Porphyry-type mineralization in fractures and in a breccia body of a Cretaceous stock
52	Billy Goat	sec. 15, 38N, 20E	Okanogan	Au, Cu, Ag	Sunshine Valley Minerals, Inc.	Repairing underground workings	Stockwork in Cretaceous(?) andesite tuff and breccia

53	Cannon mine	sec. 16, 22N, 20E	Chelan	Au, Ag	Asamera Minerals (U.S.) Inc./Breakwater Resources Ltd.	Mining; continued phasing down to planned closure in 1994	Mineralization in altered (commonly silicified) intervals in Eocene arkosic sandstone
54	Compton	sec. 27, 22N, 20E	Chelan	Au, Ag	Wilbur Hallauer	Maintained property	Mineralization in altered (commonly silicified) intervals in Eocene arkosic sandstone
55	Matthews	sec. 35, 22N, 20E	Chelan	Au, Ag	Ramrod Gold USA, Inc.	Drilling	Mineralization in altered (commonly silicified) intervals in Eocene arkosic sandstone.
56	Gold Bond	secs. 2-3, 22N, 17E	Chelan	Au	Gold Bond Mining Co.	Exploration, rehabilitation work	Vein mineralization in rocks of the Ingalls ophiolite complex
57	New Light	sec. 27, 38N, 17E	Whatcom	Au, Ag, Cu, Ni, Pt, Pb	Western Gold Mining, Inc.	Maintained property	Quartz-carbonate-cemented slate-argillite breccia in the Lower Cretaceous Harts Pass Formation
58	Azurite	sec. 30, 37N, 17E	Whatcom	Au, Ag, Cu, Zn, Pb, Pt	Double Dragon Exploration Inc.	Maintained property, seeking permits	Veins in sedimentary rocks of the Cretaceous Virginian Ridge Formation
59	Minnesota	sec. 2, 37N, 16E	Whatcom	Au, Ag, Cu	Seattle-St. Louis Mining Co.	Geologic mapping, geochemistry, maintenance/renovation	Quartz veins in argillite and feldspathic sandstone of Lower Cretaceous Harts Pass Formation
60	Lone Jack	secs. 22-23, 40N, 9E	Whatcom	Au, Ag, Cu, Bi	Diversified Development Co.	Mining	Quartz veins in metasedimentary rocks
61	South Pass Nickel	sec. 2, 39N, 4E; sec. 35, 40N, 4E	Whatcom	Ni, Co, Cr	Jackpine Mining Co., Inc.	Geologic mapping, geophysics, geochemistry	Laterite developed in peridotite at the base of Eocene sedimentary rocks
62	Skagit Copper	secs. 1-3, 33N, 5E	Skagit	Cu, Au, Ag, Pb, Zn	Cannon Minerals	Maintained a portion of property	Massive sulfide mineralization in accreted-terrane (melange?) rocks
63	Telstar	secs. 25-26, 33N, 8E	Skagit	Cu, Au, Ag, Zn, Pb	Cannon Minerals	Maintained a portion of property	Mineralization in altered ultramafic rocks
64	Tri-Lux	secs. 27-28, 32-34, 30N, 9E	Snohomish	Au, Ag, Pb, Zn	Cannon Minerals	Maintained a portion of property	Stockwork mineralization in a subaqueously extruded dome
65	Lockwood	secs. 25, 30-32, 29N, 9E	Snohomish	Au, Cu, Zn, Fe, S, Ag	Rio Algom Exploration, Inc./Island Arc Resources Corp./Formosa Resources Corp.	Geological and geophysical exploration; drilling	Kuroko-type volcanogenic massive sulfide mineralization in Jurassic volcanic rocks of the Western melange belt
66	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
67	Weyerhaeuser properties	Cascades area	King	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
68	Morse Creek	sec. 31, 17N, 11E	Yakima	Au, Ag	Ardic Exploration & Development, Ltd.	Maintained property	Tuffs of the Oligocene Ohanapecosh Formation
69	Polar Star	sec. 18, 10N, 6E	Skamania	Cu, Mo, Ag, Au	Champion International Corp.	Maintained property	Breccia pipes and porphyry-type deposit in quartz diorite of the Miocene Spirit Lake pluton
70	Wind River	sec. 9, 5N, 7E	Skamania	Au, Ag	DeLano Wind River Mining Co.	Applied for permits to mine	Epithermal mineralization in Oligocene–Miocene volcanic rocks
71	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
201	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 dolomite of the Proterozoic Z Monk Formation (Windermere Group)

Table 1. Mining and mineral exploration in Washington, 1993 *(continued)*

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
202	Mica mine	sec. 14, 24N, 44E	Spokane	clay	Mutual Materials Co.	Using stockpiled clay; no new mining at Mica pit, 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
203	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
204	Blue Silver quarry	sec. 21, 28N, 36E	Lincoln	dolomite	Blue Silver Mining	Mining, milling	Dolomite of the Cambrian–Ordovician Metaline Formation
205	Turk Magnesite	sec. 36, 30N, 37E	Stevens	magnesite	Osprey Resources	Evaluation	Magnesitization of the Proterozoic Y Stensgar Dolomite (Deer Trail Group) at the southwestern end of the magnesite belt
206	Gehrke quarry	sec. 2, 29N, 39E	Stevens	dolomite	Allied Minerals Inc.	Mining, milling	Isolated pod of Proterozoic Y Stensgar Dolomite(?) (Deer Trail Group)
207	Nine quarries		Stevens	dolomite	Nanome Aggregates, Inc.	Mining, milling	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, Farnsworth, and Watermary
208	Lane Mountain quarry	secs. 22, 34, 31N, 39E	Stevens	silica	Lane Mountain Silica Co. (*division of* Hemphill Brothers, Inc.)	Mining, milling	Cambrian Addy Quartzite
209	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
210	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)
211	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
212	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
213	Peter Janni & Sons quarry	sec. 13, 39N, 39E	Stevens	limestone	Peter Janni and Sons	Leased to Vermont Marble Company	Cambrian Reeves Limestone Member of the Maitlen Phyllite
214	Joe Janni limestone deposit	sec. 13, 39N, 39N	Stevens	limestone	Joe Janni	Leased to Pluess-Staufer Industries, Inc	Cambrian Reeves Limestone Member of the Maitlen Phyllite
215	Flagstaff Mountain	secs. 4, 9, 39N, 39E	Stevens	barite	Mountain Minerals Co. Ltd. *dba* Mountain Minerals Northwest	Awaiting favorable market conditions	Massive bedded barite in the Devonian–Carboniferous Flagstaff Mountain sequence
216	Whitestone quarry	sec. 34, 39N, 38E	Stevens	decorative stone	Whitestone Co.	Mining	Recrystallized limestone (marble) in the Cambrian Maitlen Phyllite

217	Northwest marble mine; other quarries	sec. 19, 38N, 38E	Stevens	dolomite	Northwest Marble Products Co.	Mining, milling, drying magnesite for Northwest Alloys, Inc.	Dolomite of the Cambrian–Ordovician Metaline Formation; additional colored dolomite products quarried at several locations
218	Moonlight quarry	sec. 24, 38N, 37E	Stevens	decorative stone	Whitestone Co.	Mining	Dolomite
219	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
220	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
221	Bonaparte Meadows peat	sec. 20, 38N, 30E	Okanogan	peat moss	The Bonaparte Co.	Mining	*Hypnum* moss in a peat bog south of Bonaparte Lake
222	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
223	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)
224	Brown quarry	sec. 26, 35N, 26E	Okanogan	dolomite	Pacific Calcium, Inc.	Mining	Metadolomite member of the Triassic Cave Mountain Formation
225	Coulee Chief	sec. 24, 23N, 25E	Douglas	clay	Basic Resources Corp.	Mine planning and engineering	Sedimentary interbeds in the Miocene Columbia River Basalt Group near Moses Coulee
226	Rock Top	sec. 20, 22N, 26E	Grant	clay	Basic Resources Corp.	Development drilling, trenching	Montmorillonite-group clays (bentonite) as interbeds within the Columbia River Basalt Group
227	Sec. 8 pit	sec. 8, 17N, 24E	Grant	diatomite	Celite Corp.	Mining, milling, reclamation	Miocene "Quincy Diatomite Bed", a sedimentary interbed occurring locally at the base of the Priest Rapids Member (Columbia River Basalt Group)
228	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)
229	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)
230	Chikamin quarry	sec. 22, 29N, 17E	Chelan	decorative stone	Juanita Trucking	Mining	Extensive deposits of Glacier Peak pumice
231	Nason Ridge	secs. 10, 14-15, 27N, 15E	Chelan	marble	ECC International (English China Clay)	Assessment work	Podiform bodies of high-calcium, high-brightness marble in pegmatitic tonalite and tonalite gneiss of the Chelan complex
232	Silver Lake quarry	sec. 7, 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
233	Kendall quarry	secs. 14-16, 22-23, 40N, 5E	Whatcom	limestone	Tilbury Cement Co.	Mining	Lower Pennsylvanian limestone
234	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
235	Hamilton plant	sec. 17, 36N, 7E	Skagit	olivine	Applied Industrial Materials Corp. (AIMCOR)	Milling, production of olivine products	Twin Sisters dunite

Table 1. Mining and mineral exploration in Washington, 1993 *(continued)*

Loc. no.	Property	Location	County	Commodity	Company	Activity	Area geology
236	Whatcom and Skagit quarry	sec. 6, 36N, 4E	Skagit	decorative stone	Whatcom Skagit Quarry	Mining	Darrington Phyllite
237	unnamed quarry	sec. 13, 34N, 1E	Skagit	decorative stone	Island Frontier Land-scape Construction Co.	Recently sold by Island Frontier	Andesite
238	Pacific quarry	sec. 33, 34N, 4E	Skagit	decorative stone	Meridian Aggregates Inc.	Mining	Diorite
239	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
240	Mats Mats quarry	sec. 33, 29N, 1E	Jefferson	decorative stone	General Construction Co.	Mining	Eocene basalt of the Crescent Formation
241	Mandan quarry	sec. 12, 30N, 6E	Snohomish	decorative stone	Universal Land Construction Co.	Mining	Basalt
242	Iron Mountain quarry	sec. 17, 30N, 7E	Snohomish	decorative stone	Iron Mountain Quarry	Mining	Andesite
243	Granite Falls quarry	sec. 8, 30N, 7E	Snohomish	decorative stone	Meridian Aggregates Inc.	Mining	Andesite
244	AAA Diorite quarry	sec. 23, 28N, 7E	Snohomish	decorative stone	AAA Monroe Rock Corp.	Mining	Diorite
245	Monroe Rock quarry	sec. 10, 27N, 6E	Snohomish	decorative stone	AAA Monroe Rock Corp.	Mining	Basalt
246	Cadman Rock quarry	sec. 19, 27N, 7E	Snohomish	decorative stone	Cadman Rock Co. Inc.	Mining	Basalt
247	Miller Lime quarry	secs. 15-16, 27N, 9E	Snohomish	decorative stone	Alpine Rockeries Inc.	Mining	Lenticular beds of folded and faulted, Late Jurassic or Early Cretaceous fossiliferous limestone inter-bedded with graywacke, argillite, and volcanic rocks
248	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
249	Sec. 31 pit	sec. 31, 24N, 6E	King	shale	Mutual Materials Co.	Mining	Shale and sandstone of the Eocene Puget Group
250	Spruce claim	secs. 29, 30, 24N, 11E	King	crystals	Robert Jackson	Mining, guided mineral collecting fieldtrips	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
251	Hansen Creek	secs. 21, 27, 22N, 10E	King	decorative stone	Marenakos	Drawing from talus	Snoqualmie batholith granite
252	unnamed quarry	sec. 22, 22N, 10E	King	decorative stone	Manufacturers Mineral Co.	Mining	Snoqualmie batholith granite
253	Elk pit	sec. 34, 22N, 7E	King	shale	Mutual Materials Co.	Mining	Illite- and kaolinite-bearing shales of the Eocene Puget Group
254	Ravensdale pit	sec. 1, 21N, 6E	King	silica	Reserve Silica Corp.	Mining, washing	Sandstone of the Eocene Puget Group
255	John Henry #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 #9 coal seam

256	Mine 11	sec. 11, 21N, 6E	King	decorative stone	Palmer Coking Coal Co.	Drawing from stockpile	Cinders accidently 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"
257	Franklin Rock quarry	sec. 18, 21N, 7E	King	decorative stone	Palmer Coking Coal Co.	Mining	Andesite
258	Enumclaw quarry	sec. 1, 20N, 6E	King	decorative stone	Enumclaw Quarry Inc.	Mining	Andesite flows as interbeds in volcanic breccia and sandstone
259	410 quarry	sec. 20, 20N, 7E	King	decorative stone	410 Quarry Inc.	Mining	Miocene andesite flows
260	Superior quarry	sec. 1, 19N, 7E	King	silica	Ash Grove Cement Company	Mining, milling	Silica cap in hydrothermally altered Miocene andesites on a caldera margin
261	Buckley quarry	sec. 7, 19N, 7E	Pierce	decorative stone	Washington Rock Quarries Inc.	Mining	Miocene andesite
262	Wilkeson quarry	sec. 27, 19N, 6E	Pierce	decorative stone	Rockeries Inc.	Mining	Eocene continental sandstone
263	Kapowsin quarry	sec. 8, 17N, 5E	Pierce	decorative stone	Washington Rock Quarries Inc.	Mining	Oligocene–Miocene intrusive andesite
264	Clay City pit	sec. 25, 17N, 4E	Pierce	clay	Mutual Materials Co.	Using stockpiled clay, shut-down adjacent brick plant	Oligocene–Miocene kaolin-bearing, altered andesite
265	Lynch Creek quarry	sec. 13, 16N, 4E	Pierce	decorative stone	Randles Sand and Gravel Inc.	Mining	Eocene–Oligocene andesite flows
266	Bucoda pit	sec. 14, 15N, 2W	Thurston	clay	Mutual Materials Co.	Using stockpiled clay	Glacial clay of the Pliocene–Pleistocene Logan Hill Formation overlying silty clay of the Eocene Skookumchuck Formation
267	Hercules quarry	sec. 37, 16N, 1W	Thurston	decorative stone	Northwest Stone Inc.	Mining	Middle to upper Eocene marine sedimentary rocks assigned to the McIntosh Formation (Puget Group)
268	Johnson Creek	sec. 24, 16N, 1W	Thurston	decorative stone	Sea Tac Rock Co.	Mining	Andesite of the Eocene Northcraft Formation
269	Jones quarry	sec. 29, 18N, 2W	Thurston	decorative stone	Jones Quarry	Mining	Basalt of the Eocene Crescent Formation
270	unnamed clay pit	sec. 7, 17N, 8W	Grays Harbor	clay	Aberdeen Sanitation	Mining	Lower to middle Miocene marine sedimentary rocks of the Astoria Formation
271	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
272	Snow Queen quarry	sec. 36, 14N, 11E	Yakima	decorative stone	Heatherstone Inc.	Mining	Quaternary andesite flows
273	Castle Rock Clay pit	sec. 18, 10N, 1W	Cowlitz	clay	Ash Grove Cement Co.	Mining	Eocene–Oligocene nearshore sedimentary rocks
274	Blockhouse quarry	secs. 5, 8-9, 4N, 15E	Klickitat	decorative stone	D. M. Layman Inc.	Mining	Pliocene–Quaternary scoriaceous basalt (cinder)
275	Red Rock quarry	sec. 27, 4N, 16E	Klickitat	decorative stone	Bishop Red Rock Inc.	Mining	Near-vent scoriaceous Pliocene–Quaternary basalt (cinder)
276	Fisher quarry	sec. 8, 1N, 3E	Clark	decorative stone	Gilbert Western Corp.	Mining	Pliocene–Quaternary andesite flows

Metallic Mineral Deposits

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Mining and exploration for metallic deposits were less active in 1993 than in previous years. Almost all these activities centered on precious metals, mainly gold, and on zinc and lead deposits. Gold was the most productive metallic commodity in terms of value and number of people employed in mining and processing. A discussion of mining and exploration in Washington is presented here by commodity groups and deposit types. Washington's gold deposits can be divided into epithermal, replacement/exhalative, skarn, shear zone, and alkalic deposit types. All exploration for zinc and lead deposits was on known or probable Mississippi Valley-type deposits. Exploration for polymetallic sulfide mineralization was for volcanogenic massive sulfide-type deposits. The only disseminated mineralization discussed here is porphyry-type deposits. Numbers following deposit names in this discussion are keyed to locations of deposits on Figures 2A–D.

Reserves at mines in epithermal gold deposits are largely depleted. In 1992, the Kettle deposit was mined out and closed, and the Cannon mine at Wenatchee is scheduled to be mined out and closed in 1994. Hecla's Golden Promise is approaching the end of its reserves; however, it continues to obtain small production from the nearby Knob Hill deposit. The company will probably complete mining on the majority of the Golden Promise deposit in 1994 or 1995. While exploration for replacement-type gold deposits continues, no epithermal deposit has enough reserves to sustain production at levels like those of the 1980s and early 1990s.

Additional details about the geology of these various types of metallic mineral deposits in Washington are available in reviews of Washington's mineral industry for 1991 and 1992 by Derkey (1993) and Derkey and Gulick (1992).

GOLD IN WASHINGTON

Epithermal Type Deposits

Epithermal deposits have been the mainstay of gold production in Washington over the last few years. The Cannon Mine and Hecla's Republic Unit have been the main gold producers from epithermal deposits. Combined, they produced more than 155,000 ounces of gold in 1993.

The Cannon mine (no. 53) at Wenatchee was again Washington's largest gold producer. The joint venture operation between Asamera Minerals (U.S.) Inc. (operator) and Breakwater Resources Ltd. continued to scale down operations in preparation for planned closure later in 1994. After passing the 1 million ounce production mark in 1992, the Cannon mine continued producing in 1993 with 105,477 ounces of gold and 176,240 ounces of silver recovered from 388,842 tons of ore. This head grade of ore shipped to the mill averaged 0.288 ounces per ton for gold and 0.538 ounces per ton for silver.

Nearly all production from Hecla Mining Co.'s Republic Unit (no. 20) came from the Golden Promise deposit. However, during 1993 the Knob Hill deposit furnished about 400 tons per month of the total Hecla production of 110,846 tons of ore. Ore grade at the mill was 0.480 ounces per ton for gold and 3.10 ounces per ton for silver. Gold and silver production was 49,601 and 276,688 ounces respectively in 1993. The ore is sent to Hecla's mill and refinery at the mine site, and gold is shipped as dore bars. The company continues to operate its mill at Republic at full production of 325 tons per day.

Echo Bay conducted drilling and baseline studies at the K-2 deposit (no. 26). They are planning an exploratory drift into this deposit to confirm drilling results.

Exploration and property maintenance continued at numerous other epithermal deposits in Washington (nos. 21, 22, 24, 25, 32, 37, 49, 50, 70).

Replacement/Exhalative-Type Deposits

Most of the known replacement/exhalative-type gold deposits in Washington occur in the Republic graben. This deposit type was formerly termed replacement-type (see Derkey, 1993), but because of the presence of magnetite and sulfide clasts in the sedimentary rocks immediately overlying the massive sulfides/oxides (M. Rasmussen, Univ. of Wash. doctoral candidate, oral commun., 1994) and the existence of a stockwork of pyrrhotite and quartz-sulfide veinlets that may have served as a feeder (overturned at the Overlook mine), the Republic-area deposits may be exhalative in origin. They are here reclassified as exhalative/replacement type.

The deposits at Republic occur at the contact between carbonate and clastic sedimentary rocks. Gold is sporadically distributed in massive iron oxide-sulfide zones in carbonate rocks and in stockworks of pyrrhotite and quartz-sulfide veinlets (largely pyrite) in clastic sedimentary rocks. The gold disseminated in massive magnetite and hematite and pyrrhotite, pyrite, and chalcopyrite may have accumulated simultaneously with the massive sulfide and oxide bodies formed at exhalative hydrothermal centers.

The exhalative/replacement-type Key (no. 17), Overlook (no. 16), and Lamefoot (no. 18) deposits are part of the Kettle River Project, which is now 100 percent owned by Echo Bay Minerals Co. following withdrawal of Crown Resources Corp. from the joint venture at the end of 1992. Production from the Kettle River Project in 1993 totalled 73,431 ounces of gold from 575,460 tons of ore. The head grade was 0.146 ounces of gold per ton. Total production from the Key deposits is projected at 800,000 tons of ore at a grade of 0.142 ounces of gold per ton, and a net production of 114,000 ounces of gold.

Mining at the Key deposits, which began in the fall of 1992, was completed in October of 1993. Ore from these deposits came from two small open pits about ¼ mile apart. The pits are 1 mile northeast of the Overlook mine and Echo Bay's mill. Reclamation was well under way at the east pit in October (Fig. 3), and reclamation was beginning at the west pit following completion of mining (Fig. 4). The ore from the two deposits was stockpiled at the Echo Bay's mill (Fig. 5) and will serve as feed for the mill until late spring or early summer. Additional ore at the Key West deposit is too deep to be mined as an open pit and probably will be mined by underground methods in the future.

In 1993, Echo Bay carried out exploration drilling at the Overlook mine (no. 16), the former flagship of the Kettle River project. This underground mining operation was closed at the end of 1992 in favor of producing from the Key open-pit deposits.

Underground development continued at Echo Bay's Lamefoot deposit. Announced ore reserves fall into three categories: proven, probable, and possible. Proven and probable reserves are 1,600,000 tons at 0.19 ounces of gold per ton (304,000 ounces of contained gold). The possible ore reserve is 1,330,000 tons at 0.17 ounces of gold per ton (266,100 ounces of contained gold). Full-scale mining of the Lamefoot deposit is planned to begin by mid-1994 after the stockpiled Key deposits ore has been milled. Ore mined during development at Lamefoot is being stockpiled for transport to the Overlook mill when mining begins.

Numerous exploration projects (nos. 8, 9, 10, 15, 19, 22, 23, 25, 27) continued on prospects for replacement/exhalative-type mineralization in northeastern Washington in 1993. The majority of these prospects are in the northern part of the Republic graben. Several also have potential for skarn-type mineralization.

Skarn-Type Deposits

The Crown Jewel deposit (no. 34) is the type example of a skarn-type gold deposit in Washington. The Battle Mountain Gold Corp. (operator)/Crown Resources Corp. joint venture initiated the permitting process for the Crown Jewel in 1992. A draft environmental impact statement is expected late in 1994; this is the beginning of a period of review leading to preparation of a final environmental impact statement and possible issuance of permits to mine. Announced reserves are 8.7 million tons of ore at a grade of 0.186 ounces of gold per ton, or more than 1.6 million ounces of gold. Battle Mountain's efforts in 1993 centered on the permitting process and on evaluating other parts of their property in the area.

Other exploration efforts took place on skarns (nos. 8, 10, 22, 25, 33, 35, 36, 37, 40) that have potential for precious-metal enrichment; these properties are in northeastern and north-central Washington.

Deposits in Shear Zones

Exploration for shear zone (also termed mesothermal) gold deposits was limited in 1993. Parmenter Creek (no. 46) and Wasco Ridge/Strawberry Ridge (no. 47) on the Colville Indian Reservation are perhaps the best examples of this type of deposit at which exploration activities continued in 1993. These

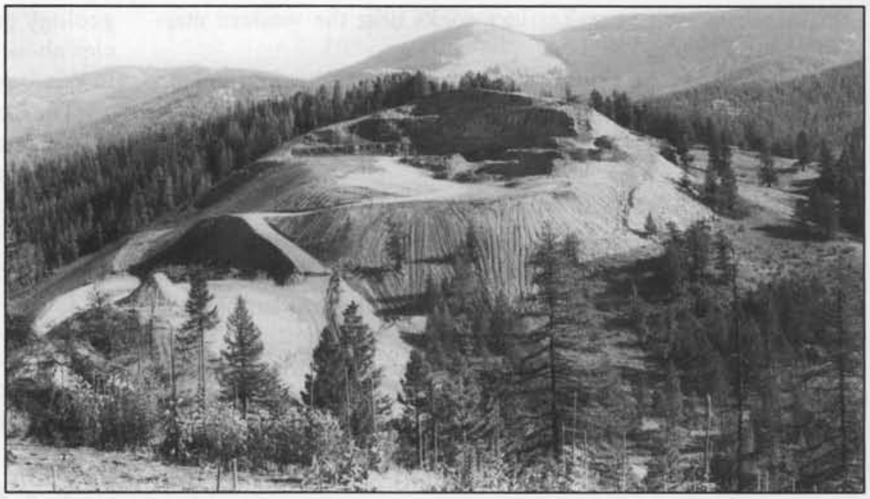

Figure 3. Reclaimed east pit of Echo Bay's Key mine. Slopes of waste piles are being recontoured and covered with topsoil in preparation for revegetation.

Figure 4. The west pit at the Key deposit just prior to completion of mining in October, 1993. View is from the east pit. Note reclaimed slopes of waste dumps in the foreground.

Figure 5. Stockpiled ore from the Key deposits at Echo Bay's Kettle River Project mill. The primary crusher is just out of view at the right; the building houses the secondary crusher. Structures between buildings are conveyor belts that move ore from crusher to mill or return oversize material to the primary crusher for additional crushing.

two deposits are in pre-Tertiary rocks near the western margin of the Republic graben.

Maintenance of claims was the only activity in 1993 on several other prospects (nos. 6, 27, 39) with potential for shear zone-type gold mineralization.

Deposits in Alkalic Rocks

Exploration or maintenance continued at the Gold Mountain mine (no. 30), the Irish mine (no. 28), and the Lone Star deposit (no. 31), all of which occur in and adjacent to rocks of the Shasket Creek alkalic complex near Danville in Ferry County. The Gold Mountain mine, a joint venture project of Gold Express Corp. and N. A. Degerstrom, Inc., has obtained permits to mine, but as in 1992, the companies continued to wait for higher gold prices before beginning to mine.

Mississippi Valley-Type Zinc and Lead Deposits

Mississippi Valley-type (MVT) deposits in Washington are found in the Cambrian–Ordovician Metaline Formation in the northeastern corner of the state. The economic focus in these types of deposits is zinc, which in the larger deposits generally exceeds lead. See Morton (1992) for more details about this type of deposit in northeastern Washington, especially those of the Metaline mining district.

Underground exploratory drifting was done at the Pend Oreille mine (no. 1) near Metaline Falls. The work consisted of 2,300 feet of drifting in ore for test mining and 1,000 feet of drifting to establish additional drill stations to better define the ore reserve identified by previous drilling. Also, more than 160 diamond drill holes between 200 and 500 feet in length were completed in 1993. The majority of previous production from the Pend Oreille mine was from the Josephine horizon; however, zinc-rich ores of the Yellowhead horizon have become more important as the demand for and the price of zinc increases. Resource Finance Corp., the operator of the project, is now studying the feasibility of mining.

Equinox Resources Ltd. operated the Van Stone mine (no. 5) in northern Stevens County for about 2 weeks in 1993 and then shut down operations due to depressed zinc prices. The future of this operation is unclear because Hecla Mining Co. announced it had reached an agreement to obtain all outstanding shares of Equinox in exchange for Hecla stock. Equinox had previously re-opened the mine in mid-1992 when zinc prices were favorable for operation. When in operation, the mine produced 150,000 tons of ore plus waste per month; ore grades averaged 4.0 percent zinc and 1.5 percent lead.

Cominco American Resources Inc. and Ramrod Gold USA, Inc., both explored for MVT deposits on Lead Hill (nos. 2, 3). Zinc and lead ores produced in this area would presumably be shipped (as it was from the Van Stone mine) to Cominco's smelter at Trail, located just north of the international border in British Columbia.

Volcanogenic Massive Sulfide-Type Deposits

Volcanogenic massive sulfide (VMS) deposits are believed to have formed adjacent to hot-spring vents (or black smokers, cover photo) that spewed sulfides onto the sea floor. Their geology and genesis are discussed in more detail in the articles about sea floor vents and the geology of the Holden mine in this issue.

The Lockwood deposit (no. 65) was the only VMS deposit at which extensive exploration activities, including drilling, occurred in Washington in 1993. Rio Algom Exploration, Inc., picked up an option on the property from Island Arc Resources Corp. and Formosa Resources Corp. and conducted geological and geophysical studies, followed by drilling in late summer.

Exploratory work on other potential VMS-type deposits in Washington (nos. 41, 62) was limited to assessment work. Cyprus Minerals Co. maintained only a few of its claims for the Lone Ranch property (no. 29) near Danville; these may be exhalative-type mineralization in sedimentary rocks.

Porphyry-Type Deposits

Porphyry-type deposits formed during crystallization of large intrusive igneous bodies (such as batholiths, stocks, and large dikes). Extensive hydrothermal systems carried heat and fluids (mostly water) away from the cooling body. The hydrothermal fluids altered and mineralized large volumes (such as the Mount Tolman deposit on the Colville Indian Reservation) of the already crystallized igneous and adjacent country rocks.

Porphyry-type deposits are best known for their copper and molybdenum resource potential. In Washington, they have been explored for associated gold and silver mineralization in recent years. In 1993, companies spent little time or money on porphyry deposit exploration in the state. Most expenditures were fee payments to maintain unpatented mining claims, which, at the larger deposits, typically cover only a portion of the entire deposit.

Kinross Gold USA, Inc. (formerly Plexus Resources Corp.), continued work toward putting their Bornite property in Oregon into production and did only maintenance work at their Silver Star property (no. 71). Champion International Corp. maintained their Polar Star property (no. 69). Other porphyry-type deposits where exploratory work was done include the Kelsey deposit (no. 38) and the Starr Molybdenum property (no. 43). ■

Note: References cited in this section are listed on p. 22.

New Paleontological Association looking for members

A new geological organization, the Northwest Paleontological Association, is in the process of forming. Its goals are to bring paleontologists, whether employed in that capacity or an enthusiastic collector, together to discuss fossils, new discoveries, and scientific advances. Bimonthly meetings are planned, initially at the Burke Museum on the campus of the University of Washington. For more information, contact the Burke Museum, DB-10, University of Washington, Seattle, WA 98195; 206/543-5590.

Industrial Minerals

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CONSTRUCTION MATERIALS

Aggregates

Washington was again a leading producer of sand and gravel, ranking (by volume) 5th in the nation. Preliminary 1993 year-end estimates by the U.S. Bureau of Mines (USBM) suggest that approximately 44.5 million short tons of sand and gravel were produced, with a value of $158 million. Production of crushed stone, for which Washington ranks approximately 27th, was estimated at 12 million short tons valued at $57 million. Quarterly and biennial USBM estimates are based on select surveys of the most significant producers, and actual total production figures are typically higher than those published by USBM.

Most major developments for the sand and gravel and crushed stone industries were related to obtaining permits for new sources of raw material. Continued growth and development throughout the state has had multiple effects. Demand for construction materials is at an all-time high. At the same time, aggregate mine sites once considered remote are now situated in urban centers and, in three important instances, nearly depleted. While population growth has increased demand, it has also necessitated finding aggregate sources away from population centers. Major Washington producers are attempting to both assuage public concerns and establish new reserves that are not so remote as to render their aggregate products uncompetitive—long overland haulage increases product prices. Depletion of Washington's large aggregate resources reinforces the importance of planning under the Growth Management Act. New sources must be designated to insure that future supplies of aggregate will be of sufficient size and quality to meet projected demands.

Lone Star Northwest's sand and gravel pit at Steilacoom on the shore of Puget Sound in Pierce County was ranked as the largest producing sand and gravel plant in the nation during 1992, when it produced 3.9 million tons (Prokopy, 1993). In 1993, comparable production continued to deplete reserves at Steilacoom, now estimated at about 5–7 years. Aggregate has been continuously produced there since 1896. Lone Star is actively pursuing efforts to permit a new operation at Dupont, which, like Steilacoom, is located on Puget Sound and allows for barge transportation. One of Lone Star's larger projects was completed in 1993 when the new I-90 floating bridge on Lake Washington was put into service. Lone Star supplied both aggregate and ready-mix concrete for the bridge project.

During 1993, production from the Associated Sand and Gravel Co. Inc. (CSR America Corp.) pit at Everett in Snohomish County was typical for this pit in previous years—about 2.5 million tons of sand and gravel. An expansion at the nearby Boeing facility was a major market for Associated's materials during 1992, and the project was completed during 1993. The Everett pit, which supplies about 40 percent of the aggregate for Snohomish County, has a mine life expectancy of less than 5 years. The company is attempting to permit a new source near Granite Falls, about 15 miles away. A draft environmental impact statement for the new resource is currently under county review. The proposed new site contains a reserve of 62 million tons of sand and gravel and more than 45 million tons of bedrock quarry material. This one site could replace the Everett pit and provide a 30-year supply of sand and gravel and a 50- to 70-year supply of quarried rock.

Another of Washington's formerly very large aggregate resources is nearly depleted. Once a major producer, the deposit owned and operated by LaFarge at Friday Harbor in the San Juan Islands is now a relatively trivial producer of (predominantly) sand. Much of their output is exported to Canada to provide aggregate for LaFarge's concrete division in the Vancouver, BC, market. Approximately one-half of the 200-acre site has now been reclaimed.

Cadman, Inc., one of the state's largest producers of crushed rock, encountered a serious problem at their crushed stone/sand and gravel High Rock quarry near Monroe (Snohomish County) on October 29, 1993. While excavating in one corner of the site, quarry personnel inadvertently penetrated a previously unrecognized artesian aquifer that released ground water at an initial rate of greater than 1,000 gallons per minute. The aquifer apparently existed as perched water sealed off by the low permeability of fine sediments that were breached during sand and gravel extraction. The turbid water and sediment washed onto adjacent property. Cadman's emergency response was exemplary; they diverted the water to their sediment retention system. An equally high priority was satisfying the needs of eight neighbors whose domestic water supply had been interrupted. Cadman delivered water to the adjacent homes and has since drilled a replacement well for the homeowners.

New provisions in the 1971 Surface Mining Act enacted during 1993 may help to avoid similar crises in the future. Revisions are also designed to assure that every mine is thoroughly reclaimed. Significant changes from the original 1971 law include the following:

- The Department of Natural Resources (DNR) has exclusive authority to regulate mine reclamation and approve reclamation plans.
- DNR now issues "Reclamation Permits" rather than "Operating Permits". Each surface mine disturbance larger than 3 acres must have a reclamation permit to continue operating.
- A high-quality reclamation plan is required for each mine. These plans will specify methods for achieving the following reclamation goals:
  - Segmental reclamation
  - Preservation of topsoil
  - Slopes restored so that highwalls are stable and rounded in plan and section
  - Slopes that are generally between 2.0 and 3.0 feet horizontal to 1.0 foot vertical or flatter

- Final topography generally comprising sinuous contours, chutes and buttresses, spurs, and rolling mounds and hills that will blend with adjacent topography
- Avoidance of straight planar slopes and right angles
- Revegetation that generally includes multi-species ground cover and trees.

Other aspects that have been changed in the law are:

- Permit fees have been increased to $650 annually.
- Areas that might cause erosion or slope failure onto neighboring properties must be reclaimed immediately.
- New compliance mechanisms have been included, such as a formalized procedure for warning of violations and easily enforceable fines for defying orders of the DNR.

The overwhelming majority of operations affected by the 1993 Surface Mining Act are aggregate producers. Of roughly 1,000 mines throughout the state that were required to have permits in 1993, approximately 90 percent were aggregate producers. They are not shown in Figures 2A–D or Table 1.

Portland Cement

1993 was the first full year of production for Ash Grove Cement Co.'s newly rebuilt 750,000 ton per year (tpa) cement plant in Seattle. The $65 million dry-process plant produced Types I and II portland cement at less than the rated plant capacity. When the new plant was completed in 1992, the preexisting, 1960s vintage, finish-grinding (comminution) circuit was retained from the original plant. This older portion of the production system created a slight bottleneck during 1993 because the new plant outperformed expectations and thereby overwhelmed the older finish-grinding equipment. The finish-grinding plant is now being refurbished, and this final modernization is expected to boost capacity beyond the 750,000 tpa rating.

The cement that Ash Grove produces at Seattle is composed of raw materials from Washington, Canada, and Mexico. Ash Grove continues to use limestone from its Blubber Bay quarry on Texada Island in the Strait of Georgia. Clay is produced in-house at Castle Rock (no. 273) and blended with clay purchased from Pacific Coast Coal at Black Diamond (no. 255), where it occurs between the Nos. 9 and 10 coal seams. Ash Grove augments these two clays with other aluminum sources, primarily dredge sediments, including some from their plant site on the Duwamish River. Mill scale from the Salmon Bay Steel plant at Seattle is a source of iron for Ash Grove's portland cement, and gypsum is purchased from James Hardie, an importer of large quantities of Mexican gypsum to Seattle for their wallboard manufacturing plant. Ash Grove's primary silica source continues to be their Superior Quarry near Enumclaw (no. 260).

Ash Grove operated three cement terminals in the state in 1993—at Bellingham, Kennewick, and Spokane. A new silo was installed at the Spokane site; this nearly doubled storage capacity and allowed for simultaneous loading of two trucks. Distribution from Spokane is supplied by the Seattle cement plant as well as by Ash Grove's plant south of Helena, MT. The Kennewick terminal distributes cement from production at Ash Grove's Durkee, OR, plant.

The Holnam, Inc., 500,000 tpa portland cement plant at Seattle continued innovative replacements or augmentation of traditional raw materials with alternate material sources. Like Ash Grove, Holnam mines limestone on Texada Island under a Canadian subsidiary and imports the stone to Seattle by barge. Some of this limestone, which is the primary ingredient in portland cement, is being replaced with flotation process waste from the Columbia River Carbonates plant at Woodland (discussed in the limestone section). This calcium carbonate-rich slurry is delivered to Seattle via tank car and provides an excellent raw material for cement; it was previously viewed as a fairly costly waste product. Similar synergy between Holnam and waste generators is being achieved through the augmentation of silica that is purchased from Reserve Silica Corp. (no. 254) (see Silica section) with spent sandblasting grit. This material provides both silica and iron and, until now, has consumed precious space in a Tacoma landfill that is nearly full.

Other cement feedstock materials (generators pay Holnam a fee to accept them for use) include petroleum-contaminated soils that are excavated when leaking underground storage tanks are removed. In western Washington these soils typically have high alumina contents, which makes them suitable for cement manufacture. The soil has helped reduce Holnam's in-house production of virgin clay from the Twin River quarry near Port Angeles (no. 239) from traditional levels of 110,000 tpa to 60,000 tpa. The past year was also notable in that Holnam has now tied 80 percent of the plant site's stormwater runoff into making wet-process cement.

The re-entry of Ash Grove, with some competitive pricing moves, and additional competition from imported cement contributed to a two-week shut down of the Holnam plant for inventory control. This was the first production hiatus in 25 years. The most significant import competition was from the LaFarge and Tilbury plants at Richmond and Delta, BC, respectively. Imported Pacific rim cement further reduced the available market share for Ash Grove and Holnam. Lone Star Northwest, which operates a cement terminal at Seattle and is now a part of the giant Japanese Onoda cement group, imported significant quantities of portland cement from China. Additional imports from Korea and the Philippines were also a factor, whereas continued tariffs assessed on Japanese and Mexican cement for dumping practices curtailed imports from those countries. Cementos Mexicanos is, however, in the process of permitting a cement terminal in Portland, OR.

Building Stone

Interest in and use of natural stone was growing in 1993. Marenakos Rock Center near Issaquah installed the largest stonecutting saw in the state. The computerized, traveling saw can accommodate a 9-foot blade that allows for a cut 45.5 inches deep and as long as 11 feet.

Quarrying of the Tenino sandstone resumed at the Hercules quarry (no. 267) (Knoblach, 1993). Masonry stone was prepared with hand mauls by employees of the new operator, Northwest Stone Inc. of Tualatin, OR. The company also experimented with using a 'ditch witch' for channeling to produce rough blocks of this relatively soft sandstone. Washington's other preeminent historical producer of sandstone for dimension stone, the Wilkeson sandstone quarry (no. 262), was also producing masonry stone (Interstate Rock Products of Washougal) and rockery rock (Rockeries, Inc.).

Associated Rockery Contractors completed the Standard Wall Construction Guidelines for rock walls during 1993. The association has 11 members, including the principal installers of rockery in the Puget Sound area (Alpine Rockeries, Parsons Brothers, Tim Starns, and Westcott Construction). The City of Tacoma and Snohomish County have adopted these new guidelines. The popularity of rock walls has created a slight shortage of suitable 5-man (4,000–6,000 pounds) and smaller ledge rocks. Many quarry blasts produce only a few boulders of the appropriate shape and size for rockery applications.

Dolomite and Limestone

Northwest Alloys, Inc. (no. 211), quarried approximately 500,000 tons of dolomite near their plant at Addy, which again makes them the largest quarrier of carbonate rock in the state. This company, a wholly owned subsidiary of Alcoa, produces magnesium metal from dolomite and ferrosilicon. The magnesium metal is alloyed with aluminum to provide strength. The value of the finished magnesium metal was second only to the value of sand and gravel produced in the state in 1993, according to USBM statistics.

Northwest Alloys instituted new efficiencies and modified their aluminothermic (magnesium production) process during the year. The resulting productivity was high, and supplies of magnesium metal outran the consumption demands of Alcoa. This relatively reduced demand, as well as sales of magnesium to other customers or so called "third party sales", was severely affected by the availability of lower cost magnesium and aluminum metals from Russia (and other countries that were formerly part of the USSR), particularly in the second half of 1993. In response to the falling price of magnesium metal, Northwest Alloys laid off 65 workers in November 1993, and the plant remains at the reduced level of 360 employees. Northwest Alloys competes with two domestic companies that produce magnesium by different (electrolytic) processes—from seawater in the case of Dow Chemical of Freeport, TX, and from magnesium chloride in the case of Mag Corp. of Salt Lake City, UT.

Northwest Alloys has taken over flux bar processing that had been the business of L-Bar Industries at Chewelah prior to their declaring Chapter 11 bankruptcy. These residues that remain after production of magnesium metal are crushed and screened to recover leftover magnesium. They are then converted into granules (prilled) and marketed as a registered soil amendment known as High-Mag-K, which is about 50 percent potash and contains soluble and insoluble magnesium and nitrogen. Inherently high chloride contents limit the applicability of this product to a few soil types. Northwest Alloys has been conducting an "interim independent remedial action" by cleaning up and stabilizing the buildings on the L-Bar site.

Nanome Aggregates of Valley (no. 207) and Northwest Marble Products Co. of Chewelah (no. 217) mined and processed multiple colors of crushed dolomite and limestone chips, primarily for exposed aggregate and terrazzo applications. Blue Silver Mining of Davenport produced white dolomite at Miles (no. 204) for landscaping rock that they commonly blend with basalt to make "salt and pepper" products that are less bright than the dolomite alone. In Whatcom County, both Tilbury Cement Co. (no. 233) and Clauson Lime Co. (no. 232) quarried limestone primarily for crushed rock applications and riprap. Alpine Rockeries Inc. of Woodinville continued to produce rockery products at the Miller Lime quarry in Snohomish County (no. 247). Alpine's installation of the white limestone rockery produces unique effects that contrast with the more widely utilized andesite and basalt rockery products.

Allied Minerals Inc. of Springdale (no. 206) and Pacific Calcium, Inc., near Tonasket were active producers of carbonates for agricultural applications. Pacific Calcium, which operates the Brown quarry near Riverside (no. 224) and the Tonasket quarry (no. 223) adjacent to the plant site, is increasing their reserve of limestone at the Tonasket quarry through a mineral lease of adjacent state land.

Northport Limestone Co., operator of the Sherve quarry near Northport (no. 212), continues to supply the Cominco smelter at Trail, BC, with fluxing-grade crushed limestone.

Columbia River Carbonates (CRC) production and sales of ground calcium carbonate (GCC) paper filler and coating continued to grow in 1993. Raw marble quarried near Wauconda (no. 220) is processed at their Woodland plant site. The giant Swiss carbonate maker Pluess-Staufer AG became a partner in the CRC operation when they acquired Genstar's interest during 1993. Thanks to the new partnership, CRC gained access to extensive technical capabilities and the large research and development staff of Pluess-Staufer. Other new benefits include access to a pilot coater that gives the company the flexibility to experiment with the amounts of GCC and work with potential customers to prepare desired base paper sheets. Many paper makers continue to investigate the synergy between precipitated calcium carbonate (PCC) and GCC. Both products replace increasingly costly pulp in fine paper. The trend toward more mineral filler in papers suggests that in the near future the amount of mineral (GCC, PCC, or a combination of the two) in glossy magazine or copier paper may grow from 15 percent to as much as 25 percent, thereby reducing the demand for trees. GCC's niche in the market appears assured by the cost savings and, more importantly, by the fact that PCC requires eight times the energy to produce and releases 13 times more carbon dioxide (Bleeck and others, 1993). CRC's growth benefits from the growth in the volume of paper being recycled and opportunities to add fresh calcium carbonate fillers to make recycled paper. CRC continues to export to Canada and China.

Diatomite

The Celite Corp. (formerly Witco Chemical Corp.) plant at Quincy was active during 1993, and diatomite continues to be a significant commodity in Washington's mineral industry. Its value ranked 7th (after sand and gravel, magnesium metal, gold, crushed stone, portland cement, and lime). Raw diatomite was quarried and stockpiled at three active pits in the Frenchman Hills (nos. 227–229). Celite markets much of their diatomite (siliceous exoskeletons of Miocene freshwater diatoms) as filtrants that, among other uses, provide final filtration for beer, wine, and apple juice. Another lucrative market for Celite's diatomaceous earth products is as plastic and paint fillers. Celite reserves the "super fine" fraction of their air-classified products for filler markets; diatomaceous earth "extends" more expensive ingredients.

Silica

Silica sand was produced by both Lane Mountain Silica Co. at Valley (no. 208) in eastern Washington and by Reserve Silica Corp. of Ravensdale (no. 254) in western Washington. Lane Mountain is the largest producer and reports mining

200,000 tons during 1993 with a net useable product of 170,000 tons. Both Lane Mountain and Reserve market most of their output to the Seattle bottle glass plant of Ball-Incon Glass. Ash Grove Cement Co.'s Superior quarry (no. 260) was also actively producing silica sand last year. Most of Ash Grove's silica sand is incorporated in portland cement that is produced in-house at their new Seattle cement plant.

Olivine

Olivine Corp. produced approximately 15,000 tons of olivine from the Swen Larsen quarry in the Twin Sisters dunite deposit southwest of Mount Baker (no. 234). Production was down from the 85,000 tons mined in 1992 as a result of excess inventory. Applied Industrial Minerals Corp. (AIMCOR) at Hamilton (no. 235) purchases most of Olivine's output as crushed rock, which they further process into various refractory sand products that foundries use for casting metals. Olivine Corp. continues to use a small percentage of olivine for in-house fabrication of waste burners. The company extended their installation of the cylindrical incinerators with a sale to Indonesia in 1993. Their incinerator at Bellingham was fully permitted and returned to service last year. For the first time in many years Olivine Corp. also sold olivine to the steel industry as a slag conditioner.

Clay and Shale

Production of clay for portland cement was the main use for Washington clay during 1993. Holnam Inc. mined 60,000 tons at the Twin Rivers quarry (no. 239) along the Strait of Juan de Fuca west of Port Angeles. Their production was down from 90,000 tons during 1992 owing to the availability of other materials that meet the high-alumina, low-alkali requirements of cement making.

Ash Grove Cement Co. mined clay at Castle Rock (no. 273) and blended it with clays purchased from the Pacific Coast Coal Co. at Black Diamond (no. 255). Pacific Coast Coal mines a 30-foot-thick clay interbed along with coal. The clay blend is used at Ash Grove's portland cement production facility at Seattle.

Brick making was the second largest application for clays mined in Washington during 1993. Mutual Materials Co. mined a total of 85,000 cubic yards of clay at two of their four western Washington pits (Sec. 31 pit and Elk pit, nos. 249, 253) and drew from existing stockpiles at the Clay City and Bucoda pits (nos. 264, 266). The company closed the brick plant at Clay City after 50 years of production but maintains the adjacent clay pits, albeit with dwindling reserves. Mutual continues to operate the Newcastle brick plant and purchased the Columbia Brick plant at Gresham, OR, which may eventually receive some clay from Washington State. Mutual also operates three concrete block plants in western Washington. In eastern Washington, Mutual continued producing brick at the Mica plant (no. 202); however, pre-existing stockpiles of clay from the Mica and Pottratz pits met demand and no new mining was conducted during the year.

Miscellaneous Industrial Mineral Commodities

Agro Minerals, Inc., was the sole producer of gypsite (an earthy form of gypsum) from the Poison Lake deposit west of Tonasket (no. 222). Peat was produced by numerous companies (nos. 221, 248, 271), but a comprehensive listing has not been compiled for peat. Barite production by both Lovejoy Mining (no. 210) and Mountain Minerals Northwest (no. 215) was inactive during 1993.

Production of silicon and aluminum metal is a significant part of the industrial output and economy of Washington. Because the raw materials are largely imported, these metals are not considered part of the Washington mineral industry by the USBM and are not included in their production value statistics. Washington is the largest aluminum producing state in the nation and has approximately one-third of the total production capacity. As with magnesium metal, the price of aluminum was hard hit in 1993 by the wide availability of material from Russia and other countries in the former USSR.

Silicon metal will continue to be produced at Rock Island following the buyout of Silicon Metaltech Inc. by SMI Group Inc. The purchase saved approximately 85 jobs in Douglas County, and 13 new ones were created with the re-start of their third furnace.

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Another fossil first for Washington

Benjamin Waggoner of the University of California, Berkeley, reports the first identifiable fossil streptomycetiform actinomycete*. This bacterium appears completely embedded in amber from a locality in the Tiger Mountain Formation near Issaquah in King County. The fossil looks like knots of branching filaments. Waggoner tentatively refers the form to *Streptomyces*, a modern genus. The amber contains at least one other bacterial form.

The clear, fractured amber in this Eocene formation contains very few bubbles or inclusions or any kind. A few insects are known but not well reported. The amber may have come from *Metasequoia*. The bacteria are thought to be terrestrial, perhaps living on or near a tree.

*Waggoner, B., 1993, Fossil actinomycetes and other bacteria in Eocene amber from Washington State, USA: Tertiary Research, v. 14, no. 4, p. 155-160.

Coal Activity in Washington—1993

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Coal activity in Washington for 1993 was limited to its two producing mines: the Centralia Mine and the John Henry No. 1. Production was down approximately 10 percent as compared to 1992 when Washington coal production recorded an all-time high.

The Centralia Coal Mine, operated by the Centralia Mining Co., a division of PacifiCorp, is Washington's largest coal mine. It is located 5 miles northeast of the city of Centralia in Lewis County (Fig. 1). The mine completed its 23rd year with a production of 4,517,882 clean short tons of subbituminous coal; this is 423,217 tons less than it produced in 1992. 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 mine supplies coal to the Centralia steam plant, the mine's sole customer, located about a mile from the mine. Coal production for 1993 comes from seven coalbeds mined at three pits. The coalbeds mined are the Smith, Little Dirty (and two splits of this coalbed), Big Dirty, 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.

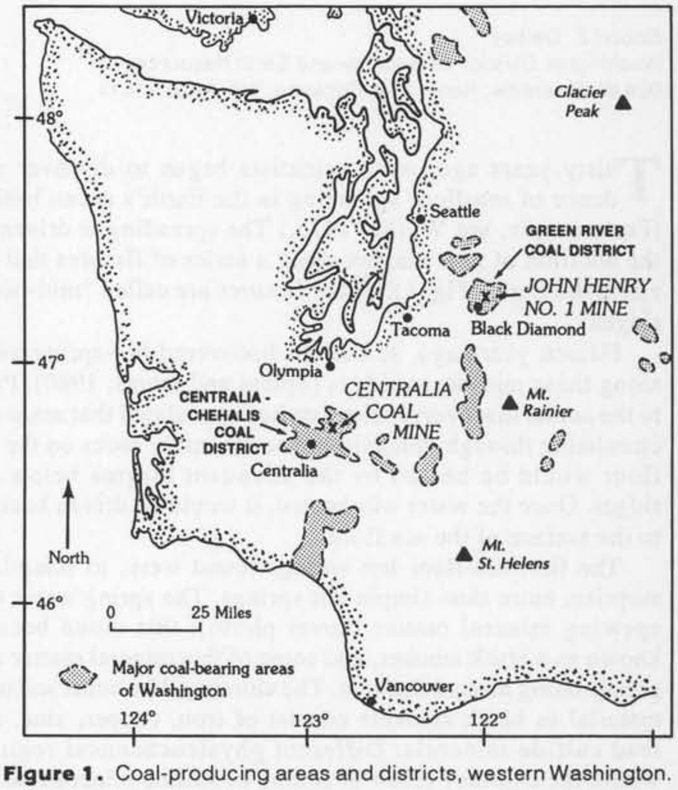

Figure 1. Coal-producing areas and districts, western Washington.

The John Henry No. 1 Coal Mine produced 221,509 clean short tons of bituminous coal in 1993, nearly 29 percent (88,728 tons) less than its peak production of 310,237 tons in 1992. The mine is operated by the Pacific Coast Coal Co. (PCCC), a joint American and Japanese venture. In 1993, PCCC exported to Korea approximately 48 percent of the coal it sold. The mine supplied the industrial sector with about 27 percent of that tonnage (up 17 percent from 1992). About 25 percent of that tonnage was sold to the Centralia Steam Plant to blend with subbituminous coal from Wyoming to be used by the plant for electrical power generation. The remainder of the sales tonnage was supplied to public institutions and residential customers for space heating.

PCCC mined coal from two pits in 1993. Nearly all (98.6 percent) of the coal was mined from Pit No. 1 from the Franklin Nos. 7, 8, 9, 10, and 11 coalbeds. The remaining production was mined from Pit No. 2 from the Franklin No. 12 coalbed. The Franklin coalbeds occur stratigraphically near the base of the Puget Group undivided in nonmarine deltaic sedimentary rocks. PCCC continued to mine coal from the south limb of the anticlinal structure exposed in Pit No. 1. It is currently mining the Franklin Nos. 8 and 9 coalbeds at the east end of the pit near the plunging, faulted crest of the anticline (Fig. 2). Mining is now being initiated in a westerly direction as PCCC begins to exploit the coal measures along the south limb of the structure at its higher levels. Backfilling has begun on the south limb where the pit has reached its maximum depth. ■

Figure 2. John Henry No. 1 coal mine, Pit No. 1, January 1994. Coal is being mined from the Franklin No. 9 coalbed (floor of pit). The Franklin No. 10 coalbed (directly beneath the light-colored sandstone) is separated from the No. 9 coalbed by a brown silty clay zone that is also mined. The clay is sold to be blended with high-alumina clays mined in Cowlitz County and used in the manufacture of portland cement in Seattle. The coal from the two Franklin coalbeds is hauled by truck to a beneficiation plant located ⅓ mile from the pit.

Hot Springs and Ore Deposition on the Sea Floor off the Washington Coast

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Thirty years ago, earth scientists began to discover evidence of sea-floor spreading in the Earth's ocean basins. (For example, see Wyllie, 1976.) The spreading is driven by the addition of new magma along a series of fissures that encircle the Earth (Fig. 1). These fissures are called "mid-ocean ridges".

Fifteen years ago, scientists discovered hot-spring vents along these mid-ocean ridges (Spiess and others, 1980). Prior to the actual discovery, scientists had speculated that sea water circulating through volcanic and sedimentary rocks on the sea floor would be heated by the abundant magma below the ridges. Once the water was heated, it would be driven back up to the surface of the sea floor.

The first sea-floor hot springs found were, to scientists' surprise, more than simple hot springs. The spring water was spewing mineral matter (cover photo); this cloud became known as a black smoker, and some of this mineral matter was precipitating around the vent. The chimney-like vents and dark material in black smokers consist of iron, copper, zinc, and lead sulfide minerals. Different physicochemical regimes within the chimney result in zoning of sulfide minerals, as indicated in a cross section of a chimney (Fig. 2).

Juan de Fuca Ridge

The Juan de Fuca (mid-ocean) Ridge, at its nearest point, is about 230 miles west of Cape Flattery (Fig. 3). The ridge is a focal point for investigations of processes operating at mid-ocean-ridge hot-spring systems. Study of the Juan de Fuca Ridge is part of the RIDGE program, an international initiative to "understand the causes and to predict the consequences of mantle-driven physical, chemical, and biological fluxes within the global spreading center system" (Ridge Events, 1990). Because the vent systems are found at depths of 2,500 meters or more, one of the principal tools used to study them is the deep diving submersible Alvin (the submersible first used in finding the Titanic). Alvin dives allow scientists to observe and collect samples of the deposits and life forms at the hot-spring vent centers.

Middle Valley at the northern end of the Juan de Fuca Ridge and southwest of Vancouver Island, BC, contains two extensively studied vent systems (Fig. 4). Observations of the active vent fields of Middle Valley indicate that hydrothermal discharge is focused into individual hot springs and that the hot springs are concentrated above a deep-seated fracture system parallel to the north trend of the rift. Mounds of hydrothermal material develop in the vent field. These mounds grow by addition of sediment contributed from collapse of vent chimneys and by inflation or mineral precipitation within the mound (Turner and others, 1993).

Life around Sea-Floor Vents

A diverse community of organisms, including giant tube worms, clams, and bacteria, lives near hydrothermal vent fields, but the fauna varies from vent field to vent field. Most communities include "vesicomyid clams, vestimentiferan tube worms, some other types of worms, crabs, and several varieties of fish. Mussels, anemones, barnacles, limpets, siphonophores, and other animals are also present in certain vent areas" (Haymon and others, 1984).

These organisms not only live, but thrive in water whose temperature is above boiling (100°C or 212°F) (Broad, 1993a,b). Life forms at these ocean depths receive no sunlight for photosynthesis; their energy comes from sulfur compounds emitted by the vents. This scientists had guessed even before analyzing the organisms because the clams and other animals smelled like rotten eggs. Most other forms of life would be poisoned by the concentrations of sulfur these faunas depend on.

Some of the bacteria in the vent communities can survive in water as hot as 700°F. Biotechnology firms are isolating, cloning, and selling enzymes from these bacteria as a heat-stable commodity for use in genetic chemistry. The enzymes are used in boiling fluids during a chemical process that

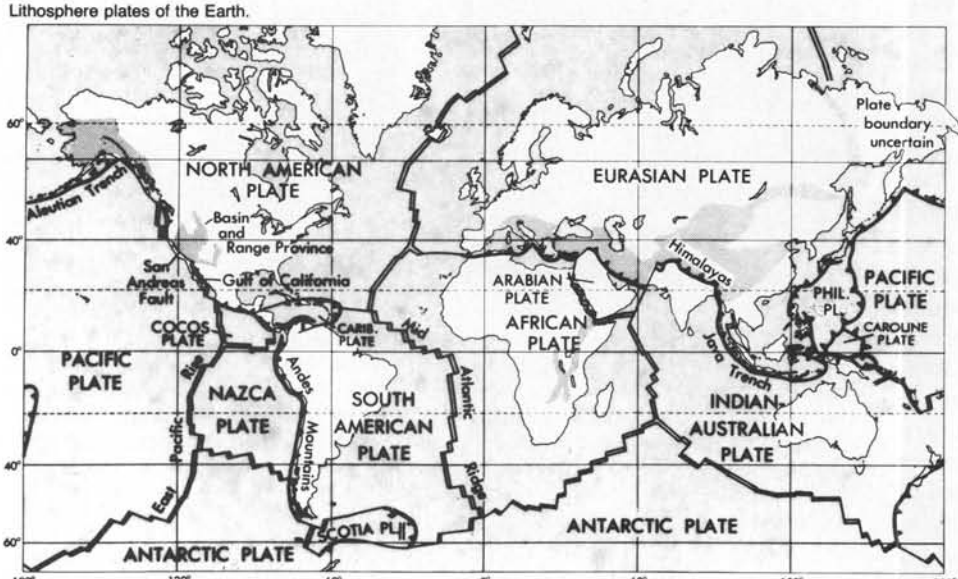
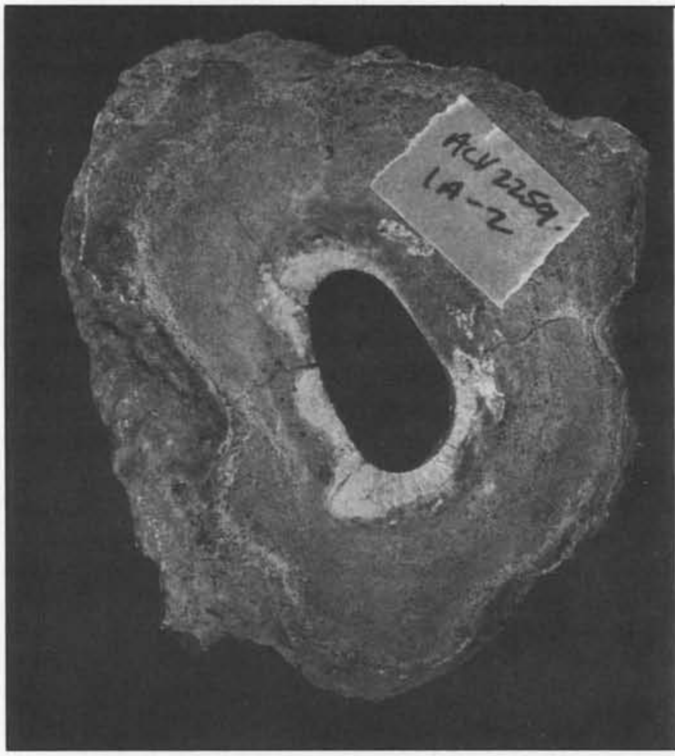


Figure 1. Major mid-ocean ridges of the world. See Figure 3 for a more detailed view of the Juan de Fuca Ridge located west of the Washington coast. (From McGregor and Lockwood, [no date].)



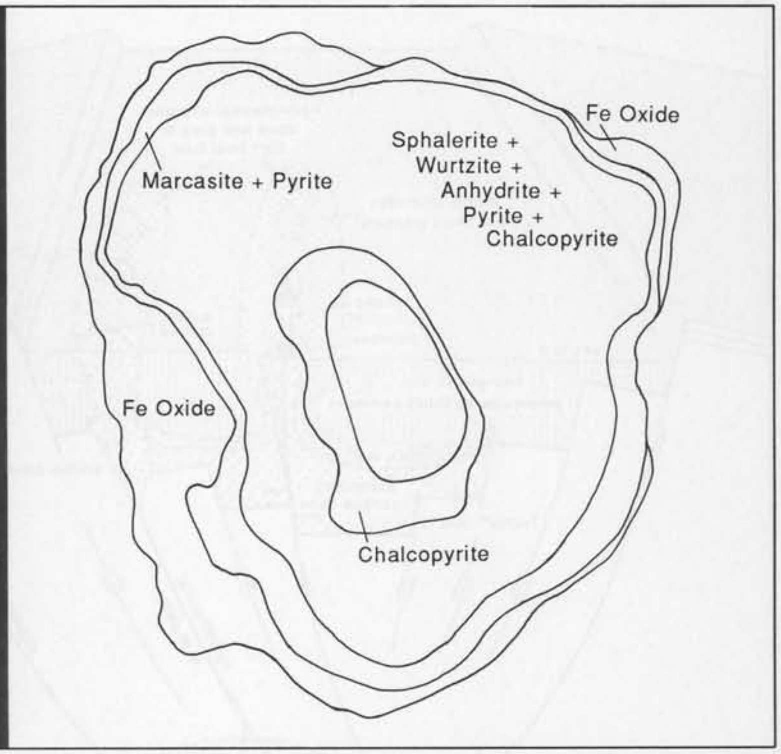


Figure 2. Cross section of a black smoker vent. Physical and chemical variations from the vent throat at the center to the outside, resulted in zoning of sulfide minerals. Predominant mineral phases from the center adjacent to the vent throat outward are copper sulfide (chalcopyrite), zinc sulfide (sphalerite and wurtzite), iron sulfide (pyrite and marcasite), and iron oxides. This resembles the zoning sequence in a sulfide mound accumulating around a chimney. Copper sulfides are abundant in the lower and central part of the mound, and zinc sulfides are more abundant at the top of the mound. (Sample provided by Randy Koski and Bill Normark, U.S. Geological Survey, 1982; photo by T. J. Walsh.)

prevents terrestrial bacteria from affecting the purity of the chemicals. Additional benefits may be realized from these unique organisms, such as detoxification of hazardous wastes (Broad, 1993a,b).

Once scientists learned about the abundant life present around sea-floor venting systems, they began to look for evidence of similar biological assemblages in on-land examples of vent deposits. Fossil worm tubes of Cretaceous age were recognized in the Bayda massive sulfide deposit of the Samail ophiolite of Oman (Haymon and others, 1984). This deposit is one of several proofs that the deposits on the sea floor can be preserved during accretion to continental landmasses.

Actively Forming Mineral Deposits

Black smokers are of special interest to economic geologists who had speculated on mechanisms of formation of volcanogenic massive sulfide (VMS) deposits (Solomon and Walshe, 1979). The scientists knew the deposits regularly occurred in volcanic or volcaniclastic rocks, were conformable with the rocks surrounding them, and, unlike many vein deposits, were not symmetrical in the walls of their host rocks. The model for VMS deposits has matured rapidly following discovery of the black smokers.

Typical VMS deposits contain a lower or original footwall zone of copper-rich minerals (dominated by pyrite and chalcopyrite). The original hanging wall portion is dominated by zinc-rich and, in some deposits, lead-rich minerals. Examples of this mineral zoning have been discovered by drilling from ships and from samples dredged from mid-ocean ridges (Fig. 2), such as the Juan de Fuca Ridge. Many on-land VMS deposits, such as the Kuroko deposits of Japan (Ohmoto and

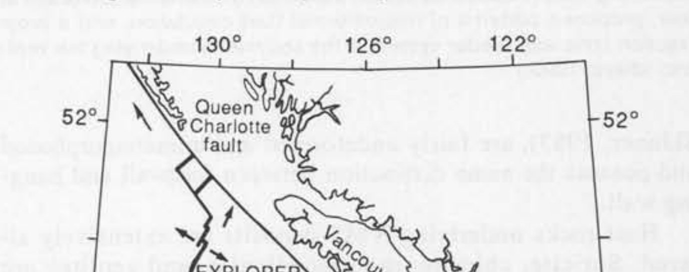


Figure 3. Location of the Juan de Fuca ridge system and Middle Valley at the north end of the ridge. (Modified from Ames and others, 1993.)

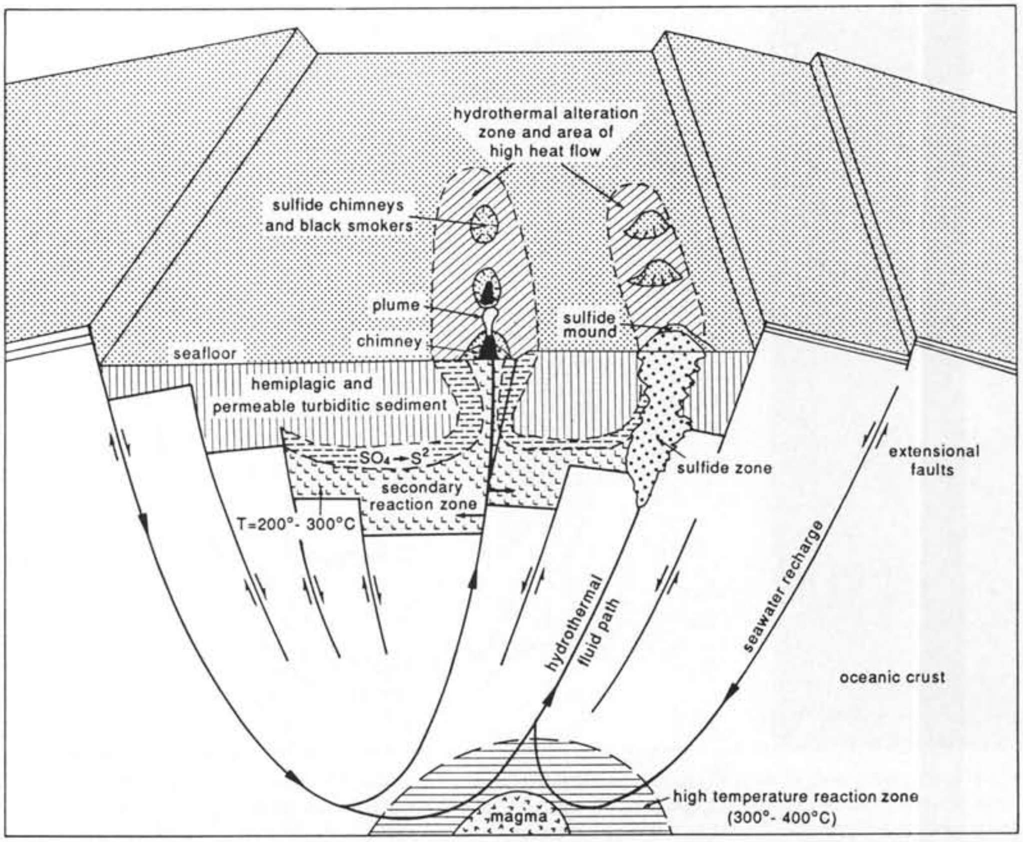


Figure 4. Schematic hydrothermal model of Middle Valley, a mid-ocean ridge, sediment-covered rift illustrating known sulfide deposits, extent of hydrothermal alteration of sediments in zones of fluid upflow, proposed patterns of hydrothermal fluid circulation, and a proposed hydrothermal "secondary" reaction zone with feeder system in the sediments underlying the vent field. (Modified from Goodfellow and others, 1993.)

Skinner, 1983), are fairly undeformed and unmetamorphosed and possess the same distinction between footwall and hanging wall.

Host rocks underlying VMS deposits are extensively altered. Sericite, chlorite, montmorillonite, and zeolites are common alteration products in rocks underlying Kuroko-type deposits (Ohmoto and Skinner, 1983). The alteration typically extends beyond the boundaries of the deposit (Franklin and others, 1981).

Metals are leached from rocks of the ocean floor as the waters move through fissures and are heated by the magma beneath the oceanic rift. When the hot, metal- and sulfur-laden fluids reach the cold ocean waters, the metals precipitate immediately, forming the black cloud of sulfide minerals. Some of these minerals drop to the sea floor, and some are swept away by slumping (Derkey and Matsueda, 1989).

Metals are also precipitated below the black smokers. They form veins, veinlets, and disseminations of the various minerals found in the black smoker. Geologists refer to the system of veins, veinlets, and disseminations underlying a VMS deposit as a feeder or stockwork for the deposit. The size and extent of a feeder system depends on the size of the hydrothermal system.

Gold in Black Smokers

Analysis of fluids venting onto the sea floor indicates the fluids may contain 0.1–0.2 micrograms of gold per kilogram of water and could transport as much as 1,000 grams of gold in a year (Hannington and Scott, 1989). Studies of several VMS deposits in Australia show two distinct occurrences for the gold: (1) in the zinc-lead-silver or the upper black ore part of the deposit or (2) in the copper or lower yellow ore part of the deposit (Large and others, 1989). In any individual VMS deposit, gold is dominant in only one of these environments and sparse to absent in the other. The gold in the zinc-rich portion is believed to have been carried as a gold bisulfide complex $Au(HS)_2^-$ by relatively low temperature (150°C to 275°C) fluids. Gold in the copper-rich portion of a deposit may have been carried as a gold chloride complex $AuCl_2^-$ by hotter (275°C to 350°C) fluids (Large and others, 1989).

Studies of black smokers are showing that trapping or retaining gold from the hydrothermal fluids varies among vent fields. If the gold is not precipitated with the sulfides near the vent, it can be widely distributed or carried away in solution in seawater.

The Holden VMS deposit (see Dragovich and Derkey, this issue) produced 600,000 ounces of gold from 10 million tons of ore (0.06 oz/short ton). Most other known massive sulfide deposits have smaller concentrations of gold.

Hot Springs and Island-Arc Magmatism

Hot-spring vents with associated mineral deposits are not restricted to mid-ocean ridges. Two other ocean-basin environments in which magmatic activity is common or widespread are back-arc basins and island arcs. Predicting where magmatic activities and associated hot-spring venting might occur in island-arc and back-arc basins is much more difficult than on the mid-ocean ridges, which are better delineated. Consequently only a few actively venting island arc-type systems have been discovered. One of these, in the Okinawa trough south of Japan, is described in Halbach and others (1989). However, in comparison to on-land mid-ocean ridge deposits, more on-land ore deposits that formed in island-arc environments are known (see Dragovich and Derkey, this issue), perhaps because island arc-type ore deposits are more likely to be preserved during accretion to the continent or because we have not yet found a consistent set of characteristics that lead to discovery of mid-ocean ridge deposits.

However, in comparison to volcanism on ridges, magmatic activity in island arcs is more explosive because of the higher proportion of volatile components in magma generated during subduction of lithosphere at an ocean trench. Explosive volcanism can be accompanied by formation of calderas, which is the case for some VMS deposits, such as the Kuroko deposits of Japan (Ohmoto and Takahashi, 1983). Extensional tectonics in andesitic to basaltic rocks in island-arc settings may be followed by caldera development, extrusion of silicic domes, and deposition of tuffaceous and related volcaniclastic rocks (Fig. 5). Sea water circulating through these rocks scavenges metals from the older rocks and the magma and is vented from black smokers, and minerals are deposited on the sea floor. The process is very similar to that on the mid-ocean ridges, but because of different metal concentrations in subducted crustal materials and commonly thicker sections of crustal material through which circulating hydrothermal systems must move, VMS deposits in island-arc terranes are likely to have metal concentrations/distributions that differ from those in the mid-ocean ridge deposits.

Other VMS Deposits in Washington

In addition to the Holden deposit, there are several known or potential VMS deposits in Washington. Four of them are the Lockwood, Alder, Copper World, and Overlook. These deposits may be the initial focus for exploration for additional deposits in the state.

The Lockwood deposit in the Sultan Basin, Snohomish County (Carithers and Guard, 1945), occurs in greenstone, gabbro, and graywacke of the Western melange belt (Tabor and others, 1982). The exposed parts of the deposit are largely pyritic, but thin discontinuous bands and lenses of fine-grained sphalerite commonly accompanied by chalcopyrite are also present. Additional polymetallic mineralization has been identified at this deposit. (See Derkey, metallic minerals summary, this issue.)

The Alder deposit southwest of Twisp in Okanogan County is concordant with bedding of dacite breccias of the Jurassic–Cretaceous Newby Group. In addition to the stratabound nature of the deposit, hydrothermal alteration at the mine is also stratabound. Veins associated with the deposit are generally small and are unrelated to the nearby Alder stock (Burnett, 1976).

Rocks of the Palmer Mountain area (Okanogan County) host deposits of possible VMS affinity, including the Copper World and Copper World Extension. Huntting (1956) described the Copper World Extension as a series of overlapping tabular lenses in shear zones. Host rock is altered andesite of the Permian–Triassic Palmer Mountain Greenstone (Rinehart and Fox, 1972).

Other deposits of possible VMS affinity are the Overlook and nearby Key and Lamefoot gold deposits northeast of Republic in Ferry County. (See Derkey, metallic minerals summary, this issue.) These deposits are in Permian sedimentary and volcaniclastic rocks. Gold is irregularly distributed in massive iron oxide and massive sulfide zones in carbonate rocks. A possible feeder has been recognized at the Overlook, where the host rocks are overturned.

Conclusions

New ideas are emerging about the effects of mantle-driven physical, chemical, and biological activities at mid-ocean ridges such as the Juan de Fuca Ridge west of Washington. Study of the life forms at these inhospitable locations is contributing to advances in biotechnology as well as to our understanding of the biota and life processes at extreme temperatures and without sunlight. Fossils similar to the fauna around hot-spring vents have been found in VMS deposits, indicating that the deposits indeed originated on the sea floor.

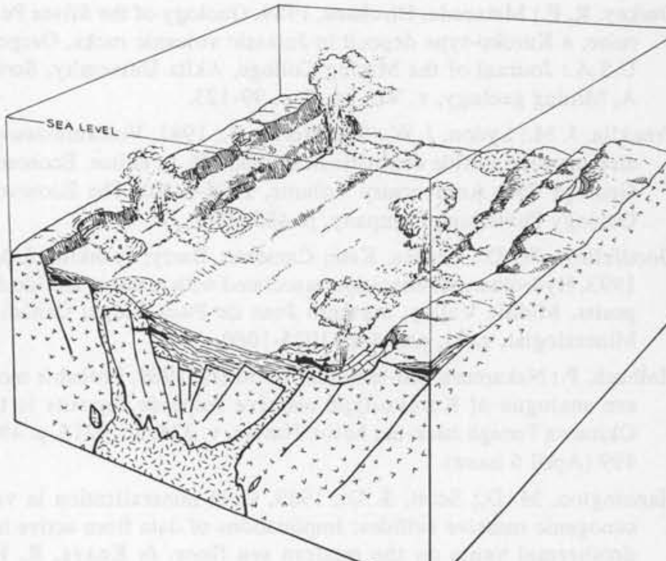


Figure 5. Schematic model of a vent field in a hypothetical sea-floor caldera. Hydrothermal systems and black smokers are fed by sea water circulating downward and being driven back to the surface by heat from cooling magma. Metals in the black smokers may be from the magma or leached from the older volcanic and volcaniclastic deposits. (From Derkey, 1982.)

No one had directly observed formation of metallic ore deposits until dives in submersible vehicles brought geologists face to face with the black smokers. Although there are differences between the on-land deposits and the actively forming deposits, there is a wealth of new observations that will influence our exploration for these types of deposits. They are widespread in the mid-ocean ridge environment; they form not only on volcanic rocks, but also on sediment-covered volcanic rocks such as those in the Middle Valley at the north end of Juan de Fuca Ridge. However, because of their great depth, mining them with today's technology is far too expensive.

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A Late Triassic Island-Arc Setting for the Holden Volcanogenic Massive Sulfide Deposit, North Cascades, Washington

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INTRODUCTION

This article discusses the local and regional geology of the Holden ore deposit and places the deposit in the new terrane framework of the crystalline core of the North Cascades. We offer a few speculations about ore genesis and then broaden the focus of the discussion to outline possible regional terrane correlations and to describe structures related to their juxtaposition. This regional model implies that deposits similar to that at the Holden mine may be present in the North Cascades.

History of the Holden Mine

In 1887, a rusty gossan, or area of weathered and oxidized metallic minerals, was observed by Major Rogers while searching the area west of Lake Chelan in Chelan County for a route for the Great Northern Railway. Rogers described the gossan to Mr. Denny of Seattle, who in 1892 outfitted J. H. Holden to evaluate the site. Holden staked claims in July 1892, and this was the start of a long series of attempts to evaluate the property and put it into production. In 1928, Britannia Mining and Smelting Co., a subsidiary of the Howe Sound Co., took control of the property, which was explored and developed by another subsidiary of the company, the Chelan Copper Mining Co.. The subsidiary relationship was dissolved in 1937, and the Howe Sound Co. began production in 1938.

The Holden mine operated from 1938 to 1957. It produced 10 million tons of ore, from which 212 million pounds of copper, 40 million pounds of zinc, 2 million ounces of silver, and 600,000 ounces of gold were extracted (McWilliams, 1958).

The average ton of ore yielded 21.2 pounds of copper (1.06 percent), 4 pounds of zinc (0.2 percent), 0.2 ounces of silver, and 0.06 ounces of gold.

The mine was closed in 1957 when costs of operation exceeded the value of minerals recovered. The property was donated to a Lutheran church group in the early 1960s, and the town of Holden is now a church retreat camp.

Regional Geologic Setting

Discussion of the regional geology centers around two areas in the crystalline core (CC) of the north part of the Cascade Range (Fig. 1A): the Holden mine area (box in Fig. 1B; Fig. 2) and the Cascade River area near Marblemount (west side of Fig. 1B).

Cascade River Unit Arc

Protolith materials and gross stratigraphy distinguish three tectonostratigraphic units in the CC: the Nason, Swakane, and Chelan Mountains terranes (CMt) of Tabor and others (1987, 1989) (Fig. 1C). Furthermore, Tabor and others (1989) have divided the CMt into an arc-related Cascade River unit (CRu) and an oceanic Napeequa unit (Nu). This nomenclature supplants localized unit names and sets previous drainage basin-scale rock-package names in coherent regional packages that emphasize provenance (that is, oceanic versus arc) and facilitate correlations and paleogeographic reconstructions. In this terrane scheme, parts of the Cascade River Schist of Misch (1952, 1966) in the Cascade River drainage (Fig. 1B) and the "younger gneissic rocks of the Holden area" of Cater and Crowder (1967), among other local (mostly informal) formation names, are included in the arc-related CRu of the CMt. Recently, Miller and others (1994), following Haugerud and others (1991; Fig. 1B), correlated the "younger gneissic rocks of the Holden area" with the CRu and suggested renaming this local sequence the Holden assemblage (Figs. 1B,C, and 2). This unit encompasses the Holden deposit. This correlation, in combination with the exhalative syngenetic model for the Holden mineralization of Nold, 1983 (described in a subsequent section), has important implications for the depositional setting and age of the Holden deposit.

The CRu consists of metamorphosed mafic to felsic flows, pyroclastic rocks, marly sediments, immature sandstones and siltstones, and rare conglomerates, pelites, and carbonate layers or pods. The Holden assemblage is dominated by hornblende-bearing rocks that include amphibolite, hornblende gneiss, and hornblende-biotite schist of mafic to felsic volcanic primary compositions. Calc-silicate rock, leucocratic gneiss, and plagioclase-biotite schist are less abundant constituents, and marble, pelitic schist, and metaconglomerate occur locally.

Marblemount Belt Subarc Plutonic Complex

The Marblemount Meta Quartz Diorite (see MMQD, Fig. 1B) and the Dumbell Mountains plutons (DMp; see explanation Fig. 2) of Cater and Crowder (1967) and Cater and Wright (1967) form a linear trend of Late Triassic quartz dioritic to tonalitic intrusive rocks termed the Marblemount belt (Mattinson, 1972). (See Fig. 1B). Although the exact timing of igneous events is still being investigated, the Marblemount belt appears to be the subarc plutonic complex to the coeval supra-arc CRu sediments and volcanic rocks (Fig. 3B).

Relative ages of the Marblemount belt plutons–CRu arc system are supplied by contact relations between the intrusive rocks and arc carapace. Absolute ages are provided by uranium-lead (U-Pb) radiometric dating of the rocks; both the MMQD and DMp's yield concordant Late Triassic ages of about 220 Ma (Mattinson, 1972).

From their observations of intrusive contact relations and the occurrence of probable CRu xenoliths in the DMp, Cater (1982) and Miller and others (1994) concluded that the DMp's of the Marblemount belt intruded the CRu. Similarly, Cary (1990) and Brown and others (1994) document that the MMQD intrudes the CRu in the Cascade River area. These relations suggest the Marblemount belt is *younger* than the CRu. Misch (1966) suggested that the metaconglomerates of the CRu in the Cascade River area lie unconformably on the MMQD basement because conglomerates proximal to the MMQD contain possible eroded MMQD clasts. This evidence suggests that the Marblemount belt is *older* than and basement to the CRu (Fig. 3A).

A CRu metatuff layer adjacent to the MMQD yields the same 220 Ma zircon age (dated by J. S. Stacey, USGS) as the adjacent Marblemount belt (Cary, 1990). To reconcile the apparently coeval ages of the *basement* MMQD and CRu volcanic rocks in the Cascade River area, Tabor and others (1988, 1989) suggested intrusion of the plutonic rocks, uplift, erosion, and deposition in rapid succession where an arc carapace could be formed on an exposed MMQD basement (Fig. 3A).

Overall, contact relations and clustered supra-arc/subarc radiometric ages provide testimony that the Marblemount belt and CRu metavolcanic rocks are a broadly cogenetic plutonic and volcanic magmatic-arc suite of Late Triassic age (Fig. 3B).

A leucogneiss in the Holden assemblage yielded a crystallization age estimate of 265 Ma (Mattinson, 1972), suggesting that the CRu is older than the Marblemount belt. If the leucogneiss is a metamorphosed keratophyre, as suggested by C. A. Hopson (*in* Mattinson, 1972), then the protolith age for this part of the CRu may be Permian. However, this zircon age is based on discordant U-Pb analyses of a single fraction that may be largely detrital, and the rock itself could be much younger (Tabor and others, 1987).

Regional Metamorphism, Intrusion, and Deformation

Paleocene or older rocks in the CC were affected by a Late Cretaceous–Early Tertiary Barrovian metamorphic-plutonic event (Mattinson, 1972), metamorphism that links the diverse terrane elements in the CC. Metamorphic grade ranges from chlorite or biotite zone of the greenschist facies (Brown and others, 1994) to kyanite or sillimanite zones of the amphibolite facies; the highest grades are coincident with migmatization. Generally, penetrative ductile deformation and widespread plutonism accompanied this metamorphism. Most Eocene and all Oligocene or younger igneous rocks in the CC cross-cut host metamorphic rocks and are unmetamorphosed.

In the Chelan block of the CC, at least two styles of penetrative deformation are discernable. The first (D1) appears to have resulted from contraction or flattening; it led to development of a strong metamorphic foliation and a weakly aligned down-dip lineation. (See Dragovich, 1989; Hurban and Talbot, 1990; Hurban, 1991; Brown and others, 1994.) Rare isoclinal folds have a well-developed axial planar foliation that parallels bedding. Superimposed on D1 fabrics are constrictional D2 L-S mylonites that are characterized by strongly developed, mostly upright foliation and subhorizontal, northwest-trending stretching lineation. D2 are upright, strike-slip ductile shear zones that commonly have dextral kinematic indicators (Dragovich and others, 1989; Brown and Talbot, 1989; Brown and others, 1994). D2 is syn- to late-metamorphic in age; locally, it is as young as late middle Eocene (43 Ma) in a poorly defined, nearly 5-km-wide zone that extends from south of the Holden mine area northwest to the Canadian border (Haugerud and others, 1991). Metamorphism continued into the Eocene in most of the Chelan Block of the CC (Fig. 1A), whereas metamorphism of the Wenatchee Block of the CC is entirely mid-Cretaceous (Mattinson, 1972; Walker and Brown, 1991; Haugerud and others, 1991; Miller and others, 1993). Because the Chelan Block remained at depth longer, it responded ductilely to transpression across the orogen while dextral strike-slip faults operated concurrently in shallow crustal blocks elsewhere in the CC (for example, concurrent Eocene offset of the Straight Creek and Entiat faults versus ductile shear zones of Haugerud and others [1991] in the Chelan block; see Figure 1A for fault locations). The Holden deposit rocks were mylonitized during D2 (late Cretaceous to Eocene?), probably overprinting mid-Cretaceous D1 structures. (See, for example, Hurban, 1991.)

Radiometric ages of late Eocene intrusive rocks in the Holden area (Fig. 2) are clustered; the Duncan Hill pluton gave potassium-argon age estimates ranging from 43 Ma to 46 Ma, and phlogopite in ore gangue from the Holden mine is about 44 Ma (Engels and others, 1976). The youngest of the larger plutons, the Railroad Creek, yielded ages of about 42 Ma and 43 Ma (Engels and others, 1976). In the Holden area, variably developed metamorphic-penetrative deformational effects on Eocene plutons (Haugerud and others, 1991; Hurban, 1991) indicate waning metamorphism and locally developed D2 shearing into the Eocene. (See Cater, 1982, for a complete description of igneous rocks in the Holden area.)

THE HOLDEN VOLCANOGENIC MASSIVE SULFIDE DEPOSIT

Volcanogenic massive sulfide (VMS), as the term is used in this article, is a body or mass containing at least 50 percent sulfide minerals and deposited on the sea floor as mounds around a series of hydrothermal vents. These mounds form both by precipitation of minerals at the vents and by inflation or replacement within the mounds. The massive sulfide forms lenses that are parallel or subparallel to bedding of the host volcanic, volcaniclastic, or sedimentary rocks. VMS deposits are typically zoned, with a copper-rich base and a zinc-rich top. (See Derkey, this issue, for additional details.)

Observations by Holden mine geologists (summarized in the next section) are essential to any discussion of the genesis of the deposit. This discussion also draws on recent observations of actively forming VMS deposits on mid-ocean ridges,

Figure 1. *(facing page)* **A**, Index geologic map of the North Cascades showing the Chelan Block of the Chelan Mountains terrane (CMt) of Tabor and others (1989). **B**, Geologic map of the Chelan Block of the CMt (modified from Haugerud and others, 1991). (See explanation, below.) The Cascade River unit (CRu) belt is a supra-arc carapace to the subarc Marblemount plutonic belt. The box outlines the geologic map of the Holden area, Figure 2. The mine symbol (–<) indicates the location of the Holden deposit. Note the Marblemount Meta Quartz Diorite (MMQD) in the Cascade River area northwest of the Holden area. **C**, Tectonostratigraphic terranes of the CC (from Tabor and others, 1989).

GEOLOGIC UNITS

13 Volcanic rocks of the Cascade arc (Neogene)

12 Plutons of the Cascade arc (Miocene to early Oligocene)

11 Middle Eocene plutons

10 Eocene continental strata—Mostly arkosic sandstones and siltstones; includes some volcanic rocks

Rocks of earliest Tertiary and Late Cretaceous orogeny

9 Earliest Tertiary and latest Cretaceous plutons (75–50 Ma)

8 Mid-Cretaceous plutons (100–85 Ma)

7 Plutons of unknown age – May be pre-Cretaceous in part

6 Skagit Gneiss Complex (Early Tertiary and Late Cretaceous) – Locally, divided into:

6a Mostly orthogneiss – Locally, divided into orthogneiss of Custer Ridge and orthogneiss of The Needles

6b Banded gneiss – Paragneiss and abundant sills of orthogneiss. Supracrustal component is mostly strata of Chelan Mountains terrane

6c Other rocks – Massive pegmatite north of the Eldorado orthogneiss. Complex of gabbro, troctolite, and norite at Skymo Lake

5 Chelan complex of Hopson and Mattinson (1971) (Late Cretaceous?) – Migmatitic gneiss; supracrustal component is mostly strata of Chelan Mountains terrane

Rocks of Pre-Late Cretaceous terranes

4 Swakane Biotite Gneiss – Protolith is Precambrian

3 Chelan Mountains terrane – Locally, divided into:

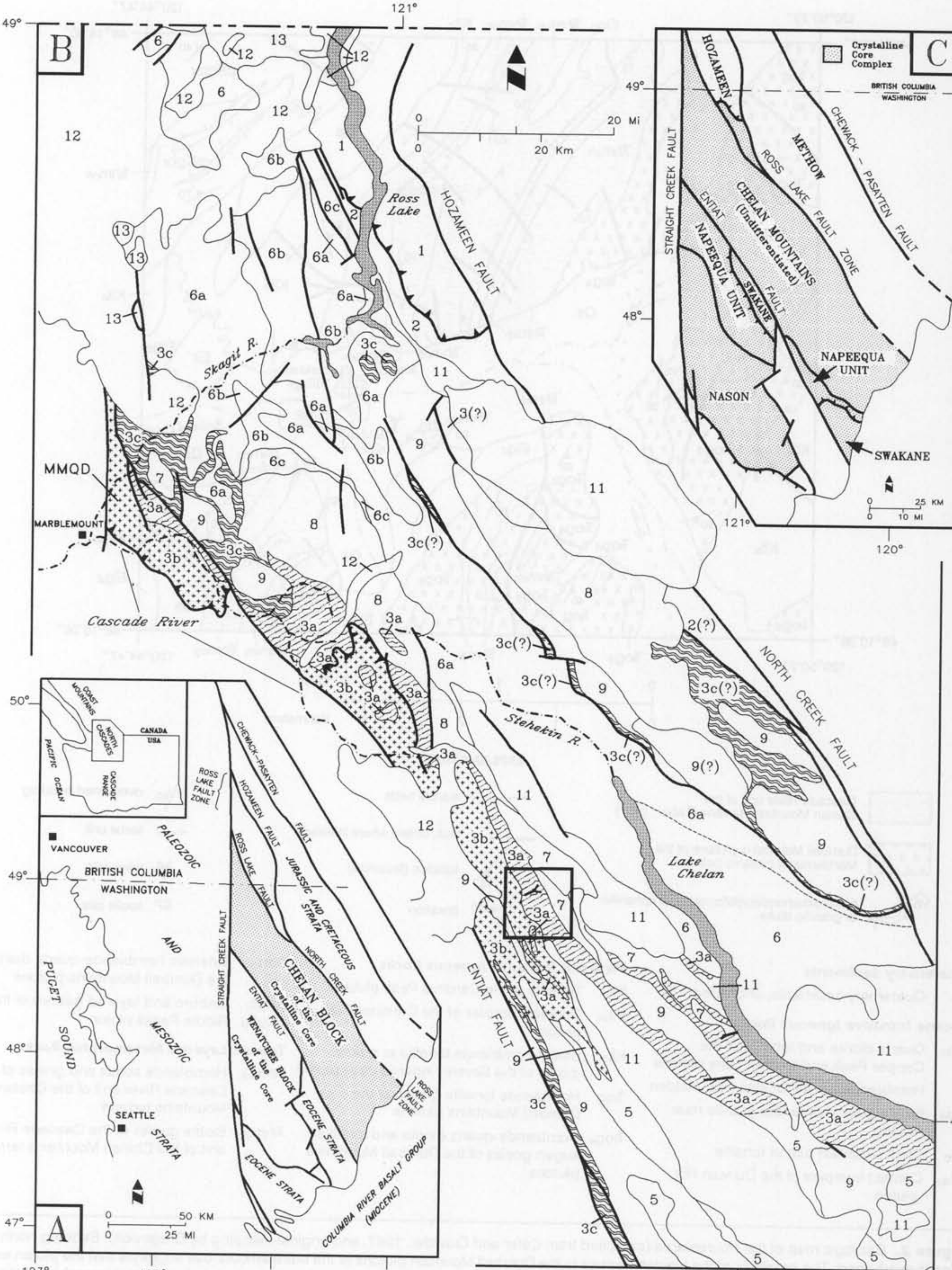
3a Cascade River unit (Late Triassic, in part) – Metamorphosed arkose, conglomerate, and pelite and associated metavolcanic rocks

3b Marblemount plutons (Late Triassic) – Quartz diorite to tonalite and derivative gneisses

3c Napeequa unit (pre(?) – Late Triassic, in part) – Metamorphosed oceanic strata

2 Little Jack terrane (age unknown) – Metapelite and metasandstone with minor marble, meta-ribbon chert, and ultramafic rock

1 Hozameen Group of Cairnes (1944) (Middle Jurassic to Permian) – Mostly basaltic greenstones, ribbon chert, and argillite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Skagit R.
MMQD
MARBLEMOUNT
Cascade River
Stehekin R.
NORTH CREEK FAULT
Lake Chelan
ENTIAT FAULT
Crystalline Core Complex
BRITISH COLUMBIA
WASHINGTON
HOZAMEEN
METHOW
CHEWACK - PASAYTEN FAULT
ROSS LAKE FAULT ZONE
CHELAN MOUNTAINS (Undifferentiated)
STRAIGHT CREEK FAULT
ENTIAT
NAPEEQUA UNIT
SWAKANE
FAULT
NAPEEQUA UNIT
NASON
SWAKANE
25 KM
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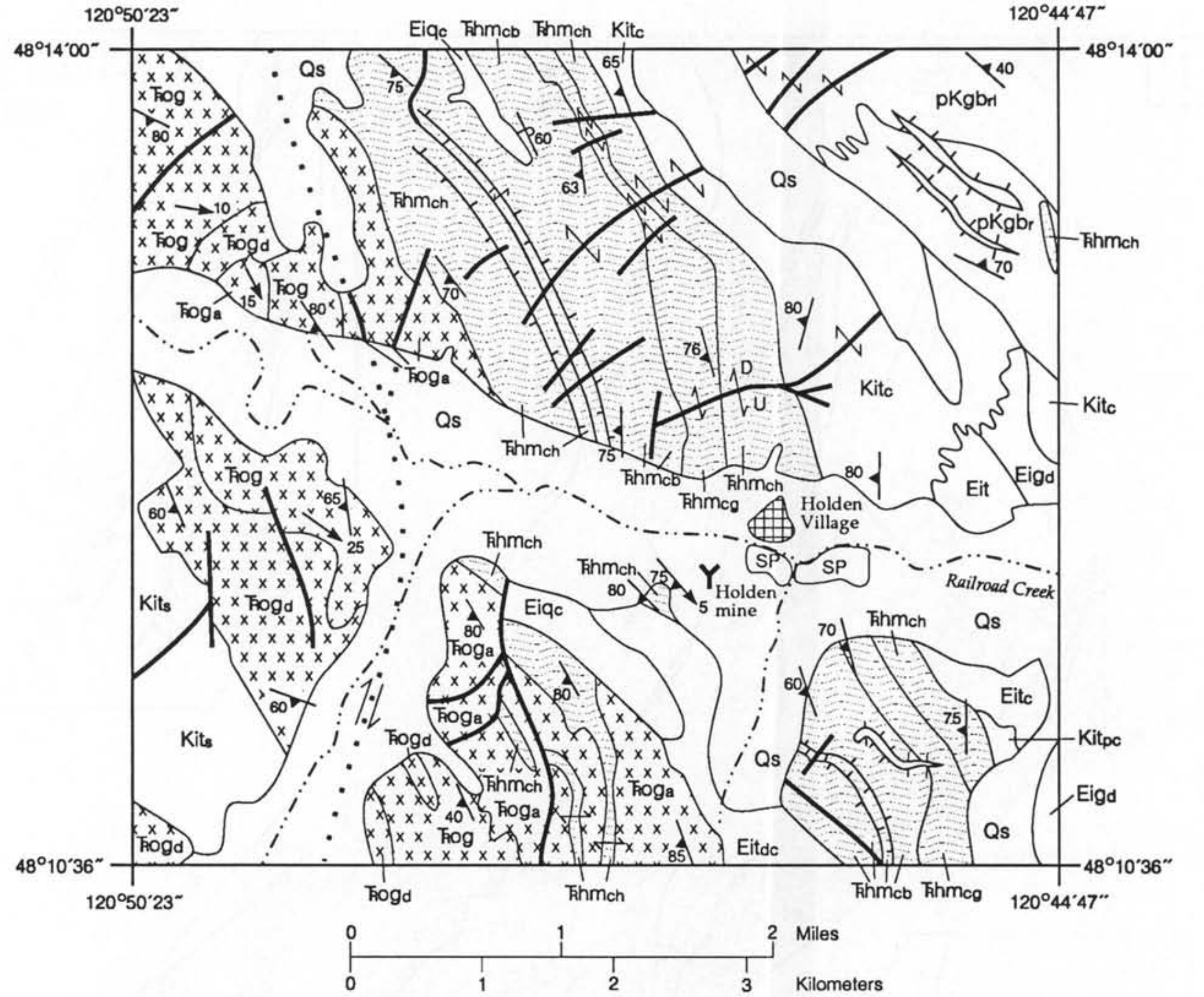
COAST MOUNTAINS
NORTH CASCADES
CANADA
USA
PACIFIC OCEAN
CASCADE RANGE
VANCOUVER
SEATTLE
PALEOZOIC AND MESOZOIC STRATA
PUGET SOUND
ROSS LAKE FAULT ZONE
CHEWACK-PASAYTEN
HOZAMEEN FAULT
ROSS LAKE FAULT
JURASSIC AND CRETACEOUS STRATA
NORTH CREEK FAULT
CHELAN BLOCK of the Crystalline Core
WENATCHEE BLOCK of the Crystalline Core
ENTIAT FAULT
EOCENE STRATA
COLUMBIA RIVER BASALT GROUP (MIOCENE)
50 KM
25 MI



EXPLANATION

Cascade River unit of the Chelan Mountains terrane (Tabor, 1987)

Dumbell Mountains plutons of the Marblemount plutonic belt

post-metamorphic/deformational aphanitic or granitic dikes

marble beds

fault, dotted where inferred

foliation (tectonite)

lineation

overturned bedding

same unit

mine adit

SP spoils pile

Quaternary Sediments

Qs — Quaternary sediments, undivided

Eocene Intrusive Igneous Rocks

Eiq$_c$ — Quartz diorite and tonalite of the Copper Peak and Holden Lake plutons

Eit — Hornblende biotite tonalite near Holden

Eig$_d$ — Biotite granodiorite and granite near Holden

Eit$_c$ — Clark Mountain pluton tonalite

Eit$_{dc}$ — Contact complex of the Duncan Hill pluton

Mesozoic Intrusive Igneous Rocks

Kit$_c$ — Tonalite of the Cardinal Peak pluton

Kit$_{pc}$ — Contact complex of the Cardinal Peak pluton

Kit$_s$ — Biotite-hornblende tonalite to quartz diorite of the Seven-Fingered Jack pluton

TRog — Hornblende tonalite gneiss of the Dumbell Mountains plutons

TRog$_a$ — Hornblende-quartz diorite and tonalite augen gneiss of the Dumbell Mountains plutons

TRog$_d$ — Gneissic hornblende-quartz diorite of the Dumbell Mountains plutons

pKgb$_r$, pKgb$_{rl}$ — Gabbro and layered gabbro of the Riddle Peaks pluton

Triassic Layered Metamorphic Rocks

TRhm$_{ch}$ — Hornblende schist and gneiss of the Cascade River unit of the Chelan Mountains terrane

TRhm$_{cg}$ — Biotite gneiss of the Cascade River unit of the Chelan Mountains terrane

Figure 2. Geologic map of the Holden area (compiled from Cater and Crowder, 1967, and original mapping by Dragovich). Bedding north of the mine is overturned. The proximity of the Holden deposit to the Dumbell Mountain plutons of the Marblemount belt suggests that the pluton was the heat source for hydrothermal circulation and resultant brine exhalation. Note the northwest-striking, southwest-dipping metamorphic foliation and related shallow southeast-trending stretching lineations. Fabric development reflects two periods of ductile deformation, both of which appear to overprint the Holden deposit, indicating that the deposit predates the Late Cretaceous metamorphism and deformation. In the unit symbols, K, Cretaceous, and TR, Triassic. The "younger gneissic rocks of the Holden area" are part of the Cascade River unit of the Chelan Mountains terrane.

comparisons with other on-land VMS deposits, and the effects of deformation and metamorphism on the Holden deposit.

Geology of the Holden Mine

Three zones of mineralization can be distinguished at the Holden deposit: (1) original footwall sulfide, (2) original footwall ore, and (3) original hanging wall ore (Fig. 4). The original footwall sulfide zone consists of pyrrhotite, pyrite, biotite, and sericite. The original footwall ore zone is interbedded with and overlies the original footwall sulfide zone. The original footwall ore contains pyrrhotite, chalcopyrite, and gold mineralization; native gold is finely divided in the chalcopyrite (Duncan, 1939; Youngberg and Wilson, 1952). Economically, the original footwall ore zone was the most important at the Holden mine. The original hanging wall ore zone is composed of pyrite and sphalerite with lesser amounts of pyrrhotite, chalcopyrite, and galena. Most of the silver recovered from the mine came from the original hanging wall zone (Nold, 1983).

Pyrite-pyrrhotite mineralization in the original footwall sulfide zone and above the original footwall ore zone is largely disseminated. Only mineralization in the original hanging wall zone contains more than 50 percent sulfides. The original hanging wall (now structural footwall) contact of the Holden deposit was sharp, and the original footwall (structural hanging wall) contact was diffuse or irregular (Nold, 1983).

An anhydrite lens was mapped for 120 feet along strike in rocks immediately overlying the original hanging wall of the deposit (Du Bois, 1954). The significance of the anhydrite is discussed in the next section on genesis of the Holden deposit.

The Holden ore deposit, like other VMS deposits (Derkey, 1982), occurs at the top of a sequence of quartz-sericite-pyrite (QSP) schist (Fig. 4). This QSP schist is traceable for at least 3 miles on the surface (Nold 1983). At the mine, the schist is approximately 300 feet thick, but it reaches a thickness of 600 feet elsewhere.

Genesis, Deformation, and Metamorphism

The geologic setting described in previous sections suggests that the Holden deposit and surrounding host rocks formed in an island arc (Fig. 3B). Gypsum and (or) anhydrite commonly occurs as lenticular or irregular masses underlying or adjacent to massive sulfide deposits in classic island-arc settings similar to the Kuroko VMS deposits in Japan (Sato, 1974). We believe that the anhydrite band at the Holden deposit is an original part of the deposit and further supports our interpretation of this deposit as a metamorphosed Kuroko-type VMS deposit.

Geologists working at the Holden mine originally classified the deposit as a vein-type deposit formed in a shear zone (Youngberg and Wilson, 1952). However, the deposit is not symmetrical across the width of the so-called vein (Fig. 4); instead, original mineral zoning has remained relatively intact. Noting that typical VMS deposit zoning consists of a copper-rich lower zone and a zinc-rich upper zone, Nold (1983) concluded that it is a VMS deposit but structurally overturned—the original footwall is now the structural hanging wall.

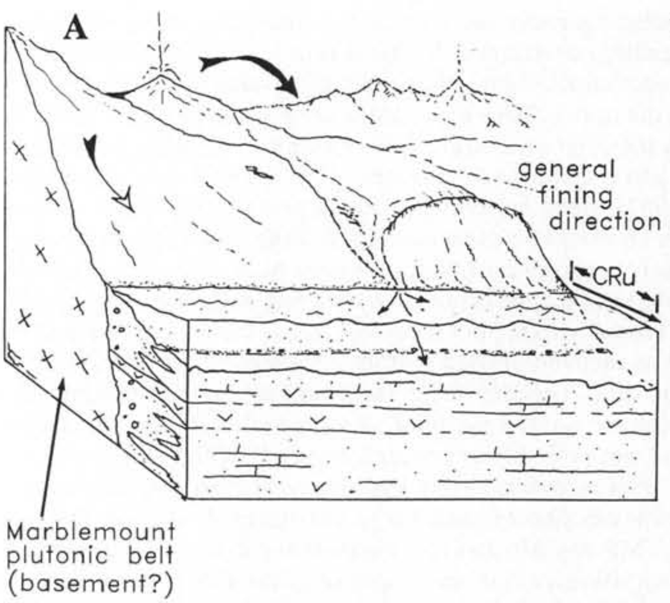
There is supporting evidence of overturning in nearby rocks as well. Cater and Crowder (1967) mapped overturned bedding in the enclosing metamorphic sequence near the deposit (Fig. 2). Youngberg and Wilson (1952) reported that the enclosing rocks are part of the limb of a large, northwest-trending, overturned, isoclinal fold; evidence for this fold includes small, tight, and commonly overturned folds observed in the mine. These small folds are presumably parasitic folds on the limb of a larger fold. However, mapping by Du Bois (1954), Cater and Crowder (1967), and Cater and Wright (1967) found no evidence for large-scale repetition of beds, which would be expected with folding. For example, two distinctive northwest-trending marble beds adjacent to the mine have been mapped continuously along strike for about 5 miles, yet these beds are not repeated. Nor is there a repetition of the gross metamorphosed protolith sequence or reversal in foliation dips. Together these facts suggest that the metamorphic sequence around the mine is a homoclinally dipping section that was probably overturned during D1 (Fig. 3C).

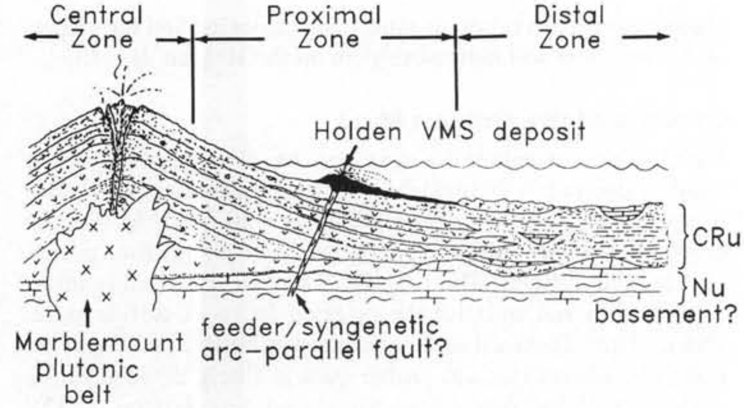
Fluids from sea-floor hydrothermal vents can carry considerable amounts of gold. Large and others (1989) note that gold in VMS deposits has two separate and distinct occurrences or associations: (1) in the zinc-lead-silver-rich upper part of the deposit *or* (2) in the copper-rich lower part of the deposit. (See Derkey, this issue, for additional details.) Gold in the Holden deposit occurs in the chalcopyrite zone, and its presence there suggests that metamorphism did not significantly modify gold distribution in the deposit.

Hydrothermal alteration is typically most extensive in rocks underlying VMS deposits (original footwall), commonly extending beyond the boundaries of the massive sulfide part of the deposit (Franklin and others, 1981). At Holden, these hydrothermally altered rocks are now the QSP schist, the metamorphic equivalent of the alteration zone. Metamorphic recrystallization and deformation have destroyed or modified the original silicate minerals, with the possible exception of quartz. Muscovite in the QSP schist is probably metamorphic, and sericite may be a retrograde product (Nold, 1983).

A typical hydrothermal alteration suite at unmetamorphosed VMS deposits includes clay, micaceous minerals, and quartz. Rock bodies containing more clay and micaceous minerals than adjacent rocks tend to be more susceptible to deformation and structural displacement. Therefore, now-recrystallized premetamorphic structures concentrated within the Holden deposit may, along with synmetamorphic deformations discussed previously (Fig. 3C), be responsible for modifications to the original Holden deposit geometry (for example, offset of the feeder system; Fig. 3B).

Despite metamorphic deformation and recrystallization, some minerals may be preserved as relics and, in thin sections, display differential strain effects as a result of contrasts in ductility. Nold (1983) has shown that Holden mineralization predated regional penetrative deformation and metamorphism: the ore minerals display plastic deformation and have been metamorphosed. At Holden, pyrite, pyrrhotite, chalcopyrite, sphalerite, and native gold are coarser grained than is typical of VMS deposits as a result of metamorphic recrystallization (grain size of the sulfides now ranges from less than a millimeter to more than a centimeter); these minerals also exhibit metamorphic textures. In some instances, the more deformation-resistant pyrite crystals are rounded or fractured during shear "rolling", whereas some of the sphalerite, pyrrhotite, chalcopyrite, and galena has been plastically deformed and has flowed around the more resistant pyrite crystals (Nold, 1983).





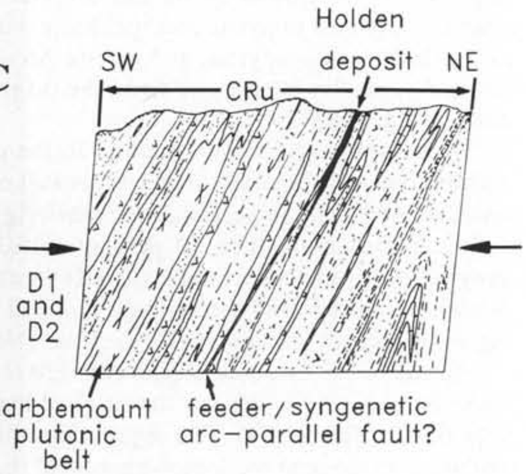


Figure 3. A, Possible depositional environment for the Cascade River unit (CRu). The metasedimentary package next to the Marblemount Meta Quartz Diorite (MMQD) in the Cascade River area (Fig. 1B) appears to be an outward-fining sequence with proximal conglomerates, tuffs, and flows grading to more distal pelites, semi-pelites, marls and minor limestone pods. In this model, the MMQD forms the basement to the CRu. **B**, Schematic cross section of a central vent volcano in an arc (modified from Williams and McBirney, 1979). This setting appears to be similar to that for the Marblemount subarc plutons and probably coeval CRu volcanic-arc carapace. We endorse this model. **C**, Schematic cross section showing intense deformation (flattening) and overturning of the Holden deposit and enclosing schists and gneisses and plutons. Flattening can be credited to D1, with some possible additional flattening during D2. However, D2 represents a constrictional ductile shear that stretches rock panels parallel to the orogen or largely in-and-out of the page along a northwest trend.

IMPLICATIONS OF THE VOLCANIC-ARC MODEL FOR THE HOLDEN DEPOSIT

Age of the Holden Deposit

Youngberg and Wilson (1952) and Du Bois (1954) related Holden mineralization to structural traps (veins, folds) produced by nearby plutonism or metamorphism and, because of the lack of absolute age constraints at that time, could only speculate on age of the deposit. Nold (1983) later recognized the premetamorphic, predeformational, syngenetic nature of the ore. On the basis of an erroneous correlation (Grant, 1969; Du Bois, 1954) of the metamorphic rocks surrounding the Holden deposit with those of the Chilliwack Group in the Northwest Cascades System west of the CC, Nold (1983) speculated that massive sulfide deposition was late Paleozoic in age. We now know from the ages of syn- and post-metamorphic plutons (Mattinson, 1972) and uplift ages (for example, Engels and others, 1976; Haugerud, 1991) that metamorphism and accompanying penetrative deformations of the Chelan block in the CC occurred from the mid-Cretaceous (about 90 Ma) to Eocene (about 43 Ma): with a high-pressure metamorphic culmination in the latest Cretaceous (Miller and others, 1993a).

As we mention in a later section, Church (1989) used lead-isotope signatures to offer evidence that deposits of the Seven Devils arc of the Wallowa terrane to the south and the Holden deposit were part of the same Permian–Triassic volcanic arc. We therefore accept a late Triassic age, approximately 220 Ma, for the syngenetic Holden deposit on the basis of the age of the host CRu arc. (See Regional Geologic Setting.)

Holden Deposit Heat Source

As shown in previous paragraphs, the Marblemount belt of plutons is likely cogenetic with the CRu volcanic carapace. The Holden deposit probably accumulated in shallow water, as indicated by lithologic characteristics of the enclosing rocks and the likely proximity of the deposit to the arc-source Marblemount belt (Figs. 1B, 2, 3A,B). Babcock and Misch (1988), Dragovich (1989), and Cary (1990) provide geochemical evidence that, on a regional basis, the CRu mafic to felsic volcanic rocks are arc-related. In fact, most CRu protoliths have a discernable volcanic component, as suggested by (1) distinct flows or tuffs, (2) poorly sorted metaconglomerates with a high percentage of volcanic clasts, or (3) calcareous sediments (metamarls) containing relict plagioclase laths. Nold (1983) describes tectonized angular plagioclase laths with oscillatory zoning from the disseminated ore zone. Similarly, metasedimentary layers elsewhere in the CRu commonly have twinned, subangular relict plagioclase clasts of volcanic origin (Dragovich, 1989).

Dragovich (1989) and Cary (1990) describe a transect through the CRu arc that appears to be an intact sequence; from southeast to northeast this comprises the subarc plutonic MMQD (Fig. 1B) of Misch (1966) flanked by proximal greenschist (meta-andesite, dacite and basalt), metaconglomerate, a thin dacitic metatuff, and a more distal shallow-water facies containing metamarl-semipelite with rare lenses of marble and pelite (Fig. 3A). This outward-fining sequence—from a near-shore volcanic clast-dominated conglomeratic facies (possibly containing some diamicton from mass wasting) to an offshore argillitic clastic facies with limy and pelitic pods—corresponds closely to principal facies variations in rocks in an arc setting (Williams and McBirney, 1979; Fig. 3B). Sediments laid down between volcanic eruptions include local shallow-water carbonates. Eruptions or other catastrophic arc phenomena such as lahar events or episodes of volcanic edifice collapse are recorded in the massive volcanic, volcaniclastic, and clastic rocks of the supra-arc carapace.

Common association of VMS deposits with synvolcanic intrusive rocks in *some* districts (Franklin and others, 1981) suggests that here the Marblemount belt may have been the heat source driving hydrothermal convective cells through the source rock. These intrusions may also have induced cross-strata permeability by causing phreatomagmatic eruptions. Calculations (Urabe and Sato, 1979; Cathles, 1977) using magmatic heat supply, time, and circulated ore-fluid volumes as variables indicate that a significant volume of hot magma (that is, a magmatic belt) is required to drive convective cells and circulate a minimum amount of brine solution. Generally, VMS districts displaying prominent coeval volcanic and intrusive suites have tonalitic-trondhjemitic intrusive rocks (Franklin and others, 1981); this is similar to the tonalitic-quartz dioritic composition of the DMp's (Cater, 1982).

Original proximity of the Holden deposit to the intrusive rocks suggested in Figure 3B is speculative, particularly in an intensely deformed orogen such as the CC. Shortening across an orogen (Fig. 3C) can juxtapose arc environment facies that were originally widely spaced perpendicular to an arc. However, significant fault displacement perpendicular to the CRu arc (such as thrusting) is not apparent in the Holden area: even assuming 200 percent ductile shortening across the CRu arc, syngenetic sea-floor mineralization probably occurred within about 10 km of the epizonal Marblemount plutonic source (Figs. 1B, 2, 3A,B).

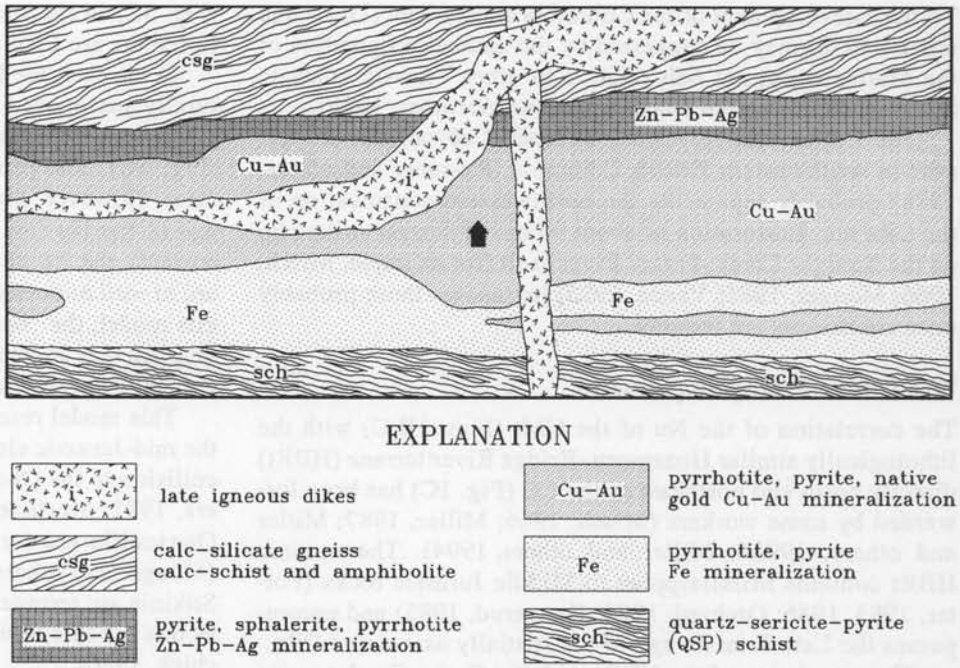


Figure 4. Idealized cross section of the *original* Holden orebody (viewed northwest along general foliation and bedding strike) showing metal zonation. Arrow points to stratigraphic top. Structural overturning has reversed the zoning typical of volcanogenic deposits. The ore now has a copper-rich hanging wall and a zinc-rich footwall. (Modified from Nold, 1983.)

Syngenetic Arc-Parallel Faults

Many volcanic chains contain arc-parallel grabens or extensional faults. (See, for example, McBirney, 1984, p. 302; Busby-Spera, 1988.) Early in the evolution of VMS deposits in these settings, hydrothermal alteration produces a silicified zone that restricts permeability (Gibson, 1979). Once formed, this upper zone acts as an impermeable cap, and the remaining metal-rich fluids are focused through localized fractures and expelled onto the sea floor to form VMS orebodies. Syndepositional extensional faulting produces avenues for fluid escape and may be critical to providing both the appropriate fluid circulation and fluid-focusing environments necessary to form VMS deposits (Mitchell, 1976; Hodgson and Lydon, 1977; Franklin and others, 1981).

In broad support of arc-parallel faulting and production of conduits for brine fluids, Busby-Spera (1988) interpreted the Late Triassic–Early Jurassic arc of Arizona, California, and western Nevada as having occupied a continuous graben depression, more than 1,000 km long and similar to the modern extension arc of Central America. We offer hypothetical arc-parallel extensional fault(s) subparallel to the northwest-trending CRu arc belt and subvolcanic Marblemount plutons (Fig. 3B). Fault parallelism to the presently northwest-trending Marblemount arc (Fig. 1B) would be accentuated during southwest-northeast directed synmetamorphic contraction and ductile strike-slip shearing (Fig. 3C). However, this metamorphism and deformation would also recrystallize and obscure the Holden deposit plumbing structure. Triassic arc-parallel extensional faults may be difficult to recognize in the CC because of overprinting by late Cretaceous to Tertiary metamorphism and ductile to brittle deformation.

Regional Correlations of Triassic Volcanic Arcs

One or more Late Triassic volcanic arc(s) were accreted to British Columbia and northeast Washington in the mid-Jurassic (Monger, 1982). On a broader scale, Mortimer (1986) correlated widespread Late Triassic volcanic-arc terranes in western North America (Fig. 5A,B) and noted that the Marblemount belt was similar in age and lithology to Seven Devils intrusive rocks. Several of these arc terranes contain VMS deposits (Church and others, 1989). Using lead isotopic signatures, Church and others (1989) correlated VMS deposits of the Seven Devils arc of the Wallowa terrane in northeastern Oregon with the Holden deposit. He further suggested that the deposits were once part of the same Permian–Triassic volcanic arc.

Independently, Mortimer (1986) used stratigraphic and geochronologic observations to correlate the Marblemount plutonic belt of the CMt with Seven Devils arc plutonic rocks. Fault separation of these arc terranes during the Cretaceous to

Tertiary development of the Columbia embayment (Davis and others, 1978) may be suggested by the anomalous position of the Marblemount arc belt relative to other Triassic volcanic arc terranes in western North America (Mortimer, 1986).

The Upper Triassic–Lower Jurassic Cadwallader arc terrane in southwestern British Columbia (Rusmore and others, 1988) probably represents the northwestern continuation of the CRu arc. Restoration of about 90 km of dextral strike-slip on the Straight Creek–Fraser River fault (for example, Misch, 1966; Monger, 1985; Vance, 1985) juxtaposes these probably once continuous arc terranes.

The Oceanic Napeequa Unit

The correlation of the Nu of the CMt (Figs. 1B,C) with the lithologically similar Hozameen–Bridge River terrane (HBRt) directly north and northeast of the CC (Fig. 1C) has been forwarded by some workers (Misch, 1966; Miller, 1987; Miller and others, 1993b; Miller and others, 1994). The oceanic HBRt contains Mississippian to Middle Jurassic rocks (Potter, 1983, 1986; Orchard, 1981; Haugerud, 1985) and encompasses the Late Triassic age of the spatially associated CRu.

The correlation of the HBRt with the Cache Creek terrane (Rusmore and others, 1988) suggests a similar, and possibly contiguous, oceanic setting for the Nu, HBRt, and Cache Creek terrane. (See Miller and others, 1993b, for discussion of the Nu–Cache Creek correlation.) In addition, correlation of the HBRt with parts of the Baker terrane of the Blue Mountains in northeastern Oregon, which is spatially associated with the Seven Devils arc, is attractive (Silberling and others, 1987). This spatial association mirrors the arc CRu–oceanic Nu–HBRt association and other paired late Triassic arc-oceanic terranes in western North America (Fig. 5A,B) and promotes broad correlation of these terranes, even though Tethyan fusulinids have not been found in the Nu and HBRt.

The Nu–HBRt may be further correlated with the late Paleozoic to Jurassic oceanic Deadman Bay and Elbow Lake terranes in the Northwest Cascade System west of the CC (for example, Miller and others, 1993b). Futhermore, correlation of the HBRt and the oceanic Cogburn Creek terrane and spatial association of these terranes with the Cadwallader arc terrane in southwestern British Columbia suggests further ties with terranes west of the CC and the Nu (Fig. 5A).

Tabor and others (1989) hypothesize that the CRu arc was built upon the older Nu oceanic crust and was therefore an oceanic island-arc (Fig. 5B). This is an attractive concept because of (1) the lack of other (exposed) "basement" rocks upon which to build an arc, and (2) the observation that most Phanerozoic massive sulfide deposits are preserved in island-arc sequences (Franklin and others, 1981). Tabor and others' (1989) interpretation that the Nu was intruded by the DMp of the Marblemount plutonic belt is based on Cater's (1982) description of intrusive contacts between these plutons and the Holden assemblage. However, Miller and others (1994) observed that the Holden assemblage is part of the CRu, not the oceanic Nu; this appears to eliminate the only field evidence for intrusion of the Marblemount belt into the Nu. To date, contacts between the CRu and Nu are exclusively tectonic, suggesting structural juxtaposition of the Nu and CRu. However, studies (Haugerud, 1985; Potter, 1986) demonstrate that the oceanic HBRt was near an arc at the end of its history. An influx of arc clastics onto the Nu–HBRt just prior to obduction (Fig. 5C) in the Jurassic may provide a depositional link between the arc CRu and the oceanic Nu–HBrt.

In the Cascade River drainage, the Nu appears to be structurally juxtaposed against the CRu along a low-angle fault (Dragovich and others, 1989; Brown and others, 1994) (Fig. 5C). The primary relations of these units are not yet clear. However, given the possible Mississippian to Jurassic age of the Nu (assuming the above Nu–HBRt correlation is correct), the Nu could easily have been basement to the CRu arc *as well as* oceanic crust obducted *onto* the arc (Fig. 5C). In this model, the "basement" oceanic Nu is older than the CRu arc, whereas an outboard (possibly younger) part of the oceanic unit was obducted/overthrust onto the arc.

This model resembles that for deformation accompanying the mid-Jurassic closing of the Cache Creek oceanic basin and collision of the Quesnellia and Stikinia arcs (Monger and others, 1982; Mortimer, 1986). During the Middle Jurassic, the Quesnellia arc terrane was obducted onto North America (Monger and others, 1982; Brown and others, 1986), and the Stikinia arc terrane was thrust under the Cache Creek terrane as this oceanic basin closed (Monger and others, 1982; Evenchick, 1986).

Closer to the CC, Rusmore and others (1986) support this model of sub- and obduction; juxtaposition of the Cadwallader and Bridge Creek terranes is recorded as Middle Jurassic deformation and is similar to coeval deformation in the Klamath Mountains and Sierra Nevada. This model may be carried into the CC where the apparent tectonic contact between the CRu and Nu of the CMt (Dragovich and others, 1989; Brown and others, 1994) may represent structural juxtaposition (obduction?) of the oceanic Nu and arc CRu during the Middle Jurassic closing of Tethyan seas documented elsewhere in North America (Davis and other, 1978). In support of this model, Miller and others (1994), observing that the CRu–Nu contacts appear to be tectonic, contend that the Nu is a separate terrane from the CRu. Furthermore, Brown and others (1994) show that metamorphic zones clearly cross-cut the low-angle tectonic boundary (thrust?) in the Cascade River area and conclude that the Late Cretaceous metamorphism postdated juxtaposition of these disparate terranes. Evidence for construction of the CRu arc on an older Nu (that is, intrusion of the Marblemount subarc plutonic belt into the Nu; Fig. 5B) has not yet been found, but the concept warrants further study. Could pre-Late Cretaceous deformation apparent in the Cascade River area of the CC document mid-Jurassic deformations recorded elsewhere where late Triassic arcs and oceanic terranes are structurally juxtaposed?

SUMMARY AND CONCLUSIONS

The Holden deposit is a metamorphosed and deformed VMS deposit that retains its original copper and zinc zoning. The presence of gold almost exclusively in the copper zone suggests that metamorphism did not affect its distribution. The most compelling evidence of overturning of the Holden deposit is copper-rich sulfides at the structural hanging wall and zinc-rich sulfides at the structural footwall.

Recent terrane analyses of the CC provide new age constraints for the Holden deposit. We conclude that the Holden deposit is a VMS deposit exhaled onto the Late Triassic CRu volcanic arc. This model provides the Marblemount plutonic belt as the subvolcanic heat source and employs possible arc-

A

Oceanic terranes (location)	Late Triassic arc terranes
Cache Creek (BC)	Stikinia (Quesnellia)
Baker (OR)	Seven Devils
Bridge River–Hozameen (BC, WA)	Cadwallader
Cogburn Creek (BC)	Cadwallader
Napeequa unit of the CMt (WA)	Cascade River unit of the CMt
Deadman Bay–Elbow Lake (WA)	---

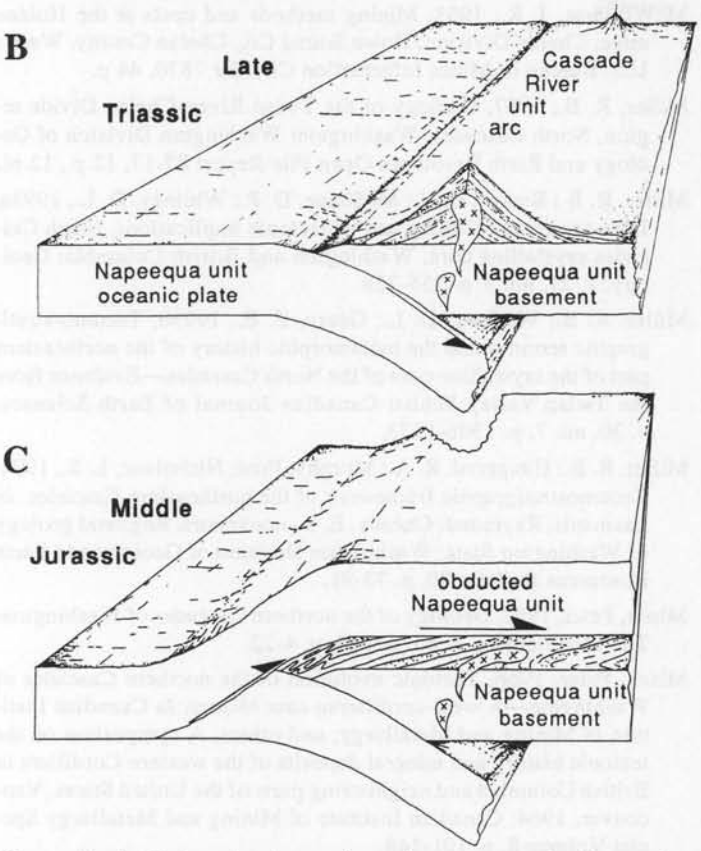


Figure 5. A, Major paired oceanic-arc terranes accreted to western North America (examples north of California). Many of these have been demonstrated to be structurally juxtaposed in the mid-Jurassic. **B**, Diagram showing Late Triassic subduction of the Nu oceanic plate beneath Napeequa unit (Nu) basement, resulting in partial melting and production of Marblemount belt plutons and Cascade River unit (CRu) volcanic rocks. Note the intrusion of the Marblemount plutons into the Nu basement. **C**, Diagram showing speculative mid-Jurassic obduction of outboard Nu oceanic plate onto the CRu arc and basement Nu. Observed tectonic contacts between the CRu and Nu and related premetamorphic structures in the Cascade River area may correlate with mid-Jurassic structures related to juxtaposition of late Paleozoic to early Mesozoic oceanic crust and Late Triassic arc rocks elsewhere in the Cordillera. The polarity of subduction and thrusting in these figures is speculative.

parallel normal faults as fluid conduits. By default and regional correlation, the oceanic Nu is basement to the CRu arc. By analogy with well-documented and correlated Canadian tectonic events, subsequent collapse and obduction of Nu oceanic crust onto the CRu in the Middle Jurassic may explain ubiquitous tectonic CRu–Nu contacts and premetamorphic juxtaposition of these units.

The Holden deposit briefly described here is only one of the known or potential VMS deposits in Washington. (See Derkey, this issue.) Accreted terranes of ocean floor and island-arc igneous and sedimentary rocks that host these deposits are fairly numerous in the state. However, common complex folding and metamorphism of the host rocks has precluded tracing (or even finding) the mineralized horizons or individual VMS deposits for great distances. New mapping by the U.S. Geological Survey and the Division of Geology and Earth Resources is helping identify some of the terranes that have potential for VMS deposits.

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Fossil Earwigs (Dermaptera) from the Klondike Mountain Formation (middle Eocene) of Republic, Washington

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Paleontologists studying the Eocene lakebed deposits in and near Republic (Fig. 1, map) have found a wide variety of fossil insects along with numerous plant species and several kinds of fish (Lewis, 1992; Wolfe and Wehr, 1987). Seven incomplete insect specimens have been identified as earwigs, members of the order Dermaptera. The fossil materials consist of parts of the abdomens and the pincher-like parts, termed anal forceps or cerci, of adult earwigs (Fig. 1A–D); they are tentatively placed in the family Forficulidae because of the shape of the forceps.

Most living species have two pairs of wings: the forewings are short, leathery, and veinless, whereas the hind wings are fan-like and have a distinctive vein pattern. The order is called Dermaptera, or skin wing, because of the texture of the first wing.

Dermapterans have a long geologic history. An extinct family has been found in Lower Jurassic (ca. 208–187 Ma) deposits of Great Britain (Whalley, 1985), and two extant families of earwigs have been found in Upper Jurassic (ca. 163–145 Ma) deposits in Kazakhstan (Vishniakova, 1980; see also 1986). Forficulids are first identified as fossils during the Tertiary, and the Republic forms are the earliest recognized (ca. 49 Ma) North American representatives. Prior to this discovery, the earliest known earwigs on this continent were those in the Oligocene Florissant beds (ca. 34 Ma) of Colorado (Scudder, 1890).

Earwigs are familiar to most of us as the small brown nocturnal insects that have the paired pinchers at the end of their abdomens. Modern species range in length from about 5 to 15 mm. There are approximately 1,100 species worldwide, most of them tropical. Eighteen species, in two families and several genera, are found in North America (Ross, 1956; Borror and White, 1970). Earwigs in the family Forficulidae are widely distributed throughout southern Canada south to North Carolina, Arizona, and California (Borror and others, 1989).

In modern mild climates, there is usually one generation of earwigs per year. The female lays the eggs in an underground chamber. Entomologists have observed maternal care of the young in some species. These insects mature quickly, after four to six molts. Most earwigs overwinter in the adult stage. Modern earwigs eat flowers, insects, and snails and are considered pests by some gardeners.

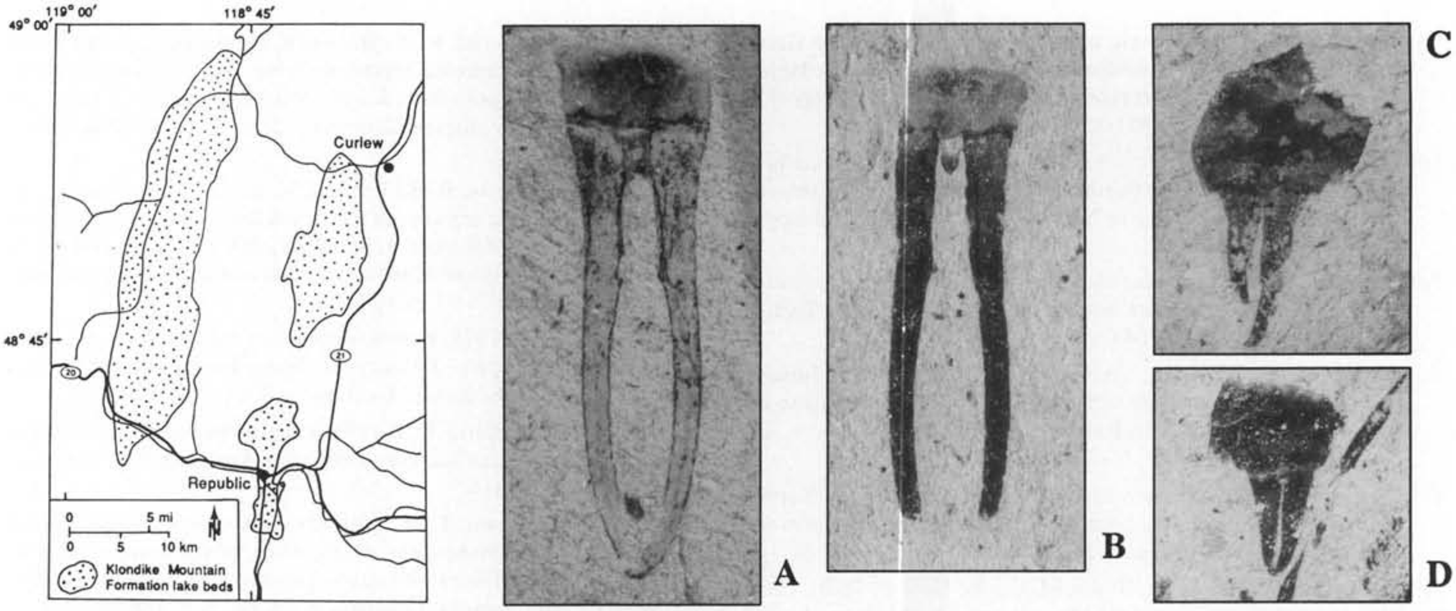

Figure 1. Location of lacustrine deposits in the Republic area of Washington and some of the fragmentary earwig (Forficulidae?) specimens recently recovered. The simple, rather straight, forceps indicate that these specimens are females, possibly two taxa. **A**, University of Washington, Burke Museum UWBM 57160 (loc. AO307) (6x); **B**, UWBM 77555 (loc. B4131) (6.25x); **C**, Stonerose collection, SR94-1-1A (6.6x); **D**, St. Cloud State University SCSU 92-157A (UWBM loc. AO307B) (6x). The remaining earwig fossils from this area are also forceps.

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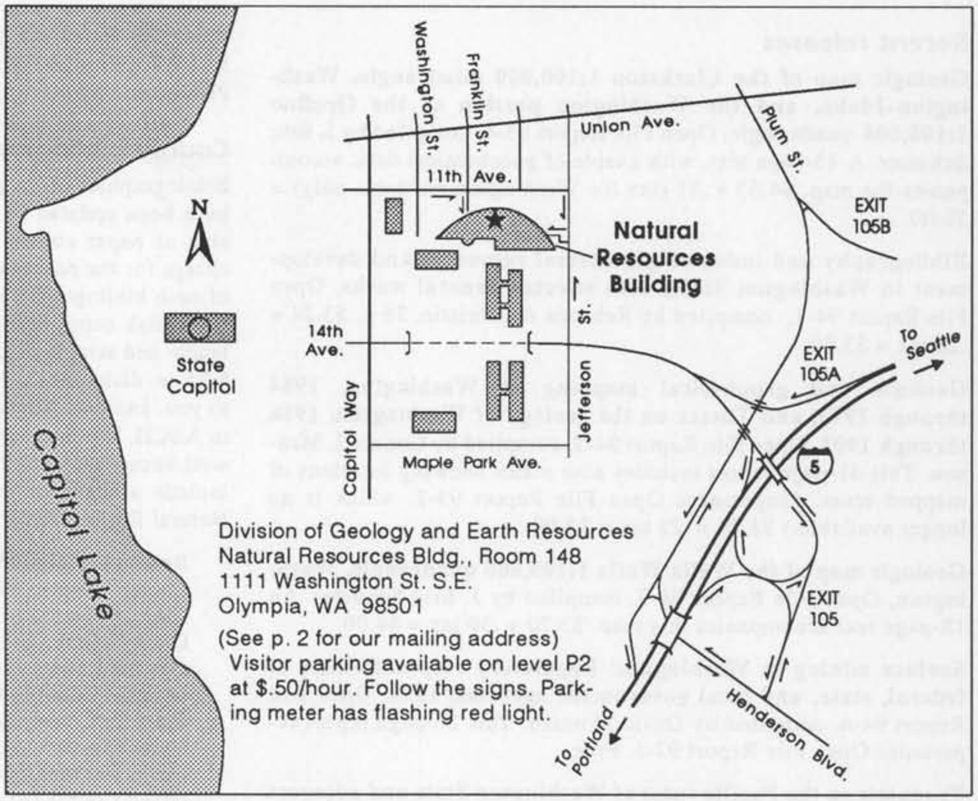

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