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Cover Photo: Diatoms, microscopic single-celled plants that secrete walls of silica, accumulated in enormous numbers in Cenozoic lakes of the Columbia Basin. The silica that remains after their death is called diatomite. Some of the diatomite mined in this pit near George, WA, is used to purify Washington apple juice; the juice is filtered through a column of diatomite. High-purity quartz mined near Valley, in Stevens Co., is used to make clear glass bottles and jars, including containers for apple juice. To learn about mining activities in the state in 1997, see p. 3.

FOOD FOR A YOUNG MIND

Raymond Lasmanis, *State Geologist*
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What backgrounds do our future earth scientists come from? How does that vast thirst for knowledge get satisfied during their formative years?

The mentor's answer is to prepare a recipe that nourishes a child's mind in such a way that learning is fun and that offers lots of decision-making options for the child. The success of this recipe was recently demonstrated to me by a nine-year-old girl, who, after two hours of working on an extra-credit science project, was still engrossed and going strong. Only dinner intervened.

At the start, the girl selected a topic, "Where do we get the materials to make the things we use every day?" And here is the recipe that was so enjoyable both for me and the child. Our ingredients: a poster board, a pile of Sunday newspaper advertisements, everyday items that one sees around the house, and a mineral collection. Mix well with lots of talking. Her product was a full poster and a game.

Questions about things within view led to her decisions on what to put on her poster. For example, should she use a small light bulb or a battery? What ore minerals provide these items? The link between cosmetics in the advertisements and the use of talc was a simple starting point for her. From the soft tactile pleasure of talc, the girl went on to feel other minerals, like crystalline gypsum, and we had a dialog about mineral hardness as she compared talc, gypsum, and quartz. She chose a quartz crystal from the Spruce claim, King County, and the final product, a piece of broken glass to put on the poster. As another product made of silica, we considered using a quartz watch, but even though we discarded that possibility, the discussion quickly turned to artificial versus natural crystals. Because they are so colorful, azurite or malachite in the mineral collection led our discussion to copper. Should a penny or copper wire go on the poster? She selected a penny. A lead sinker from the tackle box was linked with galena. The child asked for gold, but none could be donated for the cause. Native silver

Continued on p. 51.

STAFF NOTES

Philip Dobson has been promoted to Office Assistant Senior, filling the vacancy created when Judy Henderson left us.

Cathrine Kenner, one of our capable office staff, is on a 6-month temporary assignment with us.

Sheena Sallee has come to us from Community Youth Services. She is helping with office chores and working on her GED at South Puget Sound Community College.

Lysa Shaffer was with our clerical staff for a few moments; she has gone on to Forest Resources Division on a temporary assignment.

Lee Walking has acquired the title Library Information Specialist (part time). She has been working with us for about a year, apparently a willing refugee from the film industry.

The Metallic, Nonmetallic, and Industrial Mineral Industry of Washington—1997

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INTRODUCTION

Washington ranked 20th in the nation in total value of nonfuel mineral production in 1996, the last year for which production figures are available. This value, $535,289,000, represents an 8 percent decrease from 1995. The decreased production value is most evident in the nonmetallic category of commodities produced. Metals constituted about 33 percent of the total value of all nonfuel mineral commodities produced in 1996. The value of gold production increased following the 42 percent decrease in 1995 (Fig. 1) that was due to closing of mines at Wenatchee and Republic (Derkey, 1996).

This article reviews 1997 activities in the nonfuel mineral industry of Washington. Firm production values for 1997 are not yet available from the U.S. Geological Survey. Volunteered information obtained from an annual survey of mining companies and individuals provided the data for this preliminary update. In addition, several companies and individuals were contacted directly because they were known to be operating in the state. The tables in this article, therefore, are not a complete listing of mineral industry activities.

Additional details about the geology of the metallic mineral deposits and earlier industry activities in the state are available in the reviews of Washington's mineral industry published in the first issue of *Washington Geology* each year (for example, Derkey, 1995, 1996, 1997; Gulick, 1995). Questions about metallic and nonmetallic mining activities and exploration should be referred to Bob Derkey in the Division's Spokane office. Information about the sand and gravel industry and reclamation can be obtained from Dave Norman in the Olympia office. See p. 2 for addresses and phone numbers.

METALLIC MINERAL INDUSTRY ACTIVITIES

In this report, activities in the metallic mineral industry are divided into three categories: major mining and exploration projects, small-scale mining and exploration projects, and properties at which the only activity was maintenance of property. Location maps (Figs. 2, 3) are included for the first two categories, and tables are presented for each of the three categories.

Major Metal Mining and Exploration Projects

At properties considered to be major metal mining operations and about which companies furnished information, activities included extensive exploration drilling at the Pend Oreille mine and adjacent properties, submitting of permit applications required to mine at the Crown Jewel gold deposit, mining at the Lamefoot and K-2 gold deposits, and magnesium metal production from dolomite mined at the Addy dolomite quarry in 1997. All these operations are located near the northeast corner of the state (Fig. 2). This information is summarized in Table 1.

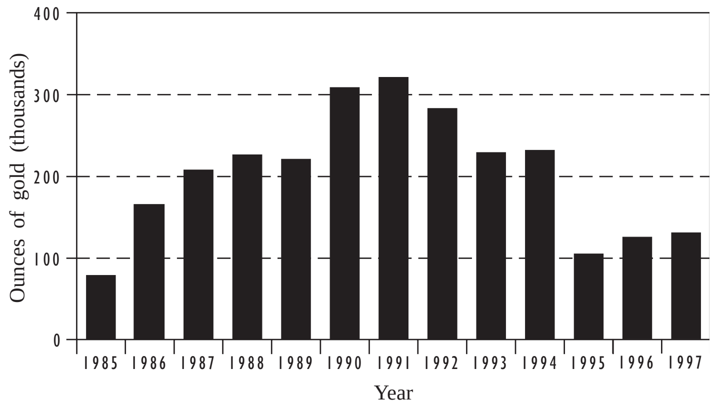

Figure 1. Gold production in Washington, 1985–1997. Echo Bay Minerals Co. was the only company with gold production in 1997. Their production (129,866 oz) increased by nearly 4,000 oz compared to that for 1996.

Lamefoot and K-2 Gold Deposits

Echo Bay Minerals Co. mined ore and produced precious metals from the Lamefoot and K-2 gold deposits. This operation, known as the Kettle River Project, is near Republic in Ferry County. These mines have been the only major gold mining operations in Washington for the past two years. In 1997, the Kettle River Project produced 129,866 oz of gold, up from the 124,910 oz produced in 1996. Recovery in 1997 was almost the same as in 1996, 85.3 percent. A total of 771,002 tons of ore was processed at the company's mill near Republic (near the Overlook mine site), compared to 601,468 tons in 1996. Although tons of ore processed in 1997 was considerably higher than in 1996, the ore grade was lower.

The majority of the ore milled at Kettle River facilities was produced from the Lamefoot deposit (Fig. 2, no. 1), an exhalative/replacement-type deposit in Permian rocks. Lamefoot produced 545,037 tons of ore that contained approximately 107,870 oz of gold. Approximately 92,000 ounces of that gold was recovered at the mill. The K-2 gold deposit (Fig. 2, no. 2), an epithermal vein-type deposit in Eocene volcanic rocks of the Republic graben, moved from development-scale operation in 1996 to full-scale production in 1997. K-2 produced 224,813 tons of ore containing approximately 44,240 oz of gold that was processed at Kettle River Project mill. Approximately 37,700 ounces of that gold was recovered at the mill. The remaining ore processed at the mill, 1,152 tons containing 45 oz of gold (approximately 38 ounces recovered), was from a low-grade stockpile of ore mined prior to 1996 at the Overlook mine.

In early 1997, Echo Bay reported proven and probable ore reserves at Lamefoot of 1,246,400 tons at 0.185 oz of gold per ton (231,000 oz of contained gold) and possible ore reserves of 108,700 tons at 0.189 oz of gold per ton (20,500 oz of contained gold). Proven and probable reserves at K-2 reported in early 1997 are 741,000 tons at a grade of 0.188 oz of gold per ton (139,000 oz of contained gold) and a possible ore reserve of 173,300 tons at 0.176 oz of gold per ton (30,500 oz of contained gold). During 1997, through the company's extensive exploration drilling program, approximately 80 percent of the reserve mined in 1997 was replaced through discovery and confirmation of new reserves. The company plans to continue their exploration program in the region in 1998, both at the operating mines and on nearby properties.

Crown Jewel Project

The environmental impact statement for Battle Mountain Gold Company's Crown Jewel gold deposit (Fig. 2, no. 3) at Chesaw in Okanogan County was released in early February 1997. The company was completing permit applications for the operation in 1997. If this process continues smoothly, the company could begin construction of the mine and mill in 1998.

Magnesium Metal Production

Northwest Alloys Inc. (a subsidiary of ALCOA) continued to produce magnesium metal at its plant near Addy in Stevens County. The amount of dolomite mined adjacent to the plant (Fig. 2, no. 5), crushed, and sent to the smelter decreased slightly in 1997, to 532,107 tons compared to 586,808 tons in 1996. The market for magnesium metal has picked up a bit, and this operation continues to be a major value-added nonfuel mineral commodity produced in Washington. Northwest Alloys also markets fertilizer and soil conditioners that are produced as byproducts of the magnesium metal smelting.

Pend Oreille Mine Exploration

Mississippi Valley-type zinc-lead mineralization has been the focus of the Pend Oreille mine (Fig. 2, no. 4) in northern Pend Oreille County for many years. Between 1917 and 1956, this deposit produced 281,290,369 lb of zinc, 145,362,573 lb of lead, 201,648 lb of copper, 257,226 oz of silver, and 95 oz of gold (Dings and Whitebread, 1965). The mine was in continuous production for 40 years beginning in 1937. Cominco American Incorporated acquired the Pend Oreille mine in 1996 and embarked on a surface and underground exploration program aimed at identifying reserves that could be shipped to their parent company's (Cominco Limited) smelter in Trail, British Columbia. Information gained from the exploration will be used in a feasibility study planned for later this year to determine how best to put the mine back into production. Startup could be sometime after closure of the parent compa-

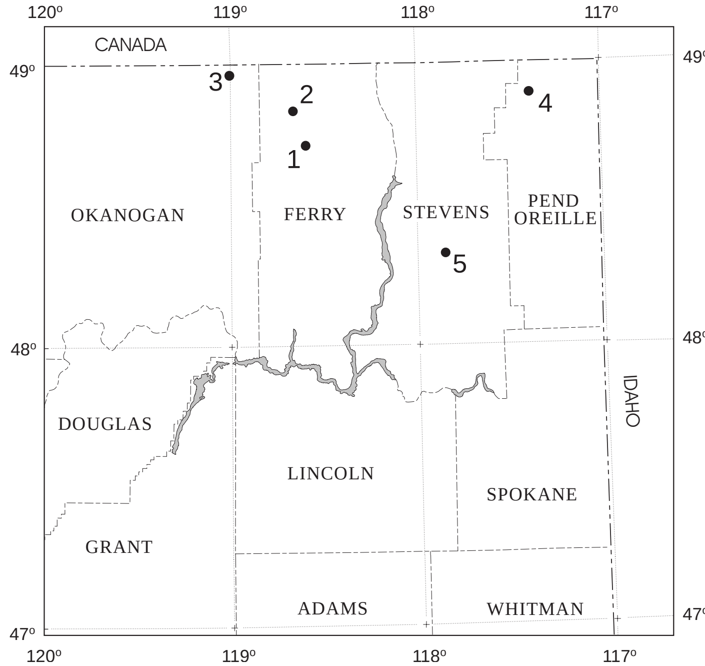

Figure 2. Location of major metal mining and exploration projects in northeastern Washington in 1997. The table below identifies mines numbered on the map.

No.	Property	Commodities	Location	County
1	Lamefoot	Au, Ag	secs. 4, 8, 37N, 33E	Ferry
2	K-2	Au, Ag	sec. 20, 39N, 33E	Ferry
3	Crown Jewel	Au, Cu, Ag, Fe	sec. 24, 40N, 30E	Okanogan
4	Pend Oreille mine	Zn, Pb, Ag, Cd	secs. 10-11, 14-15, 39N, 43E	Pend Oreille
5	Addy magnesium mine	Mg	secs. 13-14, 33N, 39E	Stevens

Table 1. Operator and brief description of the activity and geology at major metal mining and exploration projects in Washington in 1997 *(companion to Fig. 2)*

Property	Company	Activity	Area geology
Lamefoot	Echo Bay Minerals Co.	Processed 540,037 tons of ore containing 107,872 oz of gold at the mill near the Overlook mine site	Gold mineralization in massive iron exhalative/ replacement mineralization in Permian sedimentary rocks
K-2	Echo Bay Minerals Co., Kettle River Project	Processed 224,813 tons of ore containing 44,241 oz of gold at the mill near the Overlook mine site	Epithermal deposit in Eocene Sanpoil Volcanics
Crown Jewel	Battle Mountain Gold Corp./Crown Resources Corp.	EIS released in February, permitting in process	Gold skarn mineralization in Permian or Triassic metasedimentary rocks adjacent to the Jurassic–Cretaceous(?) Buckhorn Mountain pluton
Pend Oreille mine	Cominco American Inc.	Continued underground exploration drilling; obtaining data in preparation for a feasibility study on how best to reopen the mine	Mississippi Valley-type mineralization in the Yellowhead zone of the Cambrian–Ordovician Metaline Formation
Addy magnesium mine	Northwest Alloys, Inc.	Mined and crushed 586,808 tons of dolomite for smelting to produce magnesium metal	Cambrian–Ordovician Metaline Formation dolomite

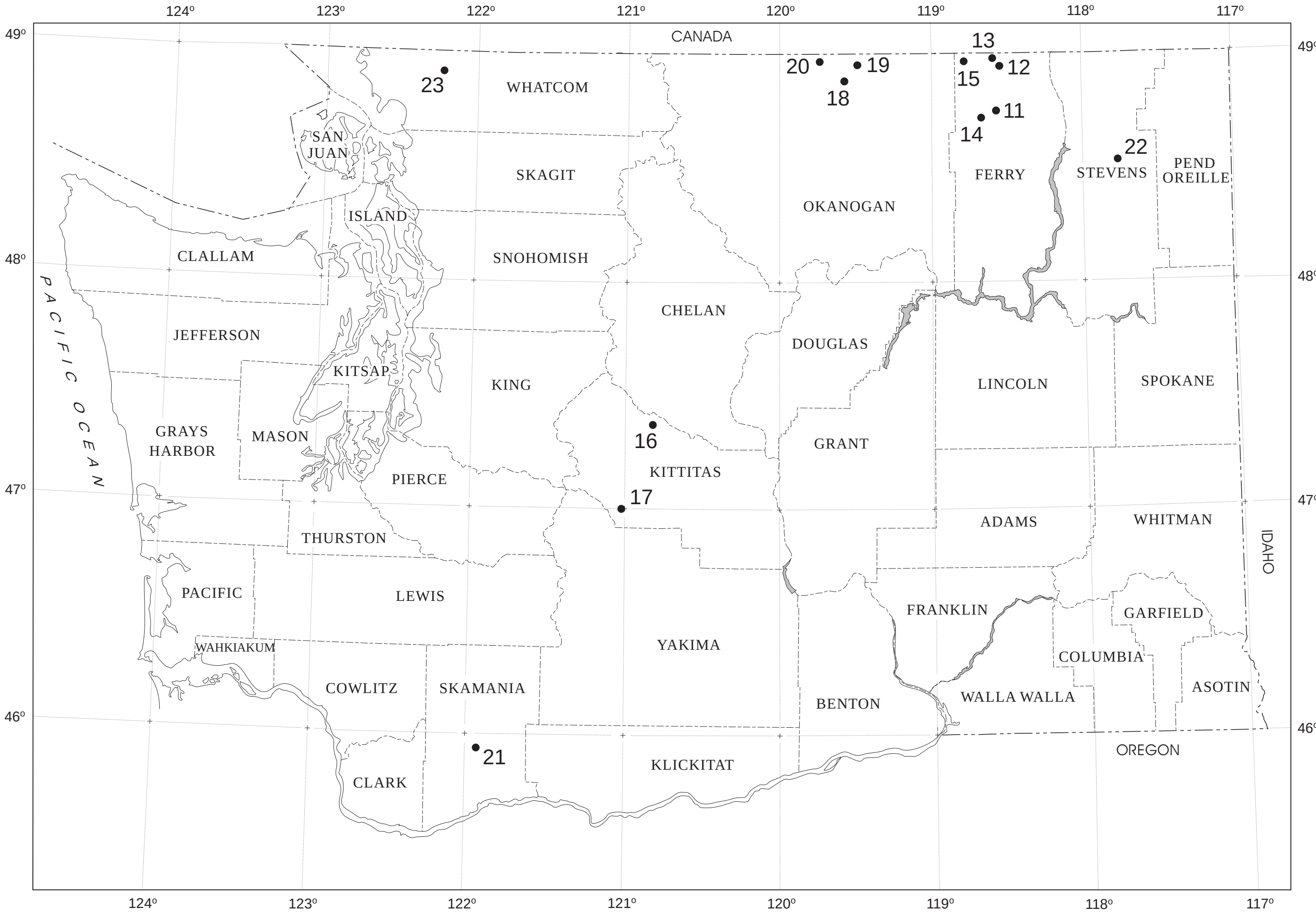

Figure 3. Location of metallic exploration and small-scale mining operations in Washington in 1997. Table at right identifies mines from numbers on the map. See Table 2 *(next page)* for additional details about each of these projects.

No.	Property	Commodities	Location	County
11	Black Hawk	Au, Ag, Cu, Fe	sec. 6, 37N, 34E; sec. 31, 38N, 34E	Ferry
12	Morning Star	Au, Ag, Cu, W	sec. 16, 40N, 34E	Ferry
13	Gold Mountain	Au, Ag, Cu	secs. 7-8, 40N, 34E	Ferry
14	Mires Creek	Au	sec. 16, 37N, 33E	Ferry
15	Kroupa Ranch	Au	secs. 21, 28, 40N, 32E	Ferry
16	Maverick	Au, Ag	sec. 30, 21N, 17E	Kittitas
17	Three Crosses	Cu, Au, Ag	secs. 25-26, 23N, 14E	Kittitas
18	Palmer Mountain	Cu, Au, Ag, Zn	secs. 20-21, 28-29, 39N, 26E	Okanogan
19	Blue Lake	Au, Ag	secs. 5-6, 39N, 27E	Okanogan
20	Four Metals	Pb, Ag, Cu, Zn, W, Mo	secs. 22-23, 40N, 25E	Okanogan
21	Wind River	Au, Ag	sec. 9, 5N, 7E	Skamania
22	Schuer Bet	Au	secs. 27-28, 35N, 39E	Stevens
23	South Pass Nickel	Sc, Ni, Co	sec. 2, 39N, 4E; sec. 35, 40N, 4E	Whatcom

ny's Sullivan mine in nearby British Columbia. Reopening the Pend Oreille mine could provide jobs in an area that has very high unemployment.

Small-Scale Mining and Exploration Projects

Several exploration and small-scale mining projects were active in 1997. Figure 3 shows the locations of these projects; Table 2 lists the mines and their activities and includes a brief comment about the geology of the deposit.

Echo Bay Minerals Co. was the most active of the companies exploring in Washington in 1997. They continued to explore at the Black Hawk property (Fig. 3, no. 11) and added the Mires Creek property, both possible sites of mineralization similar to that at their Lamefoot deposit, also in Ferry County. In addition, Echo Bay drilled at the Kroupa Ranch property (Fig. 3, no. 15), looking for Eocene epithermal-type gold mineralization.

A new company active for the first time in Washington in 1997 was Spokane-based Yamana Resources Inc. The company had been active on several foreign properties and added Palmer Mountain, Blue Lake, and Schuer Bet to their list of holdings in early 1997. They were most active at the Palmer Mountain property (Fig. 3, no. 18), which is in Permian and Triassic accreted-terrane rocks; they drilled 18 holes. The target was volcanogenic massive sulfide mineralization, and the company was encouraged by results. Yamana also drilled for gold mineralization at the Blue Lake (Fig. 3, no. 19) and Schuer Bet (Fig. 3, no. 22) properties.

At their Wind River property in Skamania County, DeLano Wind River Mining Co. was driving a drift to intercept the vein at a lower level and modifying the mill through the addition of a floatation circuit to recover the gold-bearing minerals. They also continued to mine and stockpile ore from the Wind River

Table 2. Operator and brief description of exploration and small scale mining operations in 1997 *(companion to Fig. 3)*

Property	Company	Activity	Area geology
Black Hawk	Echo Bay Minerals Co.	Drilled 2 holes totaling 1,475 ft	Gold mineralization in massive iron replacement/ skarn in Permian sedimentary rocks
Morning Star	Echo Bay Minerals Co.	Drilled 3 holes totaling 1,940 ft	Volcanogenic massive sulfide mineralization in Mesozoic accreted terrane rocks
Gold Mountain	Globex Nevada, Inc.	Conducted some reclamation work	Gold-pyrite mineralization in an alkalic dike of the Jurassic Shasket Creek complex
Mires Creek	Echo Bay Minerals Co.	Drilled 5 holes totaling 3,900 ft	Gold mineralization in massive iron replacement/ skarn in Permian sedimentary rocks
Kroupa Ranch	Echo Bay Minerals Co.	Drilled 4 holes totaling 2,435 ft	Gold mineralization in Eocene volcaniclastic and sedimentary rocks
Maverick	Wally Mieras	Small-scale mining	Gold-quartz veins in Eocene Swauk Formation
Three Crosses	Art Baydo	Continued drilling	Mineralization in diabase and gabbro of the Ingalls Complex
Palmer Mountain	Yamana Resources Inc.	Conducted spontaneous potential, induced polarization, magnetometer, resistivity surveys; drilled 18 holes for a total of 5,130 ft	Ore lenses in altered andesite of Permian–Triassic Palmer Mountain Greenstone
Blue Lake	Yamana Resources Inc.	Drilled 15 reversed circulation holes totaling 6,965 ft	Anomalous gold found along margins of Permian–Triassic limestone
Four Metals	Lovejoy Mining	Diamond drilling	Vein in Similkameen composite pluton at or near contact with a roof pendant
Wind River	DeLano Wind River Mining Co.	Mining and stockpiling ore, driving lower adit to intercept vein, setting up floatation cells at the mill	Epithermal mineralization in Oligocene–Miocene volcanic rocks
Schuer Bet	Yamana Resources Inc.	Drilled 8 reversed circulation holes totaling 2,285 ft, dropped property	Gold skarn mineralization along shallow dipping limestone–granite contact
South Pass Nickel	Consolidated Viscount Resources, Ltd.	Testing feasibility of extracting nickel and scandium from laterite	Nickel and scandium in Eocene, resedimented laterite

gold deposit (Fig. 7, no. 21). The company hopes mill modification will allow them to obtain permits to establish the milling operation.

Globex Nevada, Inc. continued its interest in the Gold Mountain deposit in northern Ferry County (Fig. 3, no. 13) in rocks of the Shasket Creek alkalic complex at the north end of the Republic graben.

The owner of the Three Crosses property near Cle Elum in Kittitas County continued exploratory drilling in 1997. Small-scale mining also continued at the Maverick property in the central part of the state.

Echo Bay Exploration drilled three holes at the Morning Star deposit (Fig. 3, no. 12), a property with volcanogenic massive sulfide mineralization potential in northern Ferry County.

Lovejoy Mining conducted diamond drilling at the Four Metals property (Fig. 3, no. 20) in Okanogan County.

Consolidated Viscount Resources, Ltd. continued to investigate methods of recovering scandium from the South Pass laterite deposit (Fig. 3, no. 23) in Whatcom County.

Maintained Property

Companies and individuals who maintained their properties in 1997, either through payment of claim lease fees or completion of assessment work on unpatented claims, are listed in Table 3.

NONMETALLIC MINERAL INDUSTRY ACTIVITIES

The combined production of nonmetallic mineral commodities (carbonates, clays, diatomite, olivine, and silica) accounted for about $118 million, or approximately 22 percent of the approximately $535,447 million total value of nonfuel mineral production for Washington in 1996, the last year for which figures are available. Figure 4 and Table 4 summarize activities for nonmetallic commodities in 1997. Information covering recent years' activities for nonmetallic commodities can be found in articles by Gulick (1995) and Derkey (1996, 1997).

Carbonates

A number of companies mined limestone and dolomite, calcium carbonate, and calcium magnesium carbonate and sold these rocks or minerals as a soil conditioner and/or as feed lime. Three of these companies are Pacific Calcium Inc., producing from their Tonasket (Fig. 4, no. 110) and Brown (Fig. 4, no. 111) quarries in Okanogan County; Allied Minerals, Inc., at the Gehrke quarry (Fig. 4, no. 116) in Stevens County; and Northwest Alloys, where calcium-magnesium lime is a by-product of magnesium metal production at Addy (Fig. 2, no. 5) in Stevens County. Columbia River Carbonates continued to produce high brightness calcium carbonate mined from the Wauconda quarry (Fig. 4, no. 112) and process it for the paper industry in Longview, Cowlitz County. Northport Limestone Company mined and shipped carbonate from its Sherve quarry (Fig. 4, no. 121) in Stevens County. Most of its product was shipped to Trail, B.C., where it was used as a fluxing agent in smelting. Northwest Marble Products (Fig. 4, no. 118) produced color- and site-specific carbonate products for terrazzo tile and related products.

The Joe Janni (Fig. 4, no. 119) and Janni Limestone (Fig. 4, no. 120) quarries in Stevens County had only limited activity in 1997.

The only known active mining of a carbonate deposit in western Washington was at the Maple Falls quarry (Fig. 4, no. 122) in Whatcom County.

Table 3. Properties known to be maintained or undergoing reclamation but where no active mining or exploration was undertaken *(no companion location map)*

Property	Location	Company	Commodities	Area geology	County
Wenatchee Gold Belt project	sec. 35, 22N, 20E	Yamana Resources Inc.	Au, Ag	Mineralization along the Wenatchee gold belt in altered (commonly silicified) horizons in Eocene arkosic sandstone	Chelan
Golden Eagle	sec. 27, 37N, 32E	Newmont Gold Co.	Au, Ag	Epithermal mineralization in Eocene bedded tuff	Ferry
Apex & Damon	sec. 34, 26N, 10E	CSS Management Corp.	Au, Ag, Cu, Pb	Quartz vein in granodiorite of the Miocene Snoqualmie batholith	King
Weyerhaeuser properties	Cascades area	Weyerhaeuser Co.	Au, Ag, Cu, Mo, Pb, Zn, clay, silica	Cascades province and adjacent volcanic, volcaniclastic, and intrusive rocks	King, Pierce, Thurston
Williams Creek	secs. 1-2, 20N, 17E	Goodfellow Construction	Au, Ag	Placer deposits along Williams Creek	Kittitas
September Morn	sec. 10, 20N, 17E	Ron Kilmer	Au, Ag	Placer deposit along Williams Creek	Kittitas
Silver Belle	sec. 25, 38N, 31E	Lovejoy Mining	Au, Ag	Epithermal mineralization in Eocene felsic volcanic rocks of Toroda Creek graben	Okanogan
Hot Lake	secs. 7, 18, 40N, 27E	Wilbur Hallauer	Au, Ag	Gold mineralization adjacent to the Kelsey porphyry-type deposit	Okanogan
Aeneas Valley property	sec. 8, 35N, 31E	Sunshine Valley Minerals, Inc.	Au, Ag, Cu, silica	Possible gold mineralization associated with large high-grade quartz bodies in probable Permian rocks	Okanogan
Ida	secs. 16, 21, 39N, 31E	Crown Resources Corp.	Au, Ag, Cu	Epithermal veins in Eocene Sanpoil Volcanics and Klondike Mountain Formation of the Toroda Creek graben	Okanogan
Billy Goat	sec. 15, 38N, 20E	Sunshine Valley Minerals, Inc.	Au, Cu, Ag	Stockwork in Cretaceous? andesite tuff and breccia	Okanogan
Kelsey	secs. 5-8, 40N, 27E	Wilbur Hallauer	Cu, Mo, Ag, Au	Porphyry-type mineralization in Jurassic–Cretaceous Silver Nail quartz diorite	Okanogan
Starr Molybdenum	secs. 8, 16, 37N, 26E	Wilbur Hallauer	Mo, Cu, W	Porphyry-type mineralization in Cretaceous Aeneas Creek quartz monzonite and granodiorite; gold in secondary enriched zone	Okanogan
Crystal Butte	sec. 35, 40N, 30E	Keystone Gold, Inc., leased to Battle Mountain Gold Corp.	Au, Ag, Pb, Zn, Cu	Skarn type mineralization in Permian Spectacle Formation intruded by Mesozoic rocks	Okanogan
Jim Creek	secs. 8-9, 16-17, 38N, 42E	Northwest Minerals Ltd.	Zn, Ag, Pb, Cu, Mo, Au, W	Contact metamorphic mineralization in Lower Paleozoic carbonate and shale intruded by Cretaceous granitic rocks with porphyry type mineralization	Pend Oreille
Silver Star	secs. 3-5, 8-9, 3N, 5E	Kinross Gold USA, Inc.	Cu, Ag, Au, Mo	Tourmaline-bearing breccia pipe associated with porphyritic phases of the Miocene Silver Star pluton	Skamania
Trout Creek property	sec. 20, 27N, 11E	Ariel Resources Ltd.	Cu, Au, Ag, Zn, Pb, W, Sn, Pt	Volcanogenic massive sulfide/contact metamorphic mineralization adjacent to the Tertiary Grotto batholith	Snohomish
Iroquois	secs. 1, 19-20, 29-30, 40N, 42E	Mines Management, Inc.	Zn, Pb, Ag, Au	Mineralization in a breccia zone in Cambrian–Ordovician Metaline Formation	Stevens
Van Stone mine	sec. 33, 38N, 40E	Zicor Mining Inc.	Zn, Pb, Cd	Mississippi Valley-type mineralization in the Cambrian–Ordovician Metaline Formation	Stevens
Toulou Mountain	secs. 6, 30-31, 39N, 37E	Northwest Minerals Ltd.	Zn, Pb, Cu, Ag, Au	Exhalative/contact metamorphic mineralization in Permian volcaniclastic and sedimentary rocks	Stevens
Cleta Group	secs. 22, 27, 40N, 37E	David Robbins and Associates	Au, Ag, Cu	Vein and replacement mineralization in sheared and contact-metamorphosed Permian Mount Roberts Formation	Stevens
Lone Jack	secs. 22-23, 40N, 9E	Diversified Development Co.	Au, Ag	Quartz veins in metasedimentary rocks	Whatcom
New Light	sec. 27, 38N, 17E	Western Gold Mining/North Cascades Exploration	Au, Ag	Quartz-carbonate-cemented slate-argillite breccia in the Lower Cretaceous Harts Pass Formation	Whatcom
Minnesota	sec. 2, 37N, 16E	Seattle-St. Louis Mining Co.	Au, Ag, Cu	Quartz veins in argillite and feldspathic sandstone of Lower Cretaceous Harts Pass Formation	Whatcom
Azurite	sec. 30, 37N, 17E	Double Dragon Exploration Inc.	Au, Ag, Cu, Pb	Veins in sedimentary rocks of the Cretaceous Virginian Ridge Formation	Whatcom
Morse Creek	sec. 31, 17N, 11E	Ardic Exploration & Development, Ltd.	Au, Ag	Tuffs of the Oligocene Ohanapecosh Formation	Yakima

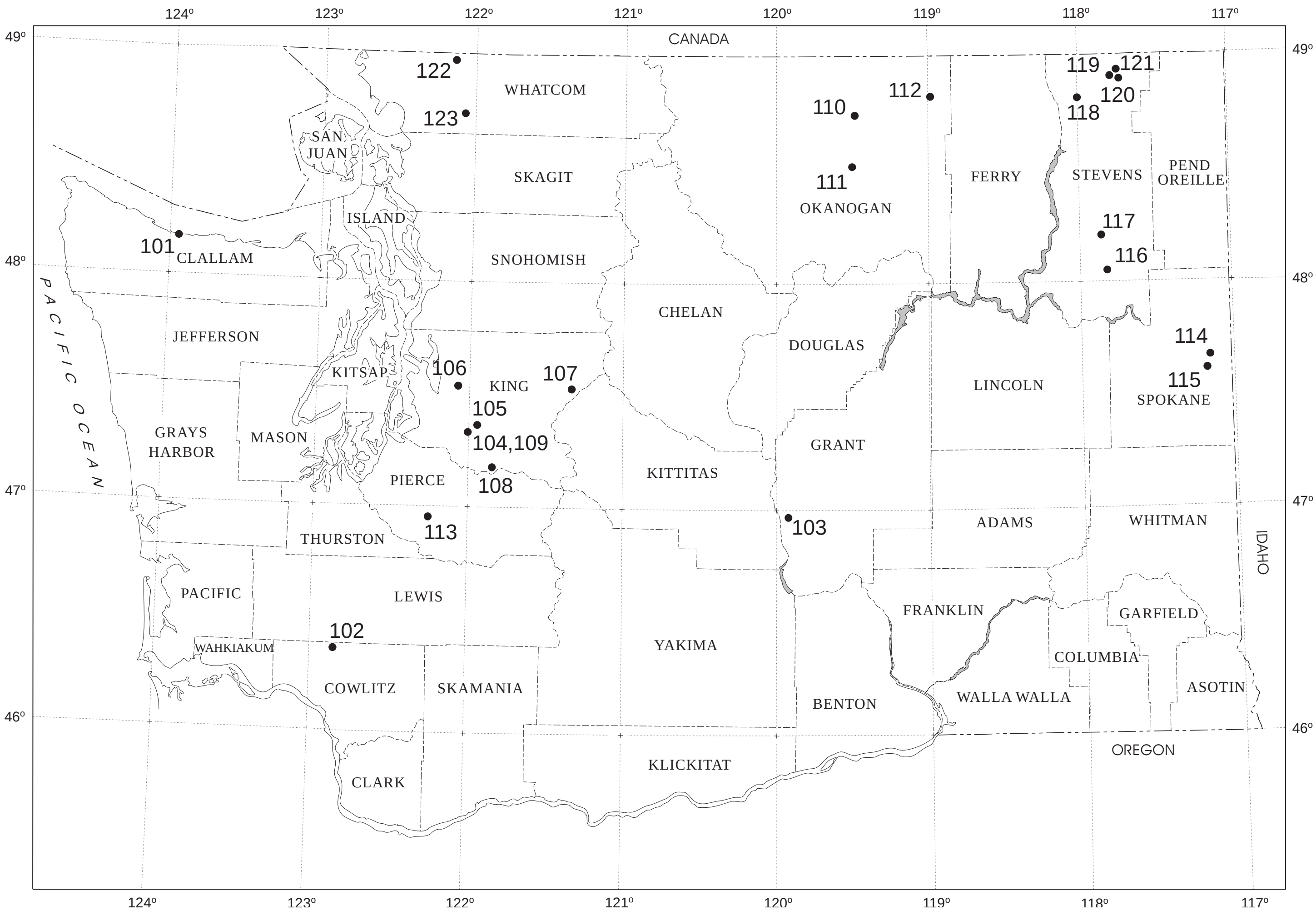

Figure 4. Location of nonmetallic mining operations in Washington in 1997. See Table 4 *(next page)* for additional details about each of these projects.

No.	Property	Commodities	Location	County
101	Twin River quarry	clay	secs. 22-23, 31N, 10W	Clallam
102	Castle Rock quarry	clay	sec. 18, 10N, 1W	Cowlitz
103	Celite Diatomite pits	diatomite	secs. 3, 17N, 23E and sec. 7, 17N, 24E	Grant
104	Ravensdale pit	silica	sec. 1, 21N, 6E	King
105	Elk pit	shale	sec. 34, 22N, 7E	King
106	Sec. 31 pit	shale	sec. 31, 24N, 6E	King
107	Spruce claim	crystals	secs. 29, 30, 24N, 11E	King
108	Superior quarry	silica	sec. 1, 19N, 7E	King
109	John Henry No. 1	clay	sec. 12, 21N, 6E	King
110	Tonasket limestone quarry	limestone, dolomite	sec. 25, 38N, 26E	Okanogan
111	Brown quarry	dolomite	sec. 26, 35N, 26E	Okanogan
112	Wauconda quarry	limestone	sec. 13, 38N, 30E	Okanogan
113	Clay City pit	clay	sec. 30, 17N, 5E	Pierce
114	Somers clay pit	clay	sec. 35, 25N, 44E	Spokane
115	Potratz mine	clay	sec. 7, 21N, 45E	Spokane
116	Gehrke quarry	dolomite	sec. 2, 29N, 39E	Stevens
117	Lane Mountain quarry	silica	secs. 22, 34, 31N, 39E	Stevens
118	Northwest marble mine; other quarries	dolomite	sec. 19, 38N, 38E	Stevens
119	Joe Janni limestone deposit	limestone	sec. 13, 39N, 39E	Stevens
120	Janni limestone quarry	limestone	sec. 13, 39N, 39E	Stevens
121	Sherve quarry	limestone	sec. 8, 39N, 40E	Stevens
122	Maple Falls quarry	limestone	secs. 7, 18, 40N, 6E	Whatcom
123	Swen Larsen quarry	olivine	sec. 34, 38N, 6E	Whatcom

Olivine

A major olivine deposit in the North Cascades, the Twin Sisters dunite, continued to be mined for refractory grade olivine. Olivine Corp. produced approximately 40,000 tons in 1997 from its Swen Larsen quarry (Fig. 4, no. 123) in Whatcom County. Olivine Corp. used about 1,000 tons of its production for refractory materials for waste incinerators. The remaining production was shipped as crushed olivine to UNIMIN, a Belgian company that produces casting sands and other refractory products at Hamilton, in Skagit County.

Clays

Much of the clay produced in western Washington was mined by or for Holnam Inc. or Ash Grove Cement Co. to produce cement. Holnam Inc. mines clay from the Twin River quarry (Fig. 4, no. 101), and Ash Grove Cement Co. mined clay from its Castle Rock quarry (Fig. 4, no. 102).

In addition to coal, Pacific Coast Coal Co. mined clay from the John Henry No. 1 (Fig. 4, no. 109) coal mine and shipped it to Ash Grove Cement Co.

Clay used predominantly for bricks and related products was mined by Mutual Materials in Spokane County at the Potratz mine (Fig. 4, no. 115), in King County at the Elk (Fig. 4, no. 105) and Section 31 (Fig. 4, no. 106) pits, and from the Clay City pit (Fig. 4, no. 113) in Pierce County. Quarry Tile Com-

Table 4. Operator and brief description of the activity and geology of nonmetallic mining operations in Washington in 1997 *(companion to Fig. 4)*

Property	Company	Activity	Area geology
Twin River quarry	Holnam Inc.	Mined 50,000 tons; development work also; used for cement manufacture	Mudstone(?) in three members of the upper Eocene to lower Miocene Twin Rivers Formation
Castle Rock quarry	Ash Grove Cement Co.	Mined 43,230 tons of shale and clay	Eocene–Oligocene sedimentary rocks
Celite diatomite pits	Celite Corp.	Mined 105,000 tons of ore and produced 72,000 tons of finished diatomite; used as filtration material	Miocene "Quincy Diatomite Bed", a locally occurring sedimentary interbed at the base of the Priest Rapids Member, Columbia River Basalt Group
Ravensdale pit	Reserve Silica Corp.	Mined and washed 70,000 tons; most production used to manufacture glass	Sandstone of the Eocene Puget Group
Elk pit	Mutual Materials Co.	Mined 8,000 tons to produce bricks	Illite- and kaolinite-bearing shales of the Eocene Puget Group
Sec. 31 pit	Mutual Materials Co.	Mined 50,000 tons to produce bricks	Shale of the Eocene Puget Group
Spruce claim	Robert Jackson	Extracting mineral and crystal specimens	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
Superior quarry	Ash Grove Cement Co.	Mined 129,433 tons of silica; used for cement manufacture	Silica cap in hydrothermally altered Miocene andesites on a caldera margin
John Henry #1	Pacific Coast Coal Co.	Mined over 61,000 tons of clay that was shipped to Ash Grove Cement Co.	Upper middle Eocene silty clay near the base of the Puget Group comprising a 30-ft-thick zone above the Franklin No. 9 coal seam
Tonasket limestone quarry	Pacific Calcium, Inc.	Mined 22,000 tons of limestone for soil conditioner and feed lime	Metacarbonate rocks in the conglomerate-bearing member of the Permian Spectacle Formation (Anarchist Group)
Brown quarry	Pacific Calcium, Inc.	Mined 4,500 tons for soil conditioner	Metadolomite member of the Triassic Cave Mountain Formation
Wauconda quarry	Columbia River Carbonates	Continued to mine limestone and ship it to Longview area for processing	High-calcium, pre-Tertiary white marble lenses in mica schist, calc-silicate rocks, and hornfels
Clay City pit	Mutual Materials Co.	Mined 4,000 tons to produce bricks	Tertiary kaolin-bearing, altered andesite
Somers clay pit	Quarry Tile Co.	Produced ceramic tile from 1,545 tons of stockpiled ore	Lacustrine clay of the Miocene Latah Formation overlain by silty clay of the Pleistocene Palouse Formation
Potratz mine	Mutual Materials Co.	Mined 14,000 tons; stockpiled to produce bricks	Lacustrine clay of Miocene Latah Formation overlying saprolitic, pre-Tertiary felsic gneiss.
Gehrke quarry	Allied Minerals, Inc.	Mined about 5,000 tons; marketed as a soil conditioner	Isolated pod of Proterozoic Y Stensgar Dolomite(?), Deer Trail Group
Lane Mountain quarry	Lane Mountain Silica Co. (division of Hemphill Brothers, Inc.)	Mined 300,000 tons, milled at plant near Valley; net production 230,000 tons; used to make clear glass	Cambrian Addy Quartzite
Northwest marble mine; other quarries	Northwest Marble Products Co.	Mining, milling, color/site specific aggregate materials for building and industrial applications	Dolomite of the Cambrian–Ordovician Metaline Formation; additional colored dolomite products are quarried at several locations
Joe Janni limestone deposit	Joseph A. & Jeanne F. Janni limestone deposits	Leased to Columbia River Carbonates; no activity in 1997	Deposit is in Cambrian Maitlen Phyllite, Reeves Limestone Member
Janni limestone quarry	Peter Janni and Sons	Leased to Columbia River Carbonates; no activity in 1997	Deposit is in Cambrian Maitlen Phyllite, Reeves Limestone Member
Sherve quarry	Northport Limestone Co. (division of Hemphill Brothers, Inc.)	Mined 30,000 tons, processed on site; most production shipped to Trail, BC, smelter as a fluxing agent	Limestone in the upper unit of Cambrian–Ordovician Metaline Formation
Maple Falls quarry	Clauson Lime Co.	Mined about 125,000 tons and did development; used for rip rap and some aggregate and landscape rock	Sheared, jointed Lower Pennsylvanian limestone overlain by sheared argillite and underlain by argillite, graywacke, and volcanic breccia of the Chilliwack Group
Swen Larsen quarry	Olivine Corp.	Mined and milled 40,000 tons for refractory/incinerator uses; used 1,000 tons for refractory materials, the remainder was shipped to Unimin Corp. at Hamilton, WA	Dunite is mined from the Twin Sisters dunite (outcrop area more than 36 mi^2) in Whatcom and Skagit Counties

pany produced ceramic tile from clay mined from the Somers pit (Fig. 4, no. 114) in Spokane County.

Diatomite

Celite Corp. mined and processed 105,000 tons of diatomite at its pits (Fig. 4, no. 103) in Grant County. The company produced 72,000 tons of finished diatomite.

Silica

Lane Mountain Silica Co. (Fig. 4, no. 117) mined 300,000 tons of Addy Quartzite from the Lane Mountain quarry in Stevens County. Following processing, the company shipped 230,000 tons of high-purity quartz, most of which was used to manufacture clear glass bottles and jars.

Reserve Silica Corp. mined 70,000 tons of quartz-rich Puget Group sands from the Ravensdale pit in King County (Fig. 4, no. 104). Most of Reserve's production is used for the manufacture of colored bottle glass.

Ash Grove Cement Co. mined nearly 130,000 tons of silica from its Superior quarry (Fig. 4, no. 108) in King County; the company uses the silica for making cement.

INDUSTRIAL MINERAL INDUSTRY ACTIVITIES

Industrial mineral commodities, construction sand and gravel, and construction stone accounted for approximately 45 percent of the $535,447 million total value of nonfuel mineral production for Washington, based on figures for 1996, the last year for which this information is available. The overall production value of construction sand and gravel, the single most valuable nonfuel mineral commodity in Washington, was nearly $162 million, a $6 million increase from 1995.

Sand and gravel operations consist of large pits near the heavily populated areas of the state and small pits operated throughout the state by city, county, and state road departments and for other smaller scale needs. A total of 11 new surface mining permits were issued by the Department of Natural Resources in 1997. In addition, the Department received 28 new permit applications.

The permitting process continued for deposits near Monroe in Snohomish County and near Shelton in Mason County. The Monroe deposit is intended to replace deposits nearly mined out as a source of aggregate for the north part of the Seattle metropolitan area. The deposit near Shelton is accessible from the water; it will also fill needs of the greater Seattle area.

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CLARIFICATION

With regard to the update on the Crown Jewel mine, *Washington Geology*, v. 25, no. 4, p. 2, the third paragraph should have stated that the application for permits could not begin until early 1997. The scoping process under the National Environmental Policy Act (leading to an environmental impact statement) was initiated by Battle Mountain Gold Company during February 1992.

COMINCO MAY REOPEN THE PEND OREILLE MINE

Cominco American Inc. has proposed to reopen the Pend Oreille mine in northern Pend Oreille County approximately 2 mi north of Metaline Falls. The mine has been operated intermittently since the early 1900s but has been inactive since 1977. Cominco would extract lead and zinc ore from underground mine workings and transport it to the surface for processing in an on-site mill. Concentrates would then be shipped by truck to the Cominco smelter in Trail, British Columbia.

Existing structures include mine portals, a ventilation shaft, two mill/processing buildings, a mine office building, an assay laboratory, various maintenance and storage facilities, a waste rock disposal area, three tailings storage facilities, and access roads. The proposed project would require construction of an additional ventilation shaft and some roads, as well as expansion of one of the existing surface tailings storage facilities. About 40 acres of land would be disturbed if the mine is reopened as proposed.

The Washington Department of Ecology is the lead agency responsible for environmental review of the proposed project and for preparation of an Environmental Impact Statement.

For more information or comments regarding the project contact: Keith Stoffel, Department of Ecology, Eastern Regional Office, 4601 N. Monroe, Suite 202, Spokane, WA 99205-1295; 509-456-3176 (phone); 509-456-6175 (fax); ksto461@ecy.wa.gov (e-mail).

LAST CHANCE TO ORDER REPORTS

Our publications list shows the following reports as out of print, but we are cleaning out the very few remaining copies and (re-)offer (first come, first served) the following at $1 each (same price for Washington residents and nonresidents). These reports will not be offered again, so if you have ever wanted a copy, this is your last chance. When ordering, please remember to add $1 for postage and handling.

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Geology and mineral deposits of the north half of the Van Zandt quadrangle, Whatcom County, Washington, Bulletin 50, by W. S. Moen, 1962.

Availability of Federal land for mineral exploration and development in the State of Washington, Geologic Map GM 30, by P. D. Banister and others, 1984, 1:500,000.

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Economic aspects of the Blewett–Cle Elum iron ore zone, Chelan and Kittitas Counties, Washington, Report of Investigations 12, by W. A. Broughton, 1944.

Mount St. Helens ash—Properties and possible uses, Report of Investigations 24, by W. S. Moen and G. B. McLucas, 1981.

Introduction to Washington geology and resources, Information Circular 22R, by C. D. Campbell (revised 1962).

The eruption of Mount St. Helens, Washington; Part I—March 20–May 19, 1980, Information Circular 71, by M. A. Korosec and others, 1980.

Washington's Coal Industry—1997

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In 1997, Washington's two coal mines, the Centralia mine in north-central Lewis County and the John Henry No. 1 mine in south-central King County, together produced 4,495,850 short tons of coal, down 69,473 tons from 1996.

The state's largest coal mine, the Centralia Coal Mine, is operated by the Centralia Mining Company, a division of PacifiCorp. The mine is located 5 mi northeast of the city of Centralia (Fig. 1). The mine's sole customer, the Centralia Steam Plant, is located about a mile from the mine.

The mine completed its 27th year of production in 1997, producing 4,427,650 short tons of subbituminous coal, about 35,000 tons more than in 1996. The mine's average annual production over the past 5 years has been 4.5 million tons; average annual production over the life of the mine is 4.3 million tons.

Coal production in 1997 came from three open pits. Coalbeds mined were the Tono Nos. 1 and 2, Upper and Lower Thompson, Big Dirty, two splits of the Little Dirty, and Smith. These coalbeds are part of the Skookumchuck Formation, made up of nearshore marine and nonmarine sedimentary rocks. The Skookumchuck is the upper formation of the Eocene Puget Group.

Washington's other producing coal mine, the John Henry No. 1, is located 2 mi northeast of the town of Black Diamond (Fig. 1). The mine produced only 68,200 short tons of bituminous coal in 1997, a drop of about 105,000 tons from its 1996 production. The dramatic change in production stemmed from a large landslide that occurred in the mine in January 1997, hampering production and supply to customers in the industrial sector. This situation was compounded by a soft export market. As a result, sales for 1997 plummeted to about 68,500 tons, nearly 104,000 tons less than in 1996. The mine is operated by the Pacific Coast Coal Co., Inc. (PCCC), which completed its 11th full year of production in 1997.

PCCC maintained its sales share for the industrial sector at 76 percent of its total sales (compared to 75 percent for 1996), while its sales fell to 39 percent of the previous year's sales. The coal is used in the manufacture of cement and lime in the Puget Sound area. Twenty-one percent of its total sales were

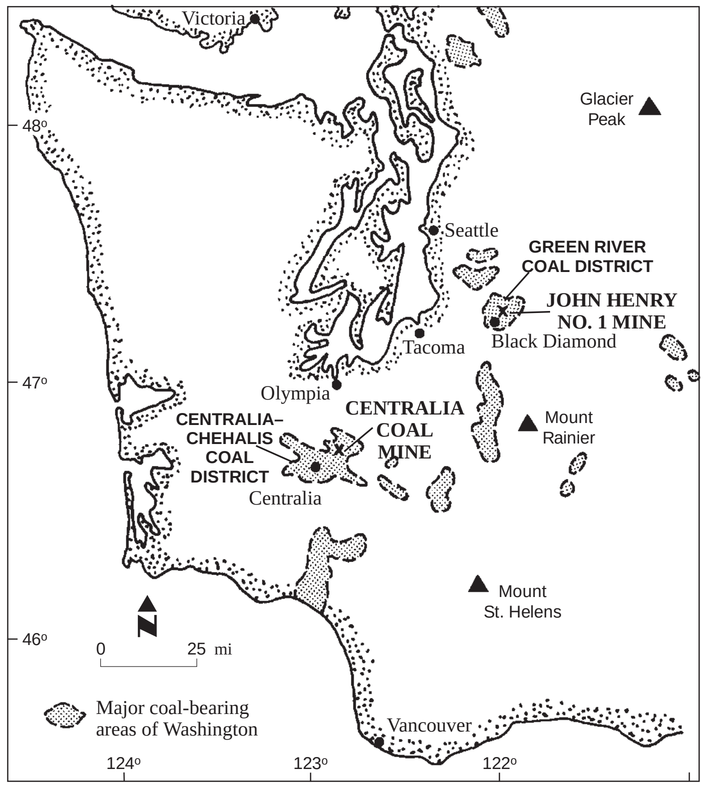

Figure 1. Coal-producing areas and districts, western Washington.

Figure 2. John Henry No. 1 coal mine, Pit No. 1, July 14, 1997. View to the southwest along the northwest limb of a plunging anticlinal structure in the mine. Features to note include the Franklin Nos. 7, 8, and 9 coalbeds being mined just left of center. Franklin No. 7 lies in contact with the anticlinal structure, which forms the floor of the No. 7 coalbed. Franklin Nos. 8 and 9 coalbeds are exposed above the lower pond adjacent to the No. 7. The Franklin No. 10 coalbed is the dark zone that begins in the right foreground and arches to the left in the highwall to the right of the haul road. A remnant of the landslide that occurred in the mine in January 1997 is exposed in the distance (left of center), left of the haul road and toward the observer from the road grader. The slide buried a backhoe, barely discernible, to the left of the road grader where the haul road disappears in the distance. The clay bed that lies stratigraphically between the Franklin Nos. 8 and 9 coalbeds and is mined for use in cement manufacturing is the darker zone just to the right of the haul road to the right of the lower pond. *(Photo courtesy of Pacific Coast Coal Company.)*

Figure 3. John Henry No. 1 coal mine, Pit No. 2, in January 1998. This view is to the southwest and shows the Franklin No. 12 coalbed exposed on the northwest limb of the anticlinal structure in the mine. The coalbed at this location is approximately 10 ft thick and contains a few bony partings along with the coal.

for coal exported to South Korea for steam generation. This percentage is nearly the same as in 1996 (24 percent), but the actual sales to that market dropped by 67 percent. The remaining sales were for electrical generation (2 percent of total sales) and to supply public and private institutions and residential customers (1 percent of total sales) for space heating.

In 1997, PCCC mined coal from two pits. At Pit No. 1, it mined coal from the Franklin Nos. 7, 8, 9, 10, and 810 coalbeds (Fig. 2). Coal in Pit No. 2 was mined from the Franklin No. 12 coalbed (Fig. 3). The Franklin coalbeds are stratigraphically near the base of the undivided Eocene Puget Group in nonmarine deltaic sedimentary rocks.

In 1997, PCCC mined coalbeds in Pit No. 1 along the northwest limb of the anticlinal structure to near the maximum mining depth for the mine (Fig. 2). PCCC also continues to mine a clay bed between the Franklin Nos. 9 and 10 coalbeds. The clay is blended with high alumina clay for manufacturing portland cement. ■

BOOK REVIEW: Environmental Interpretation—A Practical Guide for People with Big Ideas and Small Budgets

by Sam H. Ham, 1992.
Available from North American Press,
350 Indiana St., Suite 350,Golden, CO 80401-5093;
303-277-1623. Paperback, 456 p., $37.50 + $4.00 shipping.
Also available in Spanish.

Sam Ham is a professor in the Department of Forestry at the University of Idaho in Moscow. His main academic interests are resource recreation and tourism. His book is nothing less than a comprehensive, if not exhaustive, guide to environmental interpretation and communication that draws upon his 20 years of experience in the field.

Why should environmental interpretation be so important to the people of Washington State? For one thing, visitors and ecotourism dollars from around the world are rushing to the alluring natural splendor of the Pacific Northwest in ever-increasing numbers. Conferences that feature field trips to such natural laboratories as Mount St. Helens and revered natural wonders such as Mount Rainier, Puget Sound, the Olympic Mountains, and the Columbia Gorge have become an enormous draw.

Along with the growth in visitation of natural resources comes an increasing need to satisfy the educational cravings of visitors and at the same time to foster a respect for natural areas. This “eco-rush” is taking place in a dynamic academic landscape in which information about the geologic and natural environment has grown almost exponentially during the past several decades. As a result, there is an increasing need to clearly convey technical and appreciative information about natural resources to people of diverse backgrounds.

Environmental Interpretation is an excellent, easy to read treatment of the theoretical and practical aspects of communicating with a wide variety of audiences. Mr. Ham’s forte is blending a captivating thematic approach to interpretation with content that is technically sound as well as suited to the audience and the setting, be it a classroom, a scenic overlook, a trail hike, or an interpretive sign or display. The book presents about 20 case studies and contains more than 200 illustrations, several appendices (glossary, types of display and exhibit models, lettering aids, list of organizations), and numerous references. Two pages alone, “There are many ways to make technical information more entertaining”, contain plenty of inspiration for jaded interpreters.

Chapter titles include:

- What is interpretation?
- Practicing thematic interpretation
- How to prepare and present a talk
- Tips on using visual aids
- How to present a guided tour or walk
- Guidelines for other conducted activities (demonstrations, theater, roving interpretation, angry visitors, etc.)
- How to prepare and plan inexpensive exhibits
- How to develop inexpensive self-guided tours

Environmental Interpretation is an excellent resource for both the experienced scientist and the novice interpreter. Teachers, park rangers, land and program managers, museum staffs, nature and hiking groups, and others will all find parts of this book that are “essential reading”.

by Patrick T. Pringle

Marine Fauna of the Middle Eocene Tukwila Formation, King County

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Invertebrate fossils of the Tukwila Formation (nomenclature of McWilliams, 1971) are the northernmost representatives of middle Eocene marine faunas in the Pacific Northwest. The faunal diversity is considerably greater than previously reported. Eighty-four taxa have now been recognized (Table 1), almost triple the number recorded by McWilliams (1971). The majority of the fossils are mollusks, but the assemblage also includes four corals, an echinoid, polychaete worm tubes, brachiopods, crab claws, shark teeth, and benthic foraminifera. Plant fossils from the Tukwila Formation include both evergreen broadleaf and mixed deciduous forest species. The mollusks are strikingly similar to those from the well-known Cowlitz Formation of southwestern Washington. Biostratigraphic correlation indicates that the western outcrops of the Tukwila Formation are late middle Eocene in age, 39 to 41.5 m.y. More detailed investigations of the stratigraphic position of the outcrops may be needed.

The Tukwila Formation is part of the Puget Group, which also comprises the coal-bearing rocks of the Black Diamond–Carbonado area (Fig. 1). Sediments of the Puget Group were deposited over approximately 10 million years in rivers and their distributaries within a broad Mississippi River-type deltaic system (Buckovic, 1979; Burnham, 1990). Rivers flowed from what is now Idaho westward across a pre-Cascade continental plain to a fluctuating coastline situated about where Interstate Highway I-5 is today. These areas of terrestrial and marine sedimentary accumulation were part of the western Washington forearc during middle Eocene time (Nesbitt and others, 1994). In the early and middle Eocene, Pacific Northwest subduction-related volcanism was active in a belt that extended from the Republic graben in northeastern Washington, through the Challis area of central Idaho, and southwest to Clarno in northeastern Oregon. During the late middle Eocene, about 40 million years ago, the center of arc volcanism shifted to the

Table 1. Checklist of fauna from the Tukwila Formation in western King County

Scaphopods
Laevidentalium sp.

Pelecypods
Acanthocardia (*Schedocardia*) *brewerii* (Gabb)
Acutostrea idriaensis fettkei Weaver
Modiolus cowlitzensis Weaver and Palmer
Corbula dickersoni Weaver and Palmer
Crassatellites washingtoniana Weaver
Gari columbiana (Weaver and Palmer)
Glycymeris saggittata (Gabb)
Macrocallista andersoni Dickerson
Microcallista conradiana (Gabb)
Mytilus dichotomus Cooper
Nuculana cowlitzensis (Weaver and Palmer)
Nuculana washingtonensis (Weaver)
Pachydesma aragoensis Turner
Pitar (*Lamelliconcha*) *eocenica* Weaver and Palmer
Pitar californiana (Conrad)
Septifera dichotomus Gabb
Spisula packardi Dickerson
Tellina cowlitzensis Weaver
Tivelina vaderensis (Dickerson)
Venericardia clarki Weaver and Palmer

Gastropods
Acrilla (*Ferminoscala*) *aragoensis* (Turner)
Architectonica cf. *A. congnata* Gabb
Calorebama inornata (Dickerson)
Calyptraea diegoana (Conrad)
Cantharus cowlitzensis Clark
Clavus fryei Weaver
Colwellia bretzi (Weaver)
Conus vaderensis Weaver
Conus weaveri Dickerson
Crepidula pileum Gabb
Cylichnina tantilla (Anderson and Hanna)
Cymatium cowlitzense (Weaver)
Cymatium washingtonianum (Weaver)
Ectinochilus washingtonensis Clark and Palmer
Epitonium condoni Dall
Eulima lewisiana Weaver
Exilia dickersoni (Weaver)
Ficopsis cowlitzensis (Weaver)
Fissurellidae
Fulgurofusus washingtoniana (Weaver)
Fusinus willisi (Dickerson)
Galeodea trituberculata (Weaver)
Gemmula fasteni Weaver
Hemipleurotoma pulchra (Dickerson)
Latirus eocenica (Weaver)
Mitra washingtoniana Weaver
Murex sopenahensis Weaver
Nekewis washingtoniana (Weaver)
Neverta (*N.*) *globosa* Gabb
Odostomia cf. *O. winlockiana* Effinger
Olivella mathewsoni Gabb
Olequahia washingtoniana (Weaver)
Pachycrommium hendoni Turner
Patelloida vancouverensis Clark and Arnold
Polinices (*P.*) *hornii* (Gabb)
Polinices (*Euspira*) *hotsoni* Weaver
Polinices (*Euspira*) *nuciformis* (Gabb)
Scaphander costatus (Gabb)
Sinum obliquum (Gabb)
Siphonalia sopenahensis (Weaver)
Solariella olequahensis Weaver and Palmer
Solen columbiana Weaver
Sulcocypraea mathewsonii (Gabb)
Tejonia moragai (Stewart)
Turricula (*Pleurofusia*) *cowlitzensis* (Weaver)
Turricula washingtonensis (Weaver)
Turritella uvasana olequahensis Weaver and Palmer
Turritella uvasana stewarti Merriam
Whitneyella sinuata (Gabb)

Brachiopods
Terebratulina washingtoniana (Weaver)

Corals
Astreopra duwamishensis Durham
Balanophyllia washingtonensis Durham
Turbinolia weaveri Durham
Discotrochus sp.

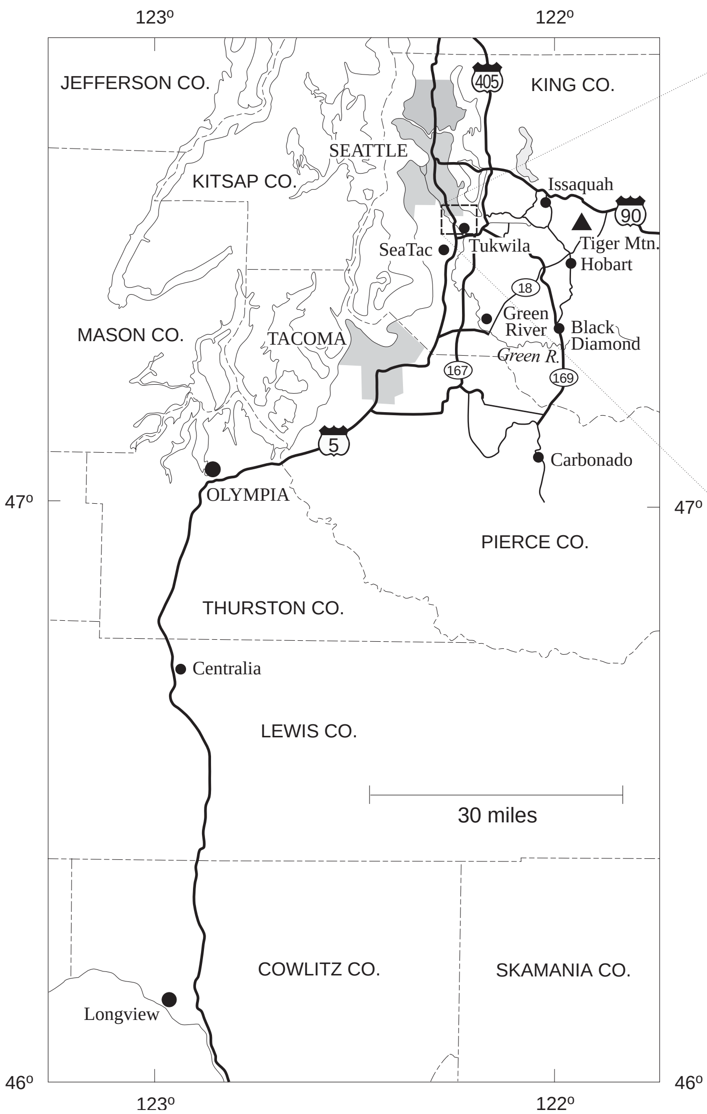
Echinoid
Brisaster sp.

Polychaetes
Rotalaria tejonensis (Arnold)
cf. *Protula* sp.

Trace fossils
Teredo-bored wood
vertical branching tubes

Crabs
Zanthopsis vulgaris Rathbun
?*Coeloma martinezensis* Rathbun

Sharks teeth
Triaenodon sp.
Mitsukurina sp.



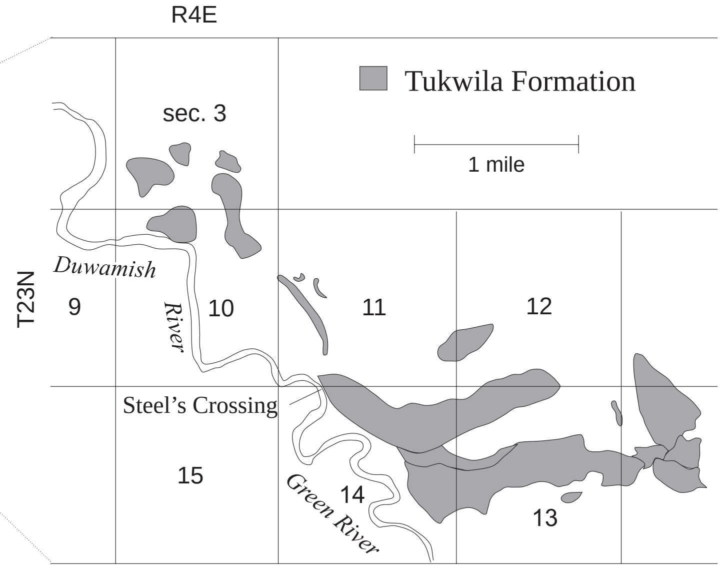


Figure 1. The Tukwila Formation outcrops in the Tukwila area have been studied for more than a quarter century. Biostratigraphic equivalents are known from localities to the south. (Inset modified from McWilliams, 1971).

west with the initiation of the western Cascades (McIntyre and others, 1982; Duncan and Kulm, 1989).

GEOLOGY

The Tukwila Formation was the name given by Waldron (1962) to andesitic volcanic and interbedded sedimentary rocks exposed within the city boundary of Tukwila, near the Duwamish River (Fig. 1). Vine (1969) expanded the definition of the unit to include a more complete section in the Taylor Mountain–Tiger Mountain area, northeast of Hobart, eastern King County. In this region, the Tukwila Formation consists of 2,100 m of volcanic and volcaniclastic rocks that are entirely contained within the coal-bearing sediments of the Puget Group. The base of the Puget Group is not exposed there, and the measured thickness for the group is more than 2,700 m (Buckovic, 1979). Rocks of the Tukwila Formation consist of andesitic tuff, massive sandstones, carbonaceous shales and coal strata, and volcanic flows and sills (Vine, 1969). The Tukwila Formation interfingers with the marginal and nonmarine sedimentary rocks of the underlying Tiger Mountain Formation and overlying Renton Formation, also part of the Puget Group (Fig. 2). Farther south, in the Green River area and the Black Diamond coal mining region, the Puget Group cannot be subdivided (Waldron, 1962). Here, coal is interbedded with sandstone and mudstone in a depositional environment characteristic of a delta that was fluvial dominated, but influenced by tides (Brownfield and others, 1994). Very rare freshwater clams, *Batissa newberryi*, have been found in these sedimentary layers (Michael Conaboy, Pacific Coast Coal Company, oral commun., 1997).

Quaternary sediments obscure any possible continuity between outcrops of Tukwila Formation in western King County and those in the Tiger Mountain area of eastern King County. The strata have been correlated on the basis of their lithological characteristics. Tukwila Formation rocks are characterized by andesite lava flows, breccias and lapilli tuff, and sediments derived from these volcanic deposits: siltstone and coarse- and medium-grained andesitic sandstone, andesite breccias, and weathered andesitic cobble conglomerates (Vine, 1962, 1969; McWilliams, 1971). Marine fossils have been found only in the western exposures close to the Duwamish River (Fig. 1). Outcrops of the Tukwila Formation in this area are capped by andesitic breccias. Immediately below the breccias and above the marine sandstones is a very thin and geographically restricted, clay-rich lakebed deposit that contains fossil plant debris.

The marine fauna occurs in discrete, densely fossiliferous strata that are exposed on the flank of an east-trending anticline (McWilliams, 1971). Six of these faunal intervals occur in one stratigraphic section that measures approximately 40 m thick, and rare scattered shells are found between each of these intervals. Most of the fossils are preserved with the shell material intact, but in some of the strata the fossils are molds and casts. Most exposures of the Tukwila Formation do not contain body fossils but are highly bioturbated.

STRATIGRAPHY AND AGE

The Puget Group consists of a thick sequence of deltaic sediments, with a few shallow marine incursions, and interfingering andesitic volcanic rocks at its northern and southern extents (Buckovic, 1979) (Fig. 2). The volcanic rocks of the Tukwila Formation have been correlated with those of the Northcraft Formation in Lewis and Skamania Counties, southwestern Washington (Buckovic, 1979). However, there is no informa-

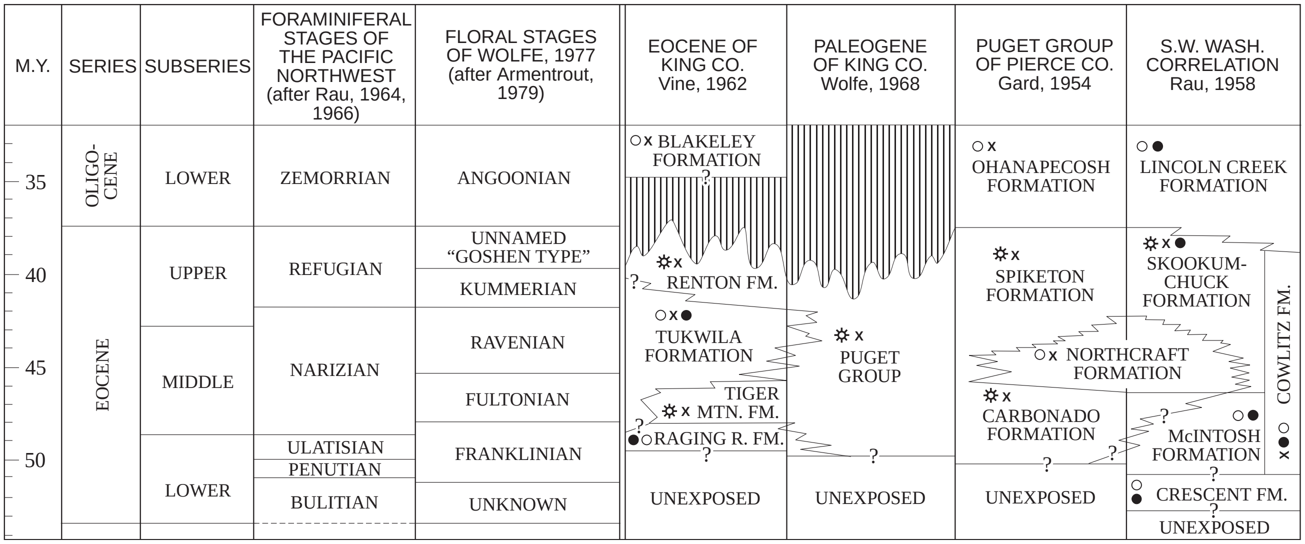
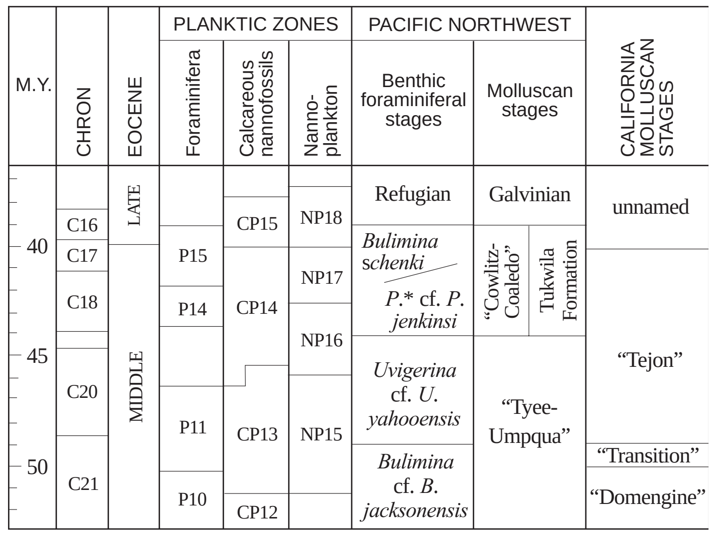


Figure 2. Correlation charts that show the stratigraphic and biostratigraphic relations of the Tukwila Formation. *(Above)* A stratigraphic correlation modified from Buckovic (1979). Note that the Tukwila Formation occurs only in King County. ☼, arkosic; ○, volcanic; ●, marine; x, nonmarine. *(Right)* Biostratigraphic correlations for the middle and late Eocene, showing the newly constrained age of the Tukwila Formation. Names in quotes are informal. **P.*, *Plectofrondicularia*. (Modified from Nesbitt, 1995, and Berggren and others, 1995.)



tion on the chemical composition of the lava from either volcanic center to confirm this correlation.

The marine mollusks of the Tukwila Formation belong to the same species as those found in the Cowlitz Formation in Lewis and Cowlitz Counties. The Cowlitz molluscan fauna is late middle Eocene in age (Nesbitt, 1995), on the basis of generic similarities with the poorly defined "Tejon Stage" of California. The rare benthic foraminifera in Tukwila sedimentary rocks have been assigned to the *Bulimina schenki–Plectofrondicularia* cf. *P. jenkinsi* Zone, modified Upper Narizian Stage (K. McDougall, U.S. Geological Survey, written commun., 1996). The middle and late Eocene Narizian and Refugian foraminiferal stages were defined on California fossils, but McDougall (1980) considered the zones in these stages to be time-transgressive and facies-controlled in the Pacific Northwest.

Calcareous nannofossils from the Cowlitz Formation place it in the upper CP14 worldwide planktonic zone (Okada and Bukry, 1980), equivalent to the P14 and lower P15 planktonic foraminiferal zones and the European Bartonian Age. Worldwide, middle and late Eocene biostratigraphy has had a convoluted history. In the most recent review of global stratigraphic correlations for the Cenozoic, Berggren and others (1995) place these planktic zones at 38.5 to 41 Ma. The flora of the Puget Group, together with Eocene fossils from Alaska, were used by Wolfe (1968, 1977) to define four Eocene paleobotanical stages. (See Fig. 2.) The Tukwila flora is included within the Ravenian Stage, which was considered by Wolfe to be late Eocene in age.

Detrital zircon fission-track dates of 39.4 ±2.8 Ma from Ravenian Stage rocks in the Puget Group (Brandon and Vance, 1992) indicate that the volcanic source for these sediments was contemporaneous with fluvial deposition. More recently, $^{39}Ar/^{40}Ar$ dates were obtained from single-crystal laser fusion of seven plagioclase crystals from a tuff in the upper Cowlitz Formation. These gave an age of 39.2 ±0.01 Ma (Irving and others, 1996). Freshly exposed basalt in the Grays River volcanic rocks that are interbedded with Cowlitz sedimentary rocks in southern Cowlitz County yield an $^{39}Ar/^{40}Ar$ age of 40.4 ±1.0 Ma (Irving and others, 1996). In summary, then, the Tukwila marine strata of western King County were deposited in the late middle Eocene, around 39 to 40.5 Ma.

TAPHONOMY

Taphonomic studies of the Tukwila shell beds indicate that the organisms were buried in living position in only a few places. Autochthonous deposition is demonstrated by double-valved clams (pelecypods) that are preserved in living position within the sediment and by branching burrows extending vertically through 10 to 40 cm of strata. In contrast, the bulk of the fossil deposits are allochthonous, that is, current sorted and densely packed into 2- to 4-cm-thick shell beds (Fig. 3). Such beds are dominated numerically and volumetrically by small (15 mm long) pelecypods. Between 70 percent and 90 percent of the shells are the small venerid *Macrocallista* (Pl. 1, fig. 1). McWilliams (1971, p. 279) reports a normal size-frequency distribution of this species, with the majority being between 5 and 10 mm in length. Most of these clams are articulated, and those with complete shells are not abraded. However, in some outcrops, ground-water leaching has destroyed the shell material, which now is either chalky or absent. Within the *Macrocallista*-dominated beds are small shells (15 mm in length) of juvenile *Glycymeris, Tellina, Spisula, Microcallista, Acanthocardia, Venericardia*, and *Pitar*. Boreholes left by sponges that grew on mollusk shells (or epibionts) are very rare and found only on shell fragments. Such deposits indicate that high energy currents have displaced the normally infaunal animals and concentrated them on the sediment surface, where they died before being able to re-establish life positions. Rapid reburial prevented surface abrasion or the growth of epibionts.

High-spired gastropod fossils generally have their canals and apices broken off and have the long axis in a northwest orientation, parallel to the bedding plane. In addition, current-oriented patches of elongate scaphopod and serpulid worm tubes lie among the clam shells (Pl. 1, fig. 2). This alignment indicates that erosion and depositional currents were strong enough to move and re-orient the shells.

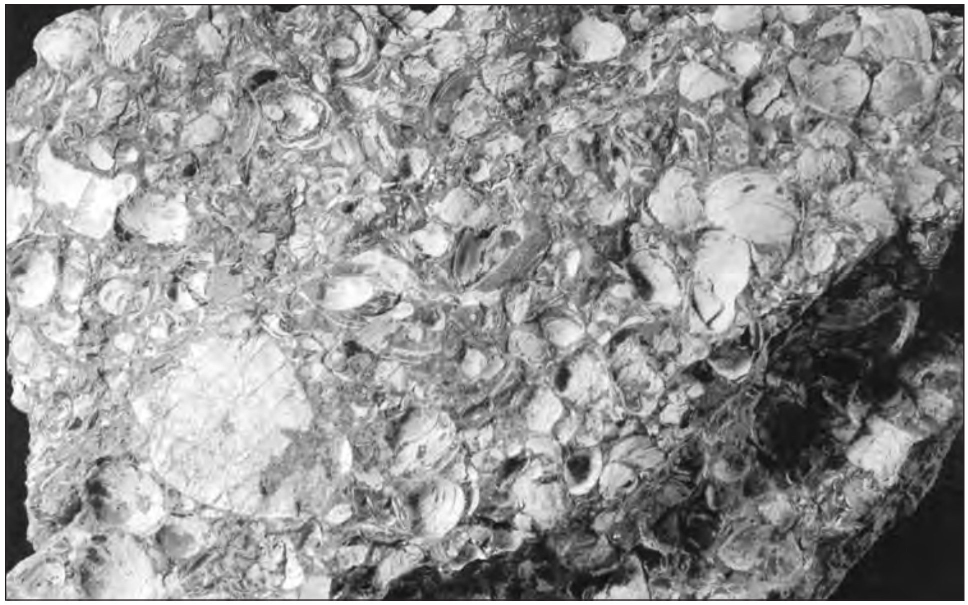


Figure 3. Densely packed pelecypods in a storm-deposited layer (tempestite), Tukwila Formation. The small shells in this sample are *Macrocallista andersoni*; the larger shell in the lower left is *Tellina cowlitzensis*. The pelecypods are shown here at about two-thirds life size. University of Washington, Burke Museum 96363/B6496.

The thin, densely packed, fossiliferous strata consist of shells that have accumulated from storm-generated bottom currents; the resulting bedforms are called tempestites. These are interspersed within many meters of sandy sediment containing few body fossils and tubes that are preserved as in-place or autochthonous fauna. Tempestites are characterized by restricted continuity of single beds that are densely fossiliferous, by hummocky cross stratification, and by amalgamation (Einsele and Seilacher, 1991). Such an environment of deposition would result in numerous local unconformities and reworking of previously deposited sediment. As a result, little can be concluded about the actual rate of deposition.

Most of the exposed sedimentary rocks of the Tukwila Formation in western King County are highly bioturbated, and very little of the original stratification is evident, except for the tempestites. In those deposits with well-preserved shells, there is very little abrasion or evidence of reworking. The shells in the tempestites indicate rapid erosion of infaunal animals from the inner neritic sea floor; these are mixed with those transported in from farther offshore and those that were attached to rocks in the intertidal zone. This mix of shells was then deposited and covered immediately by current-oriented deposition.

PALEOECOLOGY AND DEPOSITIONAL ENVIRONMENT

Defining the paleoecology of molluscan faunas depends on comparisons with the ecological parameters for living populations of the same phylogenetic families. Molluscan systematics is based on those hard and soft parts involved in feeding; therefore inferred trophic comparisons are a reliable way to reconstruct paleocommunities. In addition, the wide ranges of shell shapes and ornamentation are fundamental designs that allow prediction of life habits. However, it has also been demonstrated that, in a few families, depth ranges and temperature tolerance changed during the Tertiary, so cautious interpretation is warranted. In the final analysis of paleoecology, the information for each taxon must be consistent within the entire paleo-assemblage under study. A good example is the three species of the marine cone shells (*Conus*) in the Eocene Cowlitz fauna; all are found in the deeper water assemblage (Nesbitt, 1995), but the vast majority of cones now inhabit shallow subtidal and reef environments. These fossil cone species are unusually high-spired. High-spired cones are rare in modern faunas, and this shell design is considered primitive.

The very high species diversity of the Tukwila fauna (84 genera, of which 70 are mollusks) and the fact that almost all the genera are characteristic of warm, shallow seas indicate that, at this time, western Washington had a tropical to subtropical climate. The most notable fossils for making this determination are members of the following gastropod families: Strombidae (conches), Cypraeidae (cowries), Conidae (cones), Ficidae (fig shells), and Cymatidae (tritons). (See Pl. 1, figs. 3, 4, 6, 13.) Most of the molluscan genera in the late middle Eocene Washington faunas are the same genera that now live in southern California, Baja California, and Gulf Coast faunas. Living species of molluscan families that occur in the Tukwila Formation today inhabit shallow marine water in sandy to silt substrate environments, in the tropics of eastern and western Pacific; many of them are confined to coral reef communities. The prominent genera of tropical gastropods that are found in Eocene deposits of southern California and the Gulf Coast, *Athleta, Distorsio*, *Campanile*, and *Velates*, are absent from the middle Eocene of Washington. This and the fact that very few of the gastropods from the Tukwila and Cowlitz Formations are large or highly ornamented indicate that these species may have been on the outer edge of their biogeographic range.

Four corals, *Astroaeapora, Turbinolia, Balanophyllia*, and *Discotrochus* (Durham, 1942), have been found in the Tukwila shell beds, and all specimens are small. Corallum diameters range from 5 to 10 mm, and heights from 10 to 20 mm. Corals are very sensitive to thermal gradients. Living reef (hermatypic) corals are confined to areas where water temperatures remain higher than 20°C in winter. On the west coast of North America such conditions currently exist at the southern end of Baja California, Mexico. The genus *Astroaeapora* is a herma-

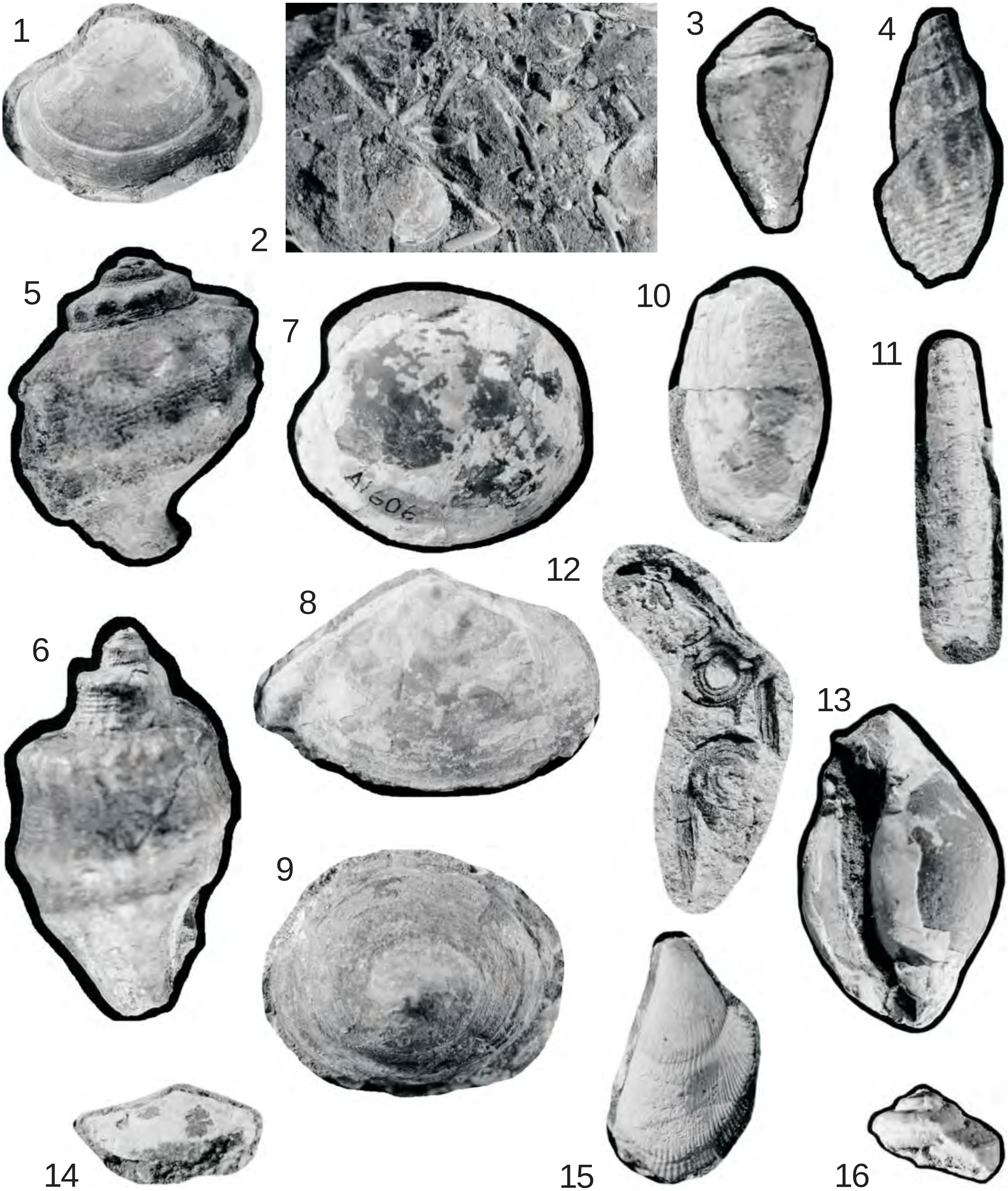


Plate 1. Fossils from the Tukwila Formation, western King County; all shown at about 2x. UWBM, University of Washington, Burke Museum specimen numbers. **1,** *Macrocallista andersoni* Dickerson, UWBM 78088; **2,** cf. *Protula* sp., worm tube, UWBM 96362; **3,** *Conus weaveri* Dickerson, UWBM 96358; **4,** *Echtinochilus washingtonensis* Clark and Palmer, UWBM 74251; **5,** *Galeodea trituberculata* (Weaver), UWBM 96360; **6,** *Ficopsis cowlitzensis* (Weaver), UWBM 74271; **7,** *Pitar californiana* (Conrad), UWBM 16337; **8,** *Tellina cowlitzensis* Weaver, UWBM 18821; **9,** *Calyptraea diegoana* (Conrad), UWBM 74259; **10,** *Scaphander costatus* (Gabb), UWBM 96357; **11,** *Laevidentalium* sp., UWBM 96359; **12,** *Rotalaria tejonensis* (Arnold), worm tube, UWBM 78082; **13,** *Sulcocypraea mathewsonii* (Gabb), UWBM 78021; **14,** *Nuculana washingtonensis* (Weaver), UWBM 16719; **15,** *Septifera dichotomus* Gabb, UWBM 18831; **16,** *Solariella olequahensis* Weaver and Palmer, UWBM 96361.

typic coral now living in the tropics of the Pacific Ocean, and *Turbinolia* is restricted to the Caribbean Sea. On the other hand, *Balanophyllia* is a solitary, nonsymbiotic coral that lives to a depth of 10 m along the California and Oregon coast in much cooler water.

Comparing the Tukwila fauna to the paleoassemblages of the contemporaneous Cowlitz Formation in southwestern Washington reveals that the majority of species are components of the *Turritella–Tivelina* Assemblage (Nesbitt, 1995) that lived in a shallow (inner neritic), normal marine environment with a sandy to silty sand substrate. This assemblage is characterized by infaunal filter-feeding mollusks: the numerically dominant, very shallowly infaunal gastropod *Turritella*, the shallow infaunal pelecypods *Venericardia*, *Pitar* (Pl. 1, fig. 7), *Acanthocardis*, and *Glycymeris*, and deep infaunal pelecypods *Tivelina*, *Tellina* (Pl. 1, fig. 8), and *Macrocallista* (Pl. 1, fig. 1). A high diversity of rare gastropods is also a characteristic of the *Turritella–Tivelina* Assemblage. In the Tukwila deposits, the small pelecypods dominate numerically and volumetrically, the most prominent being *Macrocallista*.

The Tukwila fauna also includes a mixed assemblage of mollusks from other environments of deposition. The most numerous of these belong in a group confined to intertidal, hard-ground paleoenvironments and the group restricted to fine-grained substrates in deeper water (outer neritic to upper bathyal). Hard-ground components include limpet-like *Patelloida*, *Crepidula*, and *Calyptraea* (Pl. 1, fig. 9), mussels, and the corals. Characteristic deeper water (outer neritic) components are rare, but they include gastropods from the families Turridae, Conidae, and Mitridae, opisthobranch gastropod genera *Scaphander* (Pl. 1, fig. 10) and *Cylichnella*, as well as the taxodont pelecypod *Nuculana* and the brachiopod *Terebratulina*. In addition, leaves, stems and seeds, and uncommon brackish-water mollusks (*Acutostrea*, *Corbula*, and *Eulima*) are also present in the shell deposits.

The abundant calcareous tube-shaped shells in this fauna have previously been identified as the scaphopod *Dentalium*. However, three different shell morphologies are present. The least common taxon is a scaphopod, but it is the genus *Laevidentalium* (Pl. 1, fig. 11). Scaphopod mollusks are identified on radulae and foot morphology, and it is very difficult to put fossil forms into meaningful taxa. Fossil *Laevidentalium* is identified by a thick-shelled, smooth tube that has horizontal growth lines but no longitudinal ribbing. The other two calcareous tubes are those of annelid worms belonging to the morphological family Serpulidae. These narrower tubes are attached to the substratum for much of their length and are inhabited by filter-feeding polychaete worms. One of the Tukwila tubes is similar to the fossil genus *Protula* (Pl. 1, fig. 2), which has a long, narrow, tapering tube that is circular in cross section and exhibits a smooth, thin wall. The other tube is the posterior uncoiled extension of the helically coiled *Rotalaria* (Pl. 1, fig. 12), which has a thicker wall than *Protula* and distinct longitudinal ribs.

The only taxa recorded to date that are present in the Tukwila Formation but absent in the Cowlitz Formation are the cowry *Sulcocypraea* (Pl. 1, fig. 13), a small fissurellid-like limpet, *Laevidentalium*, and the two polychaete tubes. Two genera of cephalopods, *Nautilus* and *Cimomia*, have been reported from the Cowlitz Formation but not from the Tukwila fauna.

CONCLUSIONS

Single event deposition, such as tempestites, erases any paleoassemblage data, and very little can be ascertained of the invertebrate paleoecology. Only by comparing the Tukwila species with those from the paleoassemblages recorded in the Cowlitz Formation can inferences be made. The species lists are practically identical, and evidence of mixed living assemblages indicates that the Cowlitz shallow marine environment extended to at least the central Washington Tukwila coast, almost 100 mi to the north. These may have been part of the same deltaic system, as indicated by Buckovic (1979), or they may be the terminations of different rivers. However, Tukwila Formation sediments indicate proximity of andesitic source rocks. Because there is no evidence of tectonic translation for Eocene sedimentary and volcanic rocks in western Washington, it is inferred that the subtropical belt extended to at least 46^{o} N latitude.

The Cowlitz marine sediments were deposited in a very short time, approximately 2 million years. The adjacent Skookumchuck Formation, which is mined in Centralia for coal, contains the same marine invertebrate fauna. Therefore, it may be that the Skookumchuck and the marine section of the Tukwila are coeval. This is a different conclusion from previously published correlation charts (Rau, 1958; Buckovic, 1979). Marine sedimentary rocks from the time period between 39 and 41 million years ago record a regional marine transgression. Geographically, the nearshore marine fauna, and therefore the coast of western Washington during the late middle Eocene, must have been situated in a narrow belt that extends from near Longview to Centralia and northeast to Tukwila (the most easterly outcrop). To the west of this belt, younger marine sediments subsequently covered the middle Eocene rocks.

ACKNOWLEDGMENTS

Wes Wehr, Don Hopkins, and Jackie Davis, as well as V. Standish Mallory and his students contributed many of the specimens in the Tukwila collections of the Burke Museum. I thank Ron Eng for taking the photographs, Kathy Campbell for discussions and review of the manuscript, and members of the Northwest Paleontological Association for allowing access to their private collections.

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ATTENTION, DINOSAUR FANS!

The following programs allow amateurs to dig:

Dinosaur Discovery Expeditions, 550 Jurassic Court, Fruita, CO 81512; 800-344-3466; www.dinamation.org. Five-day trips are offered at prices ranging upward from $850/person.

Dinosaur Expeditions – Museum of Western Colorado, 362 Main St., Grand Junction, CO 81501; 970-241-9210. For $86/person, you can dig on Thursdays, May–October.

Museum of the Rockies Paleontology Field Program, Montana State University, 600 W. Kagy Blvd., Bozeman, MT 59717; 406-994-6618. Day digs cost $95/person (16 or older); week-long digs (15 or older) cost $1100. Site near Choteau.

Royal Tyrrell Museum of Paleontology, Bookings Office, PO Box 7500, Drumheller, AB, Canada T0J 0Y0; 888-440-4240 or 403-823-7707; www.tyrrellmuseum.com. Weekend digs begin May 17, and daily digs run June 28 through the end of August. Prices depend on age; tours are also available.

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(Summarized from the Jan.-Feb. 1998 issue of *Compressed Air*)

BURKE MUSEUM TRIPS

Liz Nesbitt and Tony Irving are offering another of their grand sweep trips, this time to Shasta, Lassen, Crater Lake, Lava Beds National Monument, and three or four fossil collecting spots. The trip runs May 8–16, with van travel and a mix of camping and motels; cost is $585 for Burke Museum members, $615 for others. Sign up ASAP.

Burke Museum affiliate curator of fossil plants Wes Wehr and the Stonerose Interpretive Center in Republic will offer fossil collecting and identification workshops at Republic, June 12–14, June 19–21, August 21–23, and August 28–30. These field seminars include collecting 50 million year old fossil flowers, leaves, and insects at several Republic fossil localities and instruction in identifying the fossils discovered by the workshop participants. A field guide notebook and publications are included. This world famous fossil site will be featured in *Smithsonian* magazine this spring. Enrollment for each workshop is limited to 12; fee is $75.

For more information, call the Burke at 206-543-7907 before 3:00 p.m. weekdays or visit their website at http://www.washington.edu/burkemuseum.

Tertiary Andesitic Lava-flow Complexes (Stratovolcanoes) in the Southern Cascade Range of Washington—Observations on Tectonic Processes within the Cascade Arc

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INTRODUCTION

The Cascade Volcanic Arc

According to plate tectonics theory, subduction of the ocean floor beneath an adjacent continental margin produces a trench off the coast and generates magma at depths between 80 and 270 km (Gill, 1981; Tatsumi and Eggins, 1995). This magma rises through continental crust to erupt at the surface and form a chain of volcanoes, defining an arc. Most continental margin arcs surrounding the Pacific Ocean are 50 to 275 km in width and lie 125 to 250 km landward of their associated trenches or subduction zones (Moore, 1982; Gill, 1981; Tatsumi and Eggins, 1995). The trenches lie 1,300 to 13,500 km from the East Pacific Rift (spreading center). The oceanic plates subduct at angles increasing to 30 to 60 degrees at depth and at rates of 4.1 to 10.8 cm/yr (41–108 km/m.y.). The volcanoes closest to the trench are larger, closer spaced (30 to 60 km apart), and most magmatically productive in the chain. These volcanoes delineate a volcanic front that is aligned parallel to the strike of the subducting plate. Inland from the front, the volcanoes decrease in number and productivity, are more widely spaced, and may form a belt containing a minor chain.

The Cascade arc differs in some features from other arcs of the Pacific Rim. It is 50 km in maximum width and lies 250 to 350 km east of the Cascadia subduction zone (Fig. 1A). The subduction zone lies only 50 to 450 km from the Juan de Fuca–Gorda spreading ridges, and the plates subduct at only 3.4 to 4.7 cm/yr (Riddihough, 1984; Duncan and Kulm, 1989). Geophysical studies, summarized by Finn (1990), have identified the top of the subducting plates to a depth of 60 km at the northern and southern ends of the

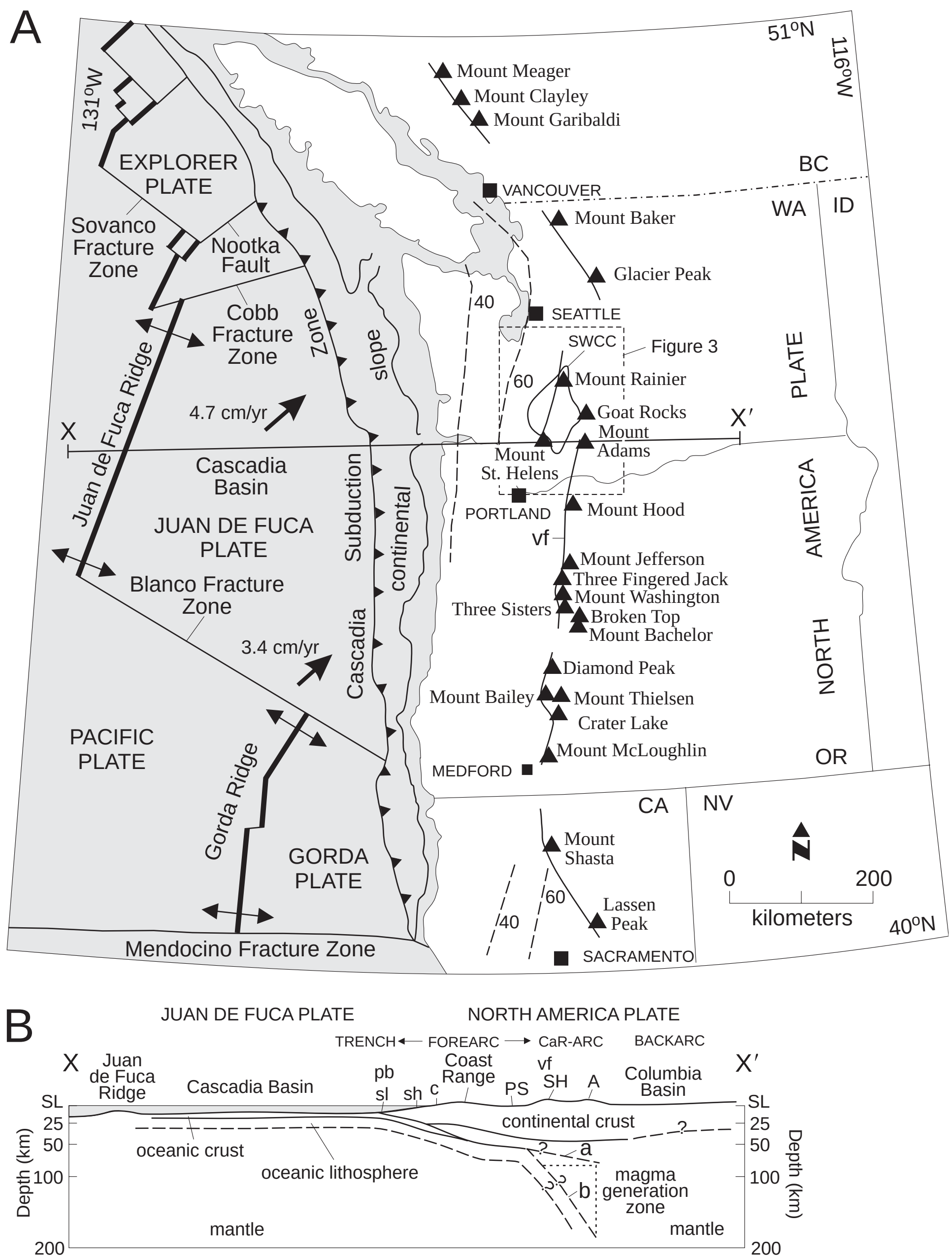


Figure 1. **A.** Simplified map of the Cascade arc, its major volcanoes (▲). ◄╫►, spreading ridge (center) with direction of movement of oceanic plates; ➔, convergence direction and rate of oceanic plate; ▲, subduction zone with barbs in direction of subduction; /40, contour on subducting plate with depth in kilometers; SWCC, southern Washington Cascades conductor; vf, volcanic front. (Modified from Hammond, 1989.) **B.** Cross section X–X′ through Cascadia subduction zone, Mount St. Helens (SH), and Mount Adams (A). Note that plate flattens between 40 and 60 km depth. a, 20°-dip projection of subducting plate from 60 km depth; b, projection of subducting plate at 60° dip; c, coast; CaR, Cascade Range (arc); pb, plate boundary; PS, Puget Sound–Willamette Valley trough; sh, edge of continental shelf; sl, foot of continental slope; SL, sea level. (Modified from Finn, 1990, and Weaver and Baker, 1988.)

arc but not beneath the volcanoes. At this depth the plate dips at an average of 20 degrees eastward, flattening between 40 and 60 km depth (Fig. 1B). Below 60 km depth the plate dips more steeply, possibly 45 to 60 degrees, to a depth of at least 80 km in order for magma to be generated.

In the Cascade arc (Fig. 1A), the volcanoes delineate a discontinuous volcanic front from Mount Meager in British Columbia south to Lassen Peak in California. A few minor volcanoes (not shown) in southern Oregon and northern California might be considered lying either trenchward or inland from the volcanic front. Overall, the Cascade arc is a single chain of volcanoes, with possibly the greatest average spacing between volcanoes, 70 ±43 km (determined from the 23 volcanoes in Fig. 1A), in all the Pacific Rim arcs.

The width of a volcanic arc (belt) is generally inversely related to the angle of subduction (Tatsumi and Eggins, 1995). Where the angle is greater than about 30 degrees, and especially where it approaches 60 degrees, a single, narrow chain is developed. And where plate convergence rate is high, more than about 6 cm/yr, the angle of subduction tends to be steeper. Other factors can affect the angle of subduction. Thickening of the overriding continental plate by underplating or compression can steepen the angle. Thinning of the plate by extension can lessen the angle. As the distance between trench and spreading rift decreases, as in the case of the Cascadia subduction zone, the temperature of the subducting oceanic plate increases and therefore its density decreases, making the plate more buoyant and lessening the angle of subduction.

In summary, the Cascade arc is among the narrowest, its volcanoes most widely spaced and least productive (fortunately for Pacific Northwest inhabitants). Its subduction zone lies relatively close to a spreading rift. And its oceanic plates subduct at a low angle at about the slowest rate of convergence. With breakup of the Juan de Fuca plate into the smaller Gorda and Explorer plates and eventually into other small plates, these conditions may presage the demise of the Juan de Fuca plate, the Cascadia subduction zone (Riddihough, 1984), and the cessation of Cascade arc volcanism. Over its 40± m.y. history, the Cascadia subduction zone has changed from rapid, 8.4 cm/yr, to slow plate convergence (Duncan and Kulm, 1989), and possibly from a steep angle of subduction to relatively shallow subduction. The Cascade arc may have changed from a wide belt to a narrow arc, from high magmatic productivity and abundant volcanoes to reduced activity and few volcanoes. And its volcanic front possibly migrated eastward with development of successive volcanoes to its present location.

Purpose

In order to investigate this possible evolution and to compare a segment of the older arc with the present arc, I located volcanoes in the older volcanic terrain of the Cascade Range in southern Washington to determine the number of volcanoes and their concentration and to delineate any volcanic fronts. Because the volcanic front is parallel to the trench, it is a tectonic line. If an alignment of older volcanoes can be recognized, it becomes a reference to determine if the arc has been deformed. Because the volcanoes can be radiometrically dated, the rate of deformation can also be determined. If an ancient volcanic front is no longer parallel to the trench, the arc has probably rotated from its former location. (See Wells, 1990.) If the volcanic front is offset, then the arc may have been deformed internally. However, this investigation is beset with unresolvable problems, as discussed below; nevertheless, it gives further insight to the tectonic processes affecting the arc since its inception.

ANDESITIC LAVA-FLOW COMPLEXES

Stratovolcanoes and Andesitic Lava-Flow Complexes

On the basis of my mapping (Hammond, 1963, 1980, 1995-97, unpub. mapping; Hammond and others, 1994), stratovolcanoes were the chief eruptive centers that contributed most rock products in the 7- to 10-km thickness of volcanic strata underlying the range (Smith, 1993; Evarts and Swanson, 1994). Similarly, Gill (1981) and Tatsumi and Eggins (1995) found that the most common volcanoes in arcs are stratovolcanoes.

Most stratovolcanoes are composed of three parts (Fig. 2A), a central cone of largely fragmented debris, a lower encircling apron of chiefly lava flows, and an outer low-lying skirt of chiefly volcaniclastic deposits, including laharic, air-fall, pyroclastic-flow, and volcanic sedimentary deposits, which

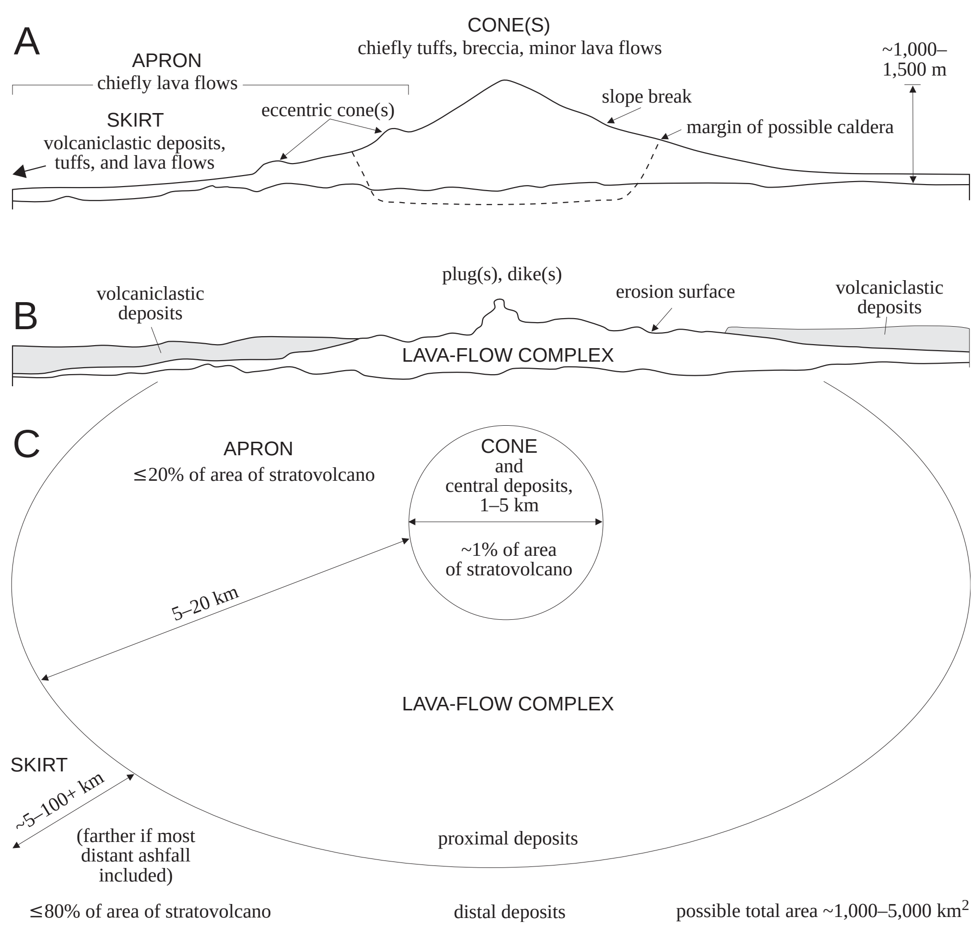


Figure 2. Profile and areal sections of (**A**) a stratovolcano, (**B**) its lava-flow complex after erosion of the volcano, and (**C**) areal dimensions of the stratovolcano and its deposits.

are the stream reworkings of the eruptive and erosional products of the volcano. In the Cascade Range, and in probably most continental margin arcs, volcaniclastic deposits constitute most of the strata in the arc. Lava flows compose the next most abundant rock type. After cessation of its eruptive activity, a stratovolcano is eroded. Because the cone is least resistant to erosion, it is the first part of the stratovolcano to be degraded, generally exposing an array of dikes and plugs that were the feeders to the volcano. Eventually erosion exposes the apron of lava flows. Because they are the most resistant part of the stratovolcano, the lava flows remain for a longer period of time, can be buried by succeeding volcanic deposits, and preserved in the stratigraphic record. Therefore, in order to identify stratovolcanoes in the older volcanic terrain, these sequences of lava flows must be recognized.

Definition

An andesitic lava-flow complex is defined here as the eroded remnant of the basal part of a stratovolcano (Fig. 2B,C). It commonly consists of a sequence of six or more lava flows that are similar in outcrop, thickness, jointing, composition, and lateral extent. The lava flows are generally andesitic in composition but may vary from basalt to dacite. In three dimensions, the complex is a pile of lava flows, commonly more than 100 m in thickness, between 5 and 20 km in diameter, and covering areas of 100 to 1,000 km^2. The lava flows dip outward from a center at less than 5 degrees. Individual lava flows range in thickness from 1 to 50 m. Interbeds of tuff and laharic and other sedimentary volcanic deposits, as much as 30 m in thickness, separate sequences of commonly two to six lava flows. The complex resembles a shield volcano but lacks the fluid basaltic (pahoehoe and some aa) lava flows that characterize this type of volcano, and a shield volcano lacks the abundant interbeds of tuff, especially those of pyroclastic-flow origin.

Recognition of lava-flow complexes is important for other studies. They serve as a basis for subdividing stratigraphic sequences and identifying deposits of specific volcanic centers in older arc terrains. Their recognition also provides a framework for geochemical studies necessary to understand the magmatic evolution of the arc and for field studies to determine possible tectonic deformation within the arc. Many older stratovolcanoes were large enough, like Mount Rainier and Mount Adams, to extend across several 7.5-minute quadrangles. Therefore, lava-flow complexes and their associated volcaniclastic deposits cover several hundred square kilometers (Fig. 2C). Because of deformation and erosion, the volcaniclastic deposits may not at first appear to be related to the complexes, but they can eventually be traced by stratigraphic, chemical, and chronologic correlation.

Other Criteria for Recognizing Stratovolcanoes and Lava-Flow Complexes

Some geologists argue that the shallow (<40 km depth) plutons of quartz diorite–granodiorite–granite, especially in the Washington segment of the Cascade arc, were the magma reservoirs that supplied stratovolcanoes. I find no compelling field evidence for a pluton of this composition to be a necessary component of a stratovolcano (see Gill, 1981; Hildreth and Lanphere, 1994). Few reports or maps document a physical connection to an overlying volcano. Only where tuff is enclosed in a caldera within plutonic rock of similar composition does the pluton appear to be the root of a volcanic system. Examples occur at the Spirit Lake pluton north of Mount St. Helens (Evarts and others, 1987), possibly at the White River pluton northeast of Mount Rainier (Murphy and Marsh, 1993), and at the Bumping Lake pluton located 15 km south of Fifes Peaks (Hammond and others, 1994; Fig. 3). Yet there is no evidence on the surface that a stratovolcano had overlain and was fed by these plutons.

However, thick andesitic sills with dikes and plugs, similar to those underlying Timberwolf Mountain (Fig. 3, Table 1) as feeders and possible subsidiary reservoirs (Gill, 1981), are likely indicators of former stratovolcanoes. The sill complex at Mowich Lake, in the northwest part of Mount Rainier National Park, and the lava flows of the Clearwater Creek complex have similar mineralogy and chemistry and are of about the same age, suggesting that they could have been fed by the same magma.

LAVA-FLOW COMPLEXES IN THE ANCIENT VOLCANIC TERRAIN OF THE SOUTHERN WASHINGTON CASCADE RANGE

I have identified 38 andesitic lava-flow complexes of former stratovolcanoes and three probable shield volcanoes between 37 Ma and 20 Ma in age in the southern Washington Cascade Range (Fig. 3, Table 1). Many were recognized in maps of the U.S. Geological Survey and the Washington Division of Geology and Earth Resources and in my maps (Hammond, 1963, 1980, 1995–97 unpub. mapping; Hammond and others, 1994). Smith's (1993) map was especially helpful in identifying some complexes. On some maps, I located complexes by interpretation: if a section of basalt, basaltic andesite, or andesite lava flows more than 100 m thick could be traced laterally, I identified it as a lava-flow complex.

Figure 3 shows the location, extent, and possible eruptive centers of the lava-flow complexes. In the eastern slope and crestal area of the Cascade Range, lava flows of the Columbia River Basalt Group and the post-middle Miocene High Cascades overlap some complexes and may conceal others. The southern two complexes dip below the Columbia River into Oregon.

The outline of a complex is its area of outcrop. I made no attempt to project the extent in the subsurface. Many complexes have poorly defined margins and lack a recognizable eruptive center. The dotted 12-km-radius ring around Fifes Peaks volcano indicates its possible former areal extent. For comparison, the bases of Mount Rainier and Mount Adams have radii of 12 and 13 km respectively. Lakeview Peak, and probably the largely buried sequences of basalt lava flows of Goat Creek and Twelvemile Creek (Table 1), are shield volcanoes and shown separately. Several complexes, such as Newaukum Lake, The Rockies, Mount Brynion, and Skamania, are large and may consist of stacked or overlapping complexes. Very small complexes, namely Vanson Peak and Tumwater Mountain, may not be the remnants of lava-flow complexes. Some complexes are dissected by erosion, for example, Clearwater Creek and Mount Wow near Mount Rainier, and Edgar Rock to the east. Rooster Comb Mountain, Kelly Butte, and the sill complex at Mowich Lake, in the northern part of the map (Fig. 3), are possible eruptive centers for local lava-flow complexes. Other andesitic sill–dike swarms and plugs could be possible centers but are not shown to avoid crowding the map.

Most complexes are named informally after geographic landmarks rather than the stratigraphic unit composing the complex to avoid confusing the nomenclature. More work is necessary to delineate the margins of these complexes, determine their eruptive centers, establish their ages more accurately, and locate additional complexes.

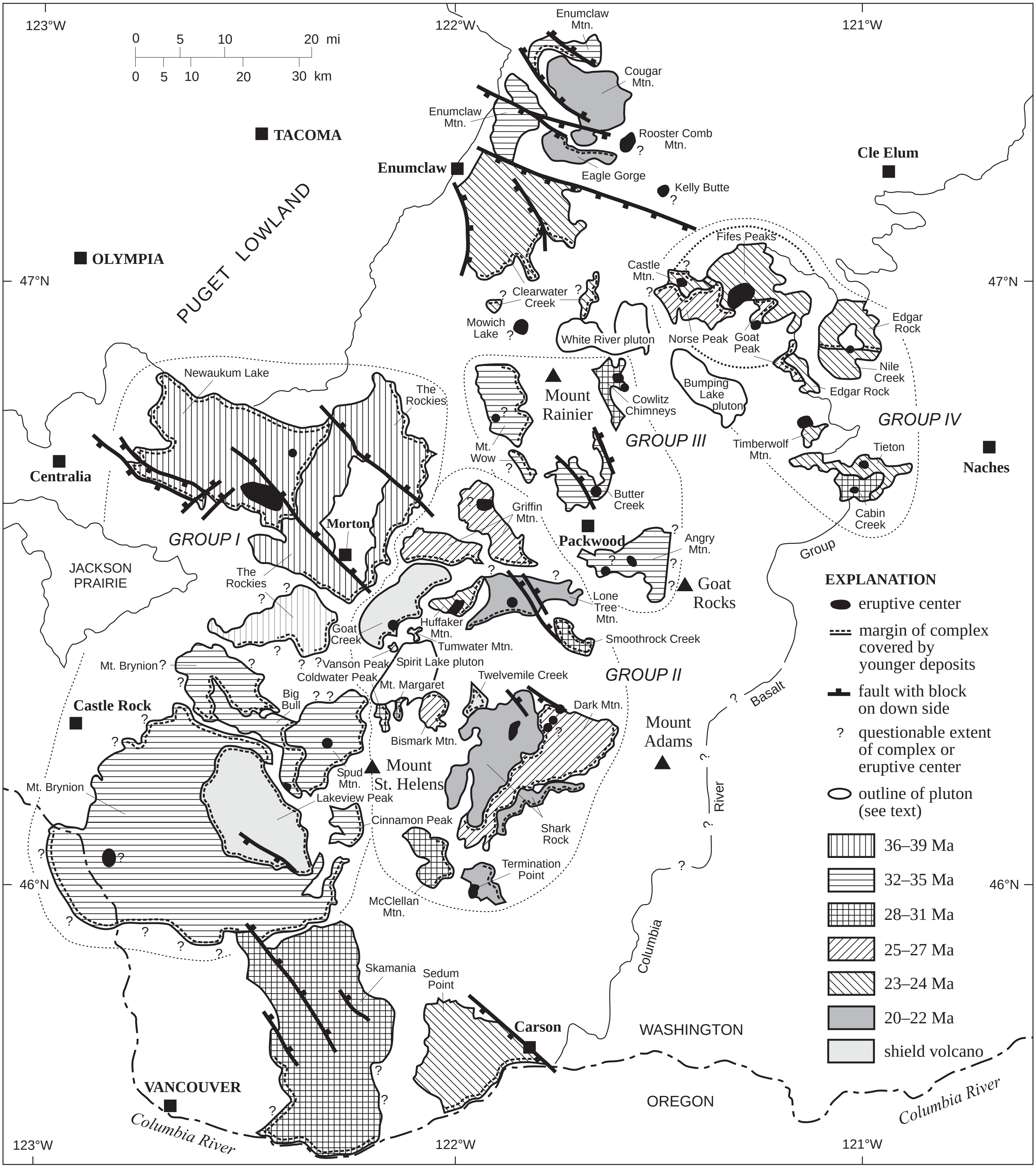


Figure 3. Lava-flow complexes in the southern Washington Cascade Range. Dotted lines outline four groups of complexes described in text.

In Table 1, the lava-flow complexes are listed alphabetically by name. A complex's age is based on analyses of the rocks either composing or stratigraphically bracketing the complex. Ages were taken from the cited references and from Phillips and others (1986) and Vance and others (1987). Thickness was either taken from the cited references or scaled from the maps. Area was scaled from the maps. Radius is the distance measured from the possible eruptive center to the exposed distant margin of the lava-flow complex. Locations of eruptive centers and their types as well as information on formational units were taken from the cited references.

Table 1. Lava-flow complexes in the southern Washington Cascade Range. Radius is measured from eruptive center to distant exposed margin. Type of eruptive center: 1, radial dike swarm; 2, rectangular dike swarm; 3, parallel dike swarm; 4, irregular dike swarm; 5, cluster of plugs; 6, underlying sill complex; 7, intrusive breccia

Lava-flow complex (volcano)	Age (Ma)	Thickness (meters)	Area (km^2) Radius (km)	Eruptive center (Type)	Formational unit	Underlying unit(s)	Overlying unit(s)	References
Angry Mountain	>24–<34	300– >1000	>200 15	N. Angry Mtn, possibly S. Point (1, 7)	unnamed andesite, basaltic andesite, and basalt lava flows	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks; rocks of Goat Rocks volcano	Swanson, 1996a,b; Swanson and others, 1997
Big Bull	34	350–450	>350 ~20	possible dikes at Big Bull (3)	unnamed andesite and basaltic andesite lava flows	unnamed volcaniclastic rocks, chiefly tuffs	unnamed tuff and lava flows of Spud Mountain complex	Phillips, 1987a; Evarts and Ashley, 1990b, 1992
Bismarck Mountain	~25	240–365	~31?	unknown (?)	unnamed andesite and basaltic andesite lava flows	unnamed volcaniclastic rocks, dacite lava flows	unnamed volcaniclastic rocks	Evarts and Ashley, 1993a
Butter Creek	25–35	~750	~125 ~10	Butter Peak (4, 5, 7)	lava flows of Ohanapecosh Fm	volcaniclastic rocks of Ohanapecosh Fm	volcaniclastic rocks of Ohanapecosh Fm	Schasse, 1987b; Evarts and others, 1983; Smith, 1993
Cabin Creek	>25–<28	900	~55 ~3	along Cabin Creek (5, 7)	lava flows of lower part of Fifes Peak Fm	Wildcat Creek beds	upper part of Fifes Peak Fm; Grande Ronde Basalt	Swanson, 1966, 1978
Castle Mountain	22–24	420	~32 5	Castle Mountain (1, 5)	Fifes Peak Fm; volcanic rocks of Fifes Peak(s)-east	Stevens Ridge Fm	upper "Keechelus"; Ellensburg Fm	Hartman, 1973; Frizzell and others, 1984; Hammond, 1997, unpub. mapping
Cinnamon Peak	32	180–250	>60 ?	unknown (?)	andesite of Cinnamon Peak	unnamed volcaniclastic rocks	volcanic breccia of Lost Creek	Evarts and Ashley, 1990a, b
Clearwater Creek	~23	760–2500	~675 ~30?	uncertain, possibly intrusive complex at Mowich Lake (5, 6)	Enumclaw Volcanic Series; volcanic rocks of Fifes Peak(s)-west	Stevens Ridge Fm	Clear West Peak complex	Fischer, 1971; Frizzell and others, 1984; Hammond, 1996, unpub. mapping
Coldwater Peak	~30	760–1000	~11 ?	unknown (?)	basaltic andesite of Coldwater Peak	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks	Evarts and Ashley, 1993c
Cougar Mountain	19–21	975–1600	~450 ?	unknown, possibly Kelly Butte or Rooster Comb Mtn (5)	volcanic rocks of Cougar Mtn	volcanic rocks of Eagle Gorge and Huckleberry Mtn	none	Hammond, 1963; Frizzell and others, 1984
Cowlitz Chimneys	~30	≤1160	~365 11	Cowlitz Chimneys (5)	lava flows of Ohanapecosh Fm	volcaniclastic rocks of lower part of Ohanapecosh Fm	Stevens Ridge Fm	Fiske and others, 1963
Dark Mountain	26–27	~825	~450 ~25	possibly 2–3 between Dark Mtn and Jumbo Mtn (1, 3, 5, 7)	unnamed andesite, basaltic andesite, basalt, and some dacite lava flows	unnamed volcaniclastic rocks; unnamed tuffs to south	unnamed volcaniclastic rocks; Shark Rock complex	Hammond, 1980; Korosec, 1987a; Swanson, 1992, 1994a; Smith, 1993
Eagle Gorge	~22	220–580	~150 ?	unknown, possibly Kelly Butte or Rooster Comb Mtn (5)	volcanic rocks of Eagle Gorge	volcanic rocks of Huckleberry Mtn	volcanic rocks of Cougar Mtn	Hammond, 1963; Frizzell and others, 1984
Edgar Rock	~24	1800	~260 10	south of Edgar Rock (1)	Fifes Peak Fm	Naches Fm; uppermost Ohanapecosh Fm	Fifes Peak Fm; Grande Ronde Basalt; upper Ellensburg Fm	Carkin, 1988; Hammond, 1996, unpub. mapping
Enumclaw Mountain	28–35	1450–2530	~450 ?	unknown (?)	Enumclaw Volcanic Series; volcanic rocks of Huckleberry Mtn	sedimentary rocks of Puget Group	volcanic rocks of Huckleberry Mtn	Weaver, 1916; Hammond, 1963; Frizzell and others, 1984
Fifes Peaks	24–25	400–1750	~260 12	Fifes Peaks (2, 5)	upper Keechelus Andesitic Series; volcanic rocks of Fifes Peak(s)-east	tuff of Bumping River; uppermost Ohanapecosh Fm	lower Ellensburg Fm; Grande Ronde Basalt	Hammond and others, 1994

Table 1. Lava-flow complexes in the southern Washington Cascade Range *(continued)*

Lava-flow complex (volcano)	Age (Ma)	Thickness (meters)	Area (km^2) Radius (km)	Eruptive center (Type)	Formational unit	Underlying unit(s)	Overlying unit(s)	References
Goat Creek	25	~700	~200 14	in lower part of Goat Creek (4, 5)	basalt of Goat Creek—shield volcano?	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks	Evarts and Ashley, 1993b,d
Goat Peak	>25	120	~20 5	Goat Peak (1, 5)	uppermost lava flows of Ohanapecosh Fm	volcaniclastic rocks of upper Ohanapecosh Fm	tuff of Bumping River, volcanic rocks of Fifes Peak(s)-east	Hammond and others, 1994; Hammond, 1996, 1997, unpub. mapping
Griffin Mountain	27	~500	~450 ?18	unknown, possibly plug at Whalehead Ridge (5?)	lava flows of Ohanapecosh Fm	lower part of Ohanapecosh Fm	uppermost part of Ohanapecosh Fm	Schasse, 1987a,b; Smith, 1993
Huffaker Mountain	23	550	~50 6	SW part of Huffaker Mountain (3)	basalt of Huffaker Mountain	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks	Swanson, 1989; Evarts and Ashley, 1993d
Lakeview Peak	>36	300–1,000	>285 ?	unknown (?)	basalt of Kalama River—shield volcano	unnamed volcaniclastic rocks	olivine basaltic andesite lava flows and volcaniclastic rocks	Evarts and Ashley, 1991, 1992; Evarts and Swanson, 1994
Lone Tree Mountain	22	200–450	>200 ~12	1 km SW of Lone Tree Mtn (1)	unnamed andesite and basaltic andesite lava flows	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks	Swanson, 1989, 1991, 1993; Swanson and others, 1997
McClellan Mountain	29	~300	>100 ?	unknown (?)	unnamed andesite lava flows	unnamed quartz-bearing tuff	unnamed volcaniclastic rocks	Phillips, 1987a
Mount Brynion	~35	~1000	~3000 40?	unknown, possibly a cluster of plugs along lower Kalama River (5?)	Goble Volcanics	Cowlitz Fm	unnamed volcanic rocks	Phillips, 1987a,b
Mount Margaret	~26–28	~450	~16 ?	unknown (?)	unnamed basaltic andesite and andesite lava flows	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks	Evarts and Ashley, 1993c
Mount Wow	30–33	≤2135	~260 ~14	unknown, possibly dike swarm at Mount Wow (3)	lava flows of Ohanapecosh Fm	lower part of Ohanapecosh Fm	Stevens Ridge Fm	Fiske and others, 1963
Newaukum Lake	~39	~3000	>600 30?	Newaukum Lake area (1, 5, 7)	lower? part of Northcraft Fm	Carbonado Fm of Puget Group	upper? part of Northcraft Fm, The Rockies complex	Hagen, 1987; Schasse, 1987a; Smith, 1993
Nile Creek	19?–24	450–550	~120 ?	unknown (?)	Fifes Peak Fm	Fifes Peak Fm; uppermost Ohanapecosh Fm; Wildcat Creek beds	Grande Ronde Basalt; upper Ellensburg Fm	Carkin, 1988; Hammond, 1996, unpub. mapping
Norse Peak	>25	240–450	>90 ?	unknown (?)	lava flows in upper Ohanapecosh Fm	volcaniclastic rocks of Ohanapecosh Fm	upper Ohanapecosh Fm; volcanic rocks of Fifes Peak(s)-east	Hartman, 1973; Frizzell and others, 1984; Hammond, 1997, unpub. mapping
Sedum Point	24	300	>360 ?	unknown (?)	volcanic rocks of Stevenson Ridge, andesite lava flows of Three Corner Rock	unnamed volcaniclastic rocks	Eagle Creek Fm	Hammond, 1980; Korosec, 1987b; Phillips, 1987b
Shark Rock	<23	~1000	~500 ~20	in area of Shark Rock (3, 5, 7)	unnamed andesite, basaltic andesite, and basalt lava flows	unnamed volcaniclastic rocks, chiefly tuffs to south	unnamed volcaniclastic rocks	Hammond, 1980; Korosec, 1987a; Swanson, 1992, 1994a
Skamania	27–28	365	1125? ?	unknown (?)	unnamed basaltic andesite and andesite lava flows	unnamed volcaniclastic rocks and lava flows	Troutdale Fm	Phillips, 1987b
Smoothrock Creek	30±	>300	>60 ?	unknown (?)	unnamed andesite and basaltic andesite lava flows	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks	Swanson, 1993

Table 1. Lava-flow complexes in the southern Washington Cascade Range *(continued)*

Lava-flow complex (volcano)	Age (Ma)	Thickness (meters)	Area (km^2) Radius (km)	Eruptive center (Type)	Formational unit	Underlying unit(s)	Overlying unit(s)	References
Spud Mountain	31–33	240–800	250 11	Spud Mountain area (1, 5)	unnamed andesite, basaltic andesite, and basalt lava flows	unnamed volcaniclastic rocks, chiefly tuffs	unnamed volcaniclastic rocks	Evarts and Ashley, 1990b, 1992, 1993c; Evarts and Swanson, 1994
Termination Point	20	~180	>60 8?	possibly plug at Termination Point (5)	unnamed andesitic lava flows	unnamed volcaniclastic rocks	unnamed volcaniclastic rocks, basalt lava flows of Indian Heaven	Hammond, 1980; Korosec, 1987a,b
The Rockies	33?–38	~1000	>1400 ?	unknown (?)	lava flows in upper? Northcraft Fm	volcaniclastic rocks and lava flows of Northcraft Fm	unnamed lava flows and volcaniclastic rocks	Hagen, 1987; Schasse 1987a; Smith, 1993
Tieton	23	200–1700	~240 ~6	south part of Bethel Ridge (1, 7)	upper part of Fifes Peak Fm	lower part of Fifes Peak Fm, Wildcat Creek beds	Grande Ronde Basalt	Swanson, 1966, 1978
Timberwolf Mountain	22–23	300	~65 ~8	north of Timberwolf Mtn (2, 5, 6)	Fifes Peak Fm	tuff of Cash Prairie; Wildcat Creek beds	Grande Ronde Basalt	Shultz, 1988; Hammond and others, 1994; Hammond, 1995, unpub. mapping
Tumwater Mountain	24	300	>9 ?	unknown (?)	basaltic andesite of Tumwater Mtn	unnamed volcaniclastic rocks, dacite lava flows	none	Evarts and Ashley, 1993d
Twelvemile Creek	>23	>450	>1 ?	unknown (?)	basalt of Twelvemile Creek—shield volcano?	unexposed	unnamed volcaniclastic rocks, lava flows of Shark Rock complex	Swanson, 1989
Vanson Peak	25	~425	>1 ?	unknown (?)	unnamed andesite and basaltic andesite lava flows	unnamed volcaniclastic rocks	none	Evarts and Ashley, 1993b

All lava-flow complexes are folded, and some are faulted, forming structures oriented generally northwest-southeast. These structures and their orientations indicate that the arc has been subjected to possible recurrent tectonic activity along a north–south to northeast–southwest axis of compressive stress since the early Tertiary.

Most complexes on the western flank of the range have an easterly component of dip. They were tilted by the early Tertiary axial depression of the arc (Swanson, 1994b; Evarts and Swanson, 1994), which has not been obliterated in the late Cenozoic uplift of the range. The Lone Tree Mountain, Shark Rock, and Dark Mountain complexes, located near the axis of depression, are nearly horizontal, and were minimally affected by the late Tertiary deformation. Local folding has tilted the Cowlitz Chimneys complex westward. This folding, as well as uplift of the range, has tilted the complexes in

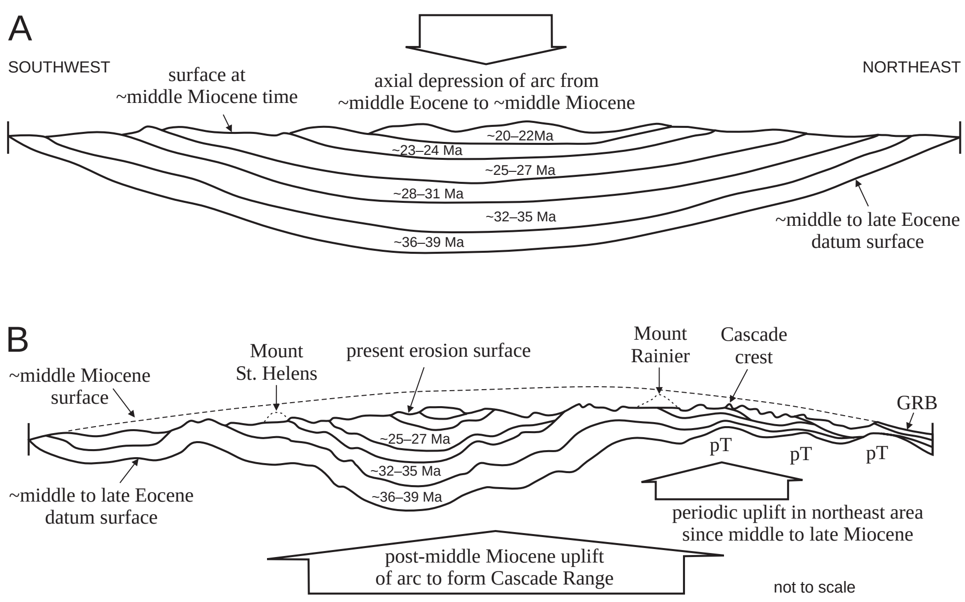
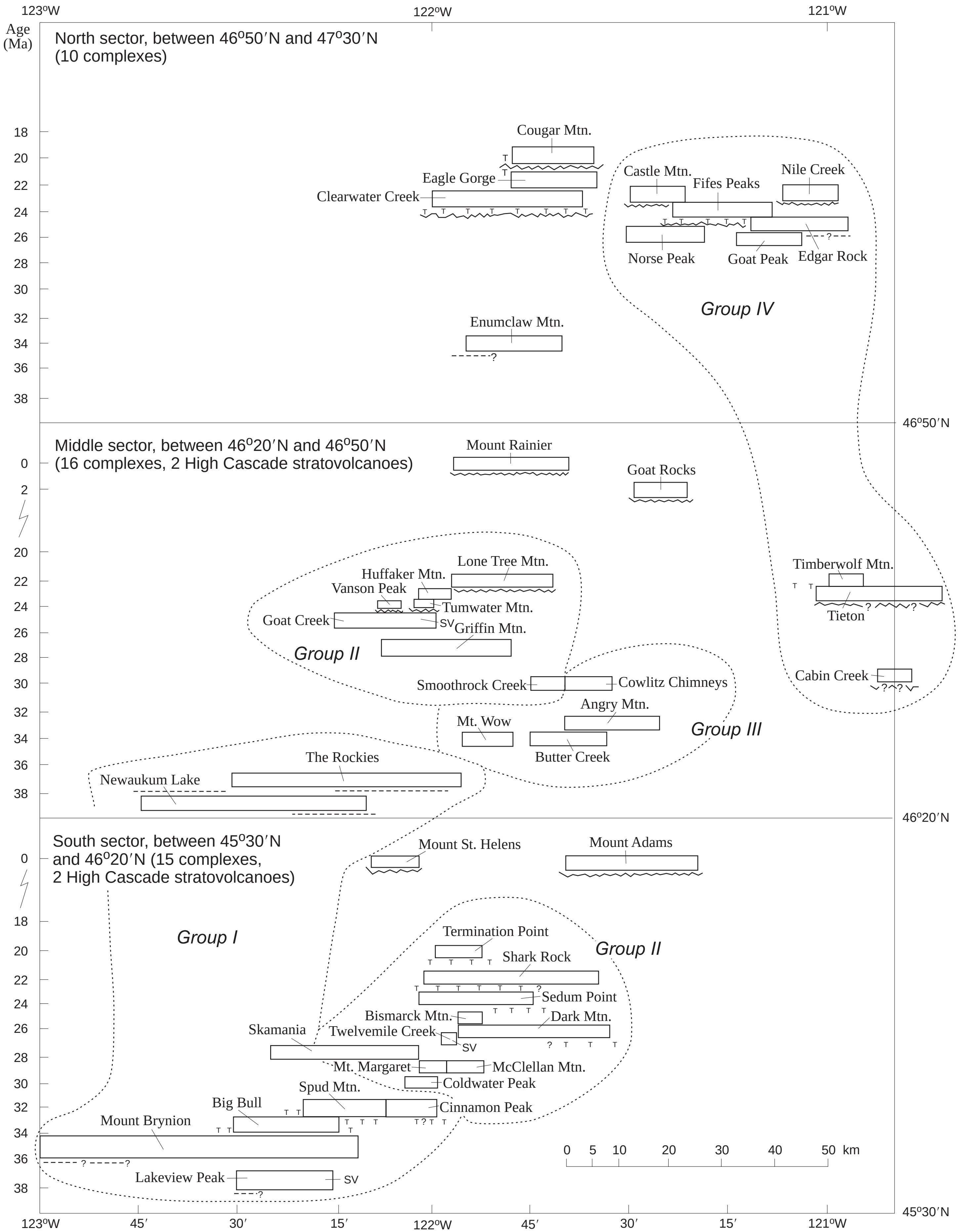


Figure 4. Schematic southwest–northeast cross sections showing (**A**) axial depression of the Cascade arc at about middle Miocene time with stratigraphy in age ranges given in Figure 3, and (**B**) uplift of the Cascade arc to form the Cascade Range. GRB, Grande Ronde Basalt of the Columbia River Basalt Group; pT, pre-Tertiary rock. Note the greater uplift in the northeast and the shortening in cross section by tectonic compression.

Figure 5. *(facing page)* Lava-flow complexes in plots of age versus longitude in three sectors across the southern Washington Cascade Range. Location of sector and number of complexes shown in upper left corner of each sector. ~~~~~, unconformity at base of complex; ------, arkosic sedimentary beds; sv, shield volcano; T T , thick tuff beds; ?, indefinite extent of beds. Dotted lines outline four groups of complexes described in text. High Cascades volcanoes Mount Rainier, Goat Rocks, Mount St. Helens, and Mount Adams shown for comparison. East–west width of complexes scaled approximately from Figure 3.



123°W
122°W
121°W
Age (Ma)
North sector, between 46°50′N and 47°30′N (10 complexes)
18
20
22
24
26
28
30
32
34
36
38
Cougar Mtn.
Eagle Gorge
Clearwater Creek
Castle Mtn.
Fifes Peaks
Nile Creek
Norse Peak
Goat Peak
Edgar Rock
Group IV
Enumclaw Mtn.
46°50′N
Middle sector, between 46°20′N and 46°50′N (16 complexes, 2 High Cascade stratovolcanoes)
0
2
20
22
24
26
28
30
32
34
36
38
Mount Rainier
Goat Rocks
Lone Tree Mtn.
Huffaker Mtn.
Vanson Peak
Tumwater Mtn.
Goat Creek
SV
Griffin Mtn.
Group II
Timberwolf Mtn.
Tieton
Cabin Creek
Smoothrock Creek
Cowlitz Chimneys
Angry Mtn.
Mt. Wow
Butter Creek
Group III
The Rockies
Newaukum Lake
46°20′N
South sector, between 45°30′N and 46°20′N (15 complexes, 2 High Cascade stratovolcanoes)
0
18
20
22
24
26
28
30
32
34
36
38
Mount St. Helens
Mount Adams
Group I
Termination Point
Shark Rock
Group II
Sedum Point
Bismarck Mtn.
Dark Mtn.
Skamania
Twelvemile Creek
SV
Mt. Margaret
McClellan Mtn.
Coldwater Peak
Spud Mtn.
Big Bull
Cinnamon Peak
Mount Brynion
Lakeview Peak
SV
0 5 10 20 30 40 50 km
45°30′N
123°W
45′
30′
15′
122°W
45′
30′
15′
121°W

the northeastern area (Fig. 3) to the east. In addition, the Fifes Peaks, Goat Peak, Timberwolf Mountain, and Tieton complexes are warped by northeast-plunging folds.

OBSERVATIONS

The scattered distribution of lava-flow complexes of different ages in Figure 3 is caused primarily by the structures and erosion affecting the volcanic rocks. (See Evarts and Swanson, 1994.) Prior to the middle Miocene, the arc subsided along a north–south axis, resulting in volcanic strata covered by successively younger rocks toward the axis of the arc (Swanson, 1994b; Fig. 4A). Lava-flow complexes tend, therefore, to be exposed in parallel belts that decrease in age toward the center of the arc. Most older complexes (32–39 Ma) crop out along the western edge of the Cascade Range. Other older complexes could occur in the eastern flank of the range, if it were not for the cover of lava flows of the Columbia River Basalt Group. Occurrences of 28–35 Ma complexes in the center of the arc near Mount Rainier are a result of deformation within the arc and erosion. Other complexes possibly occur along the crest of the range, west of the margin of the Columbia River Basalt Group, but are buried by post-middle Miocene lava flows. Lack of complexes in other areas may be due to the possibility that few stratovolcanoes exist more than 1 m.y., as indicated by a study of Mount Adams (Hildreth and Lanphere, 1994). Erosion could have erased many complexes, even before they were covered by younger volcanoes. Thus, to locate older volcanoes in the Cascade arc and use their alignment as a reference against which to measure deformation of the arc is not feasible. Erosion and burial have removed or covered most evidence.

However, four groups of complexes, which are elongate roughly northwest–southeast, provide insights into the structural deformation that has affected the range (Figs. 3 and 5). Group I of 32–39 Ma complexes occurs along the western side. Group II of 20–31 Ma complexes is concentrated in the center of the range. Group III of 32–35 Ma complexes lies near Mount Rainier. Group IV of 23–31 Ma complexes is located in the northeastern area of the map (Fig. 3).

In Figure 5, I have plotted the complexes by age versus longitude in cross sections in three sectors across the range. The figure shows the trend in ages of the complexes, from oldest in the west to youngest and most concentrated in the center of the range. Some older complexes in the western side and the Edgar Rock complex in the northeastern area overlie or are interstratified with arkosic sedimentary rocks. Other complexes are interstratified with thick tuff beds or sequences of tuffs. Many complexes in the northeastern area and a few in the center of the range have unconformable bases.

Group II in the center of the range, between Mount St. Helens and Mount Adams and south of Mount Rainier, is located within the area of greatest subsidence and accumulation of strata in the region. It lies within the area of the southern Washington Cascades conductor (Stanley and others, 1987; Fig. 1).

Group III to the north, extending northwest–southeast through Mount Rainier, and Group IV to the northeast are located along structural highs, indicating that this part of the range has been uplifted (Fig. 4B). The lack of complexes older than 31 Ma in the northeast area (Fig. 3) and the existence of unconformities at the bases of most complexes here (Fig. 5) further suggest that uplift was periodic during the early Tertiary. In contrast, in the central and southwest areas of the range, subsidence was more or less continuous during the early Tertiary.

The lack of complexes older than 31 Ma in the northeastern area also suggests the possibility that the volcanic front migrated eastward between about 37 and 31 Ma as the arc evolved.

The lava-flow complexes of 23–24 Ma extend across the arc in a belt 80 km wide. Other ages of complexes form narrower belts. Nevertheless, they indicate that formerly the arc was a wide belt similar to many present arcs of the Pacific Rim. Since about 20 Ma, the width of volcanoes has narrowed to the present arc.

In the northeast concentration of lava-flow complexes (Fig. 3), the four complexes (Fifes Peaks, Edgar Rock, Timberwolf Mountain, and Tieton) that are 23 ±2 Ma in age are spaced 15 to 22 km apart, a considerably shorter distance than the average 70 km between the present volcanoes, suggesting that former volcanoes were more closely spaced.

Complexes within the 22 to 25 Ma range are most numerous (Fig. 5). Either these complexes are better preserved because of their structural setting, or possibly a greater number of stratovolcanoes of this age were formed. And in studying the maps to identify the lava-flow complexes, I noted that Castle Mountain, Clearwater Creek, Huffaker Mountain, Lone Tree Mountain, and the southern parts of Dark Mountain and Shark Rock complexes occur at lower elevations than complexes of equivalent or older age, suggesting that they occupy broad valleys eroded into older volcanic rocks.

CONCLUSIONS

On the basis of limited data, the number of recognizable lava-flow complexes, their narrow spacing, and wide distribution in the older arc terrains suggest that stratovolcanoes were abundant and spread across the arc during the early history of the Cascade arc. The belt has apparently narrowed from the mid-Tertiary to the present. These traits further suggest the possibility of there having been greater magmatic activity than in the present Cascade arc and accompanying higher rate of convergence and steeper subduction in the Cascadia subduction zone.

- Structural deformation and erosion within the arc obscures any alignment of former volcanic fronts and prevents determination of any deformation with respect to this alignment.
- Most lava-flow complexes are preserved in the central part of the range in the area of greatest subsidence and within the location of the southern Washington Cascades conductor.
- Arc terrain at Mount Rainier and to its northeast is structurally higher and has been periodically uplifted compared to terrains south of Mount Rainier.
- Recognition of a lava-flow complex can facilitate mapping in older arc terrains, making it possible to trace different types of volcanic deposits to their source areas and to subdivide the rock units stratigraphically.

Acknowledgments

I thank R. C. Evarts for review of an early draft and W. S Lingley, T. J. Walsh, and K. M. Reed for their helpful reviews and edits, which considerably improved the content and discussion in the paper. The author, however, accepts full responsibility for all its shortcomings.

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Point to Ponder

The oldest reference to Washington's geology in our library was published in London 200 years ago (1798) entitled "A voyage of discovery to the North Pacific ocean, and round the world; in which the coast of north-west America has been carefully examined and accurately surveyed. Undertaken at His Majesty's command, principally with a view to ascertain the existence of any navigable communication between the North Pacific and North Atlantic oceans; and performed in the years 1790, 1791, 1792, 1793, and 1795, in the *Discovery* sloop of war, and armed tender *Chatham*, under the command of Captain George Vancouver."

Association of Engineering Geologists

The Association of Engineering Geologists holds its 41st Annual Meeting, Sept. 30–Oct. 3, 1998, at the DoubleTree Guest Suites Hotel in Tukwila. The theme is "Engineering Geology—Knowledge for better decisions". Symposia topics will include "Flooding in the Pacific Northwest in the late 1990s" and "Engineering geology and the media". Short courses: Computerized analyses in engineering geology applications; Preparing and delivering technical presentations. For more information, contact AEG '98, c/o Julie Keaton, 130 Yucca Dr., Sedona, AZ 86336-3222; 520-204-1553; -5597 (fax); aegjuliek@aol.com.

Wright State Environmental Science Courses

Starting September 28, 1998, Wright State University offers six 12-week distance learning courses through its Interactive Remote Instructional System (IRIS). The courses, geared for professionals, are: site remediation; environmental geophysics; soil and ground-water contamination; ground-water hydrology; aquifer test analysis/well hydraulics; and ground-water flow modeling using MODFLOW. For information about credits, costs, or the program, contact: Wright State University, Center for Ground Water Management, 3640 Colonel Glenn Hwy., Dayton, OH 45435-0001; 937-775-3648, -3649 (fax); IRIS07@wright.edu; http://geology.wright.edu/iris.html.

Northwest Paleontological Association

Dr. Greg MacDonald of the Hagerman Fossil Beds National Monument in south-central Idaho, home of a famous fossil horse, will be the speaker at the May 2 meeting of the Northwest Paleontological Association. Meetings are at 1:00 p.m. in the Burke Room, Burke Museum, University of Washington, just off 45th Ave. The public is welcome. NPA dues are $15 a year ($25 for a family). *The Aturian*, the NPA newsletter, comes out bi-monthly, just before the meetings. Checks made out to NPA can be sent to Betty Jarosz, 17807 NE 102nd Ct., Redmond, WA 98073. The NPA web page is at http://www.cnw.com/~mstern/npa/npa.html; watch this space for news about upcoming events.

New Radiocarbon Ages of Major Landslides in the Cascade Range, Washington

Note: The original printed version of this article was missing several paragraphs of text that have been restored here.

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INTRODUCTION

We present radiocarbon ages for eight major landslides in the Cascade Range: at Church Mountain, Racehorse Creek, Canyon Lake, Day Lake, Damnation Creek, Slide Lake, Glacier Lake, and Packwood Lake (Fig. 1). Our new data for the Church Mountain rock slide–debris avalanche indicate that its age is about 300 years younger than previously reported. This new information allows a more accurate correlation of the Church Mountain landslide with other geologic events that could be proxy indicators of earthquake-generated strong ground motion. The ages of the other seven landslides are new data for each of these probably coseismic rock slides and debris avalanches.

TERMINOLOGY

In this paper we follow the terminology of Varnes (1978) and Cruden and Varnes (1996) that classifies landslides according to the type and nature of their movement and material. For example, a *rock slide* is predominantly made up of rock fragments that are inferred to have failed (slid) along a visible or invisible surface or within a narrow zone, for example, along a bedding plane or major discontinuity. A *debris avalanche* is a flowing mixture of rock fragments and finer material whose internal energy is dominated by inertial forces instead of viscous forces, such as pore-water pressure, as in a *debris flow* (Pierson and Costa, 1987). These terms describe only three of the many types of mass wasting that are part of a continuum of processes. Where deposits indicate more than one type of process has occurred during the same event, we combine terms, as in *rock slide–debris avalanche*. Herein we use the term *landslide* in the general sense to refer to mass-wasting events and features without specifying the nature of the process or material.

As will be noted below, subfossil trees are one clue to the age of a deposit. Bates and Jackson (1987) defined *subfossil* as "A fossil that is younger than what would be considered typical fossil age (i.e., preserved since about 6,000 years ago, by common convention) but not strictly recent or present day." However, for preserved wood we avoid this arbitrary cutoff of 6,000 years and use the term in the qualitative sense to mean any ancient wood that is not significantly permineralized. This usage is more consistent with that of dendrochronologists.

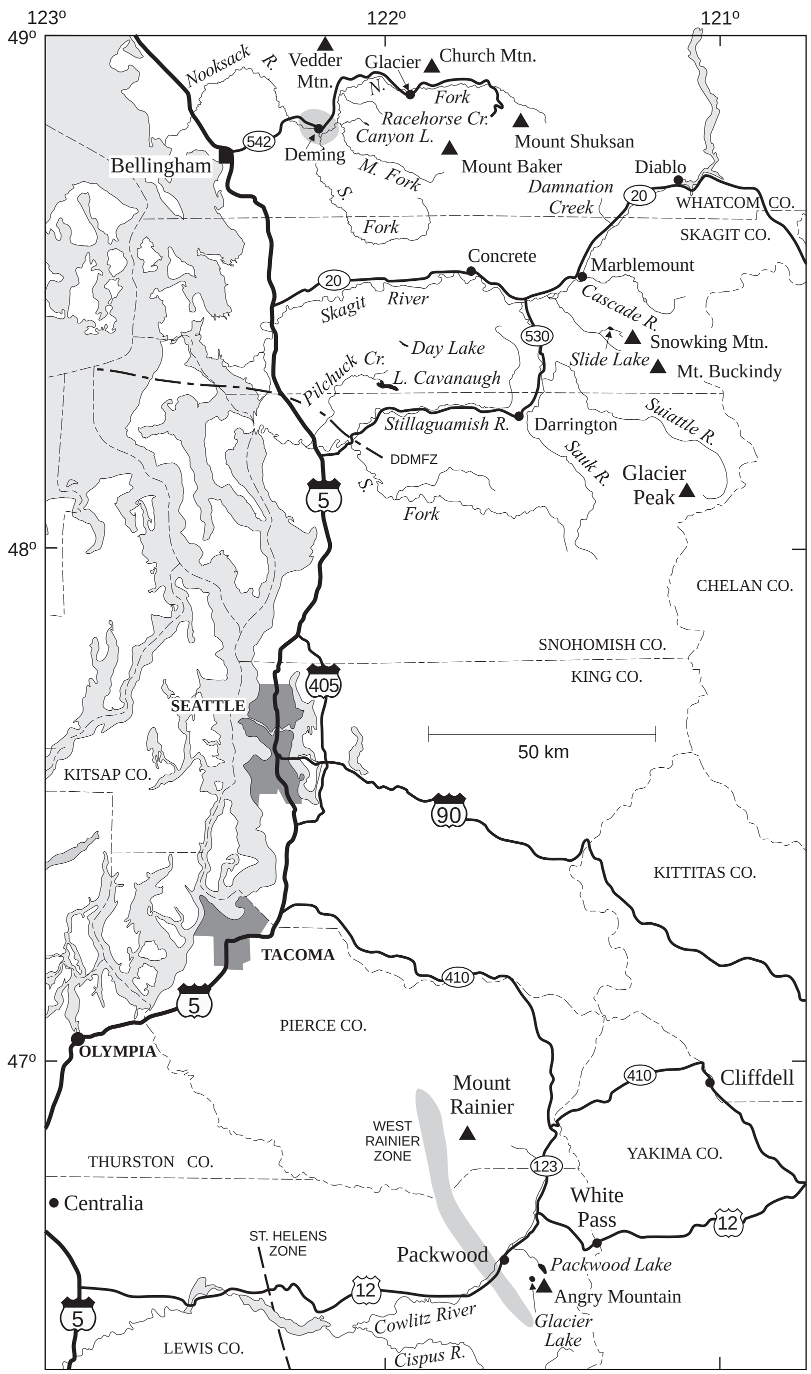

Figure 1. Locations of selected landslides in the Cascade Range, Washington. Selected shallow-crustal faults from Rogers and others (1996) are the Darrington–Devils Mountain fault zone (DDMFZ) and St. Helens zone, shown as heavy dashed lines. Other areas of diffuse and poorly defined seismicity (stippled areas with no border) include the West Rainier zone and an area of seismicity near Deming that includes the Macaulay Creek thrust recently discussed by Dragovich and others (1997b).

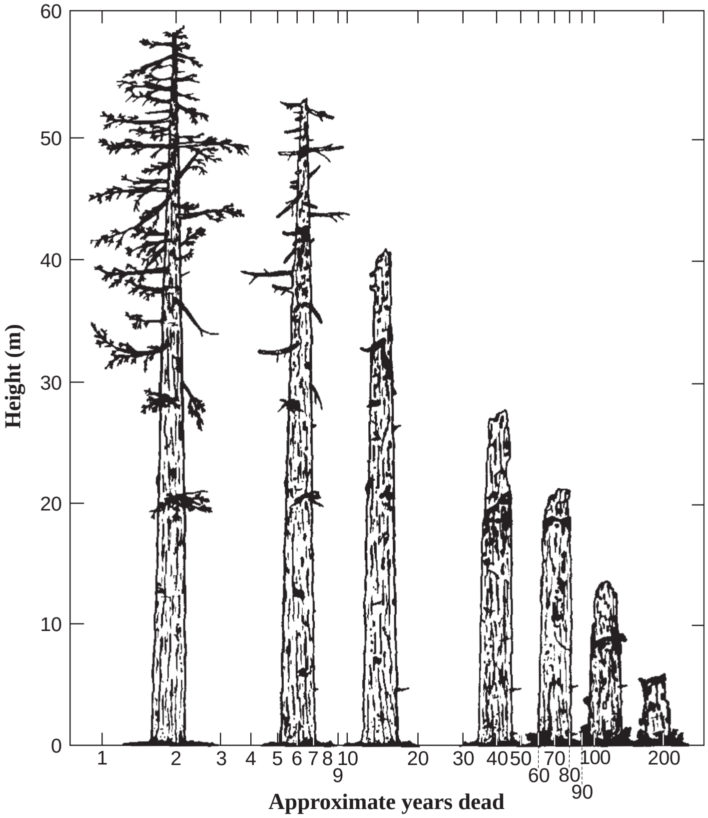

Figure 2. Subaerial decomposition of Douglas-fir snags. Modified from Cline and others (1980).

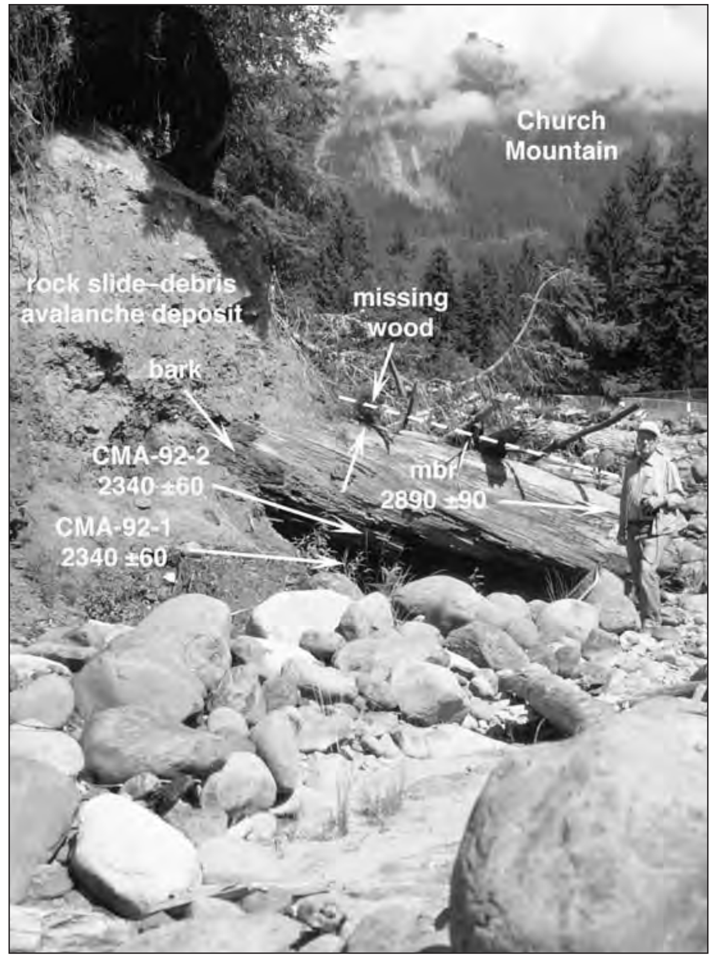

Figure 3. Protruding logs exposed along Glacier Creek in Whatcom County were buried by the Church Mountain rock slide–debris avalanche deposit about 2,340 yr B.P. The rock slide–debris avalanche originated at Church Mountain (partially cloud covered in the background) about 6.5 km to the northeast across the North Fork Nooksack River valley. The lower log (in shadow) is western redcedar (sample CMA-92-1), and the upper Douglas-fir log is the source of samples CMA-92-2 and mbr of Cary and others (1992) mentioned in Table 1.

Age estimates that have been derived from radiocarbon (^{14}C) dating methods are given as "yr B.P.", meaning radiocarbon years before present, where the "present" is A.D. 1950. Radiocarbon years can differ slightly from calendar years because of variations in the carbon-isotope content of atmospheric carbon dioxide through time. For simplicity, raw radiocarbon ages are used in this text. Table 1 on p. 34 shows both raw ages and calibrated ages.

Previous researchers have suggested that rock slide and debris-avalanche deposits record prehistoric seismic shaking in Washington (Schuster and others, 1992, 1994, 1995; Engebretson and others, 1995, 1996), neighboring British Columbia (Clague and Shilts, 1993; Evans and Savigny, 1994), and elsewhere (Keefer, 1984). The landslides mentioned herein were likely to have been triggered by strong shaking for reasons similar to those noted by Schuster and others (1992) in their study of rock avalanches in the eastern Olympic Mountains:

- The rocks that slid or avalanched have not failed at such scales historically during storms.
- Worldwide, 29 of 71 rock avalanches that are included in an inventory of landslide dams (Costa and Schuster, 1991) were triggered by earthquakes having magnitudes of 6.0 or greater (Keefer, 1984).
- In New Zealand, the distribution of lakes dammed by landslides approximates the locations of shallow earthquakes of magnitude 6.5 or greater (Perrin and Hancox, 1992).

Evidence of these earthquakes can be preserved when the landslides bury forests and (or) create natural dams that cause a lake to form and thereby a forest to drown. The lakes and landslide deposits commonly provide a fairly anoxic environment that drastically slows the rate of decomposition of drowned or buried snags (dead trees), including Douglas fir and western hemlock, which are susceptible to relatively rapid deterioration in air (Cline and others, 1980; Harmon and others, 1986; Fig. 2). By studying and radiocarbon dating the remains of plants, such as rooted trees that are preserved in the lakes (subfossil trees), we can estimate the age of the landslide and of its possible triggering earthquake.

At five of the sites mentioned in the introduction, landslide-dammed lakes that were impounded at the time of the landslide are still in existence. The drowned forests preserved in these lakes, the snags or carbon preserved in deposits at the other locations, and the landslide deposits are the subject of this paper.

During the study, we also visited Tomyhoi Lake, a landslide-dammed lake in the North Cascades (T40N, R5E); landslides along the Cascade River at Kindy Creek (T34N, R12E), at Newaukum Lake (T14N, R3E), and at Hager Lake (T13N, R9E). In addition we visited three landslides along the upper Cispus River: west of Blue Lake (T11N, R9E) and at Johnson Creek and Wobbly Lake (both T11N, R10E). We could not find subfossil trees or other organic material suitable for dating at any of these sites. A carbon sample found beneath a rock slide deposit on the north flank of Vedder Mountain (Figs. 1, 6) has not yet been analyzed.

CHURCH MOUNTAIN

Church Mountain (elev. 1926 m) is about 16 km north-northeast of Mount Baker (Fig. 1). The summit of this peak towers 1.6 km above the adjacent valley bottom of the North Fork Nooksack River. Church Mountain, which has most recently been mapped by Jones (1984) and Tabor and others (1994), consists of a fault block or blocks of predominantly volcaniclastic rocks of the Chilliwack Group of Paleozoic age. The Chilliwack rocks are thrust over argillites and minor sandstones of the Nooksack Formation of Mesozoic age.

Moen (1969) first described landslide deposits in the area southwest of Church Mountain near the town of Glacier, but he did not speculate on the source, age, or cause of the landslide. Cary and others (1992) and van Siclen (1994) first made the interpretation that the source of the rock slide debris was Church Mountain. Cary and her associates obtained a radiocarbon age of 2,890 ±90 yr B.P. on a tree buried in the landslide deposit, first described the deposit's approximate dimensions, and suggested a subduction zone earthquake as a possible trigger. Carpenter and Easterbrook (1993) described the landslide in greater detail and called it the Church Mountain "sturzstrom" because they inferred that the deposit was left by a fast-moving rock avalanche. They estimated a volume of 300 x 10^6 m^3 and interpreted the age at 2,700 yr B.P., on the basis of their new radiocarbon data. Carpenter (1993) revised the volume estimate to 280 x 10^6 m^3. Engebretson and others (1996) later inferred that the Church Mountain rock slide–debris avalanche and several other landslides in the area were caused by "ancient, nearby, large, shallow-focus earthquakes".

Although the radiocarbon ages of wood samples that were considered by Carpenter range from 2,450 ±80 to 2,890 ±90 yr B.P. (mentioned above; Table 1), she estimated the age of the debris avalanche at 2,700 yr B.P. We noted an error in Carpenter's table 2 (1993, p. 27) wherein 40 years was added to the date of the Gallup Creek sample (to compensate for the distance of the sample from the outside of the tree) instead of being subtracted. This error resulted in overestimation of the age of that sample by 80 years.

In 1992, we visited the site of the first tree in the Church Mountain rock slide–debris avalanche to be radiocarbon dated (Fig. 3) and noticed that this earlier Cary and others (1992) sample (mbr in Table 1) had been taken from wood in an inner part of the tree (not close to the bark) and hence had yielded a radiocarbon date that was too old. An outside section of this tree had been eroded by the rock slide–debris avalanche or by subsequent activity along a zone of rot, and at least one outer slab consisting of about 300 annual growth rings had been removed. Our radiocarbon ages of 2,340 ±60 yr B.P. of the outer 10 rings of a western redcedar log and 2,340 ±60 yr B.P. for the outer 15 rings (under bark) of a large Douglas-fir log (source of mbr) confirm that the landslide is about 300 years younger than indicated by previous estimates based on averaging.

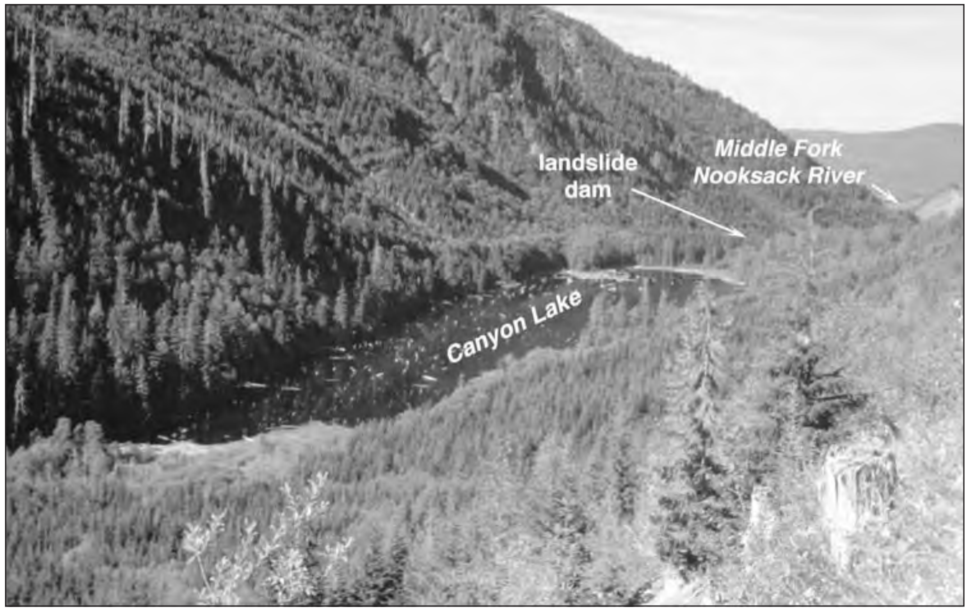

Figure 4. View to the west-southwest of Canyon Lake and its landslide dam.

CANYON LAKE

Canyon Lake (elev. 705 m) was created by a landslide that dammed Canyon Creek (Figs. 1, 4). The extent of the Canyon Lake landslide has been mapped by Brunengo (map 4 in Fiksdal and Brunengo, 1981) and by Schmidt (1994). However, this deposit is part of a more extensive landslide complex that probably has had a history of activity throughout the Holocene. For example, in the valley bottom of the Middle Fork Nooksack River downslope of the landslide, an unsorted deposit containing sandstone blocks of the Eocene Chuckanut Formation underlies the extensive Middle Fork lahar deposit from Mount Baker. That deposit has been described by Hyde and Crandell (1978) and, more recently, by Kovanen (1996), who obtained an age estimate for the lahar of about 5,500 yr B.P. The underlying landslide deposit, therefore, is at least that old.

Our radiocarbon ages of 170 ±100 and 160 ±100 yr B.P. (Fig. 5; Table 1) on subfossil trees that are apparently rooted in Canyon Lake indicate that the landslide damming it is relatively young. We will attempt to use dendrochronology to obtain a more precise age on the landslide and to test the hypothesis that it could have been triggered by the large (approx. magnitude 7.1–7.4) 1872 North Cascades earthquake (Stover and Coffman, 1993; Malone and Bor, 1979; Rogers and others, 1996). If so, it could be the same age as the Ribbon Cliffs rock slide along the Columbia River, about 3 km upstream of Entiat (Madole and others, 1995).

RACEHORSE CREEK

A rock slide–debris avalanche deposit south of Racehorse Creek was first described by Moen (1962) as a block glide (Figs. 1, 6). This deposit comprises mounds as high as 5 m and large blocks of sandstone, some larger than railroad cars, of the Slide Member of the Chuckanut Formation (Johnson, 1982). Bedding planes of this rock unit dip about 11 degrees to the west-northwest at the slide headscarp, an orientation roughly similar to the direction of movement of the slide, and one noted by Schmidt and Montgomery (1995, 1996) to be highly susceptible to failure for the Chuckanut rocks.

In their geologic maps, Kovanen (1996) and Dragovich and others (1997a) indicated that the Racehorse Creek rock slide

Table 1. Radiocarbon age data for selected major landslide deposits in the Cascade Range, Washington

Landslide	Radiocarbon age[1] (^{14}C B.P.)	Calibrated age[2] (cal. years B.P.)	Calibrated and corrected age[3] (years B.C. or A.D.)	δ^{13}C (‰)	Lab no.	Sample no.	Source of sample and comments
Church Mountain	2890 ±180	3325 (2983) 2781	1090 (749) 546 B.C. [+285]	?	?	mbr	Age from Cary and others (1992). Wood from Douglas fir buried in rockslide–debris avalanche deposit, right bank Glacier Creek at Mount Baker Rim.
Church Mountain	2450 ±160	2749 (2468) 2330	759 (479) 340 B.C. [+40]	?	?	gal	Age from Carpenter (1993) from wood at Gallup Creek.
Church Mountain	2710 ±160	2960 (2781) 2728	1010 (832) 778 B.C.	?	?	mbr2	Age from Carpenter (1993) from wood sample at Mount Baker Rim.
Church Mountain	2340 ±120	2700 (2344) 2051	750 (395) 207 B.C.	–24	Beta-58566	CMA-92-1	Sample from outer 10 rings under bark of cedar log lying under CMA-92-2.
Church Mountain	2340 ±120	2700 (2344) 2051	750 (395) 207 B.C.	–25	Beta-58567	CMA-92-2	Sample from outer 15 rings under bark of Douglas fir sample *mbr* above.
Day Lake	1650 ±100	1690 (1535) 1409	260 (415) 541 A.D.	–26.3	Beta-58568	DAL-92-1	Sample from 90-cm diameter snag in Day Lake; estimated >100 rings missing?
Day Lake	1820 ±100	1952 (1720) 1522	83 (230) 341 A.D.	–25.4	Beta-58569	DAL-92-2	Sample from 1.5-m diameter snag in Day Lake; estimated >100 rings missing?
Slide Lake	450 ±100	543 (506) 329	1417 (1454) 1631 A.D. [+10]	–27	Beta-58579	SLL-92-1	Sample from outer 20 rings of rooted stump from Slide Lake. Same stump as SLL-1 but from near roots.
Slide Lake	610 ±100	660 (628, 610, 557) 524	1290 (1322, 1340, 1393) 1426 A.D.	–24.4	Beta-50548	SLL-1	Sample from outer part of tree stump submerged annually in Slide Lake.
Slide Lake	390 ±120	525 (472) 299	1425 (1478) 1651 A.D.	–26	Beta-50549	SLL-2	Sample from outer part of tree stump submerged annually in Slide Lake.
Racehorse Creek	3840 ±140	4418 (4234) 3991	2408 (2205) 1981 B.C. [+60]	–23.4	Beta-96308	34c	Sample from innermost 10 rings of cedar log having about 65 rings and buried in silt under Racehorse Creek rockslide deposit.
Canyon Lake	170 ±100	299 (270, 197, 146, 13, 0*) 0*	1651 (1680, 1753, 1804, 1937, 1954) 1955 A.D.*	–24.9	Beta-50541	CYL-1	Sample cut from the outside of a tree stump in Canyon Lake.
Canyon Lake	101 ± 0.7% (modern)[4]	244 (125, 125, 62, 42, 0*) 0*	modern	–24.2	Beta-50542	CYL-2	Sample yielded a modern carbon value and was not used in interpretations.
Canyon Lake	160 ±100	296 (267,205, 143, 17, 0*) 0*	1654 (1683, 1745, 1807, 1933, 1954) 1955 A.D.*	–23.7	Beta-50543	CYL-3	Sample cut from the outside of a tree stump in Canyon Lake.
Damnation Creek	7030 ± 60	7907 (7884, 7863, 7820) 7755	5957 (5935, 5914, 5871) 5805 B.C.	–25.6	Beta-96393	Dam-9	Organic horizon in lacustrine silt upstream of rockfall and under Mazama ash.
Packwood Lake	970 ±120	972 (918) 732	978 (1032) 1218 A.D.	none	Beta-32673	PA-1	60-cm diameter vertical snag apparently rooted on the bottom of Packwood Lake.
Packwood Lake	1140 ±120	1175 (1057) 933	775 (893) 1017 A.D.	none	Beta-32674	PA-2	46-cm diameter snag apparently rooted on the bottom of Packwood Lake.
Glacier Lake	660 ±120	675 (648) 540	1275 (1302) 1410 A.D.	none	Beta-32670	GL-2	Sample from rooted stump at Glacier Lake 11 m below high water line.

[1] Radiocarbon ages are normalized to δ^{13}C = –25.0‰ unless queried in column 5. Error terms are 1σ with a lab error multiplier of 2 unless noted.

[2] Calibrated ages corrected using tree ring data in the CALIB 3.0.3 program of Stuiver and Reimer (1993) and reported as [–1σ, (calculated intercept age), +1σ] using a lab error multiplier of 2. Commonly, fluctuations in the calibration curve may yield more than one intercept or calibrated age. B.P. (before present) ages are reported with respect to A.D. 1950 with the exception of sample CYL-2 mentioned in footnote 3. (See Coleman and others, 1987, for a discussion of ^{14}C terminologies.)

[3] Calibrated age in sidereal (calendar) years. To derive this value, correction factor in brackets was applied to adjust lab data for approximate number of growth rings of the sample from the bark. Samples mbr and gal are corrected by +285 yrs and +40 yrs respectively (see text).

[4] This sample is reported as 101 ±0.7% of the modern reference standard, not B.P.

* Denotes influence of bomb ^{14}C.

deposit is more extensive than was shown by Moen (1962) or by Schmidt (1994). The presence of large boulders of the Slide Member on the west side of the North Fork Nooksack River shows that the avalanche crossed the valley bottom and that it probably temporarily dammed the river. Our soil cores showed the deposit extending in the subsurface to the south to at least the SW1/4SW1/4 sec. 15, T39N, R5E, where it is buried under younger alluvium. Engebretson and others (1996) estimated the volume of the Racehorse Creek landslide deposit at 2.5 km^3.

We obtained a radiocarbon age of 3,840 ±70 yr B.P. on a prone western redcedar snag that protrudes from a sandy silt bed under the landslide deposit (Fig. 7). This exposure is along the east bank of the North Fork Nooksack River in sec. 10, T39N, R5E, about 75 m south of its confluence with Racehorse Creek. The centroid (center of mass) of the dated sample, consisting of 10 growth rings, was about 60 rings from the outside of the tree; hence the tree died about 3,780 radiocarbon years ago.

Figure 5. View to the west showing sampling of vertical snags rooted in the bottom of Canyon Lake. Photo by R. L. Schuster.

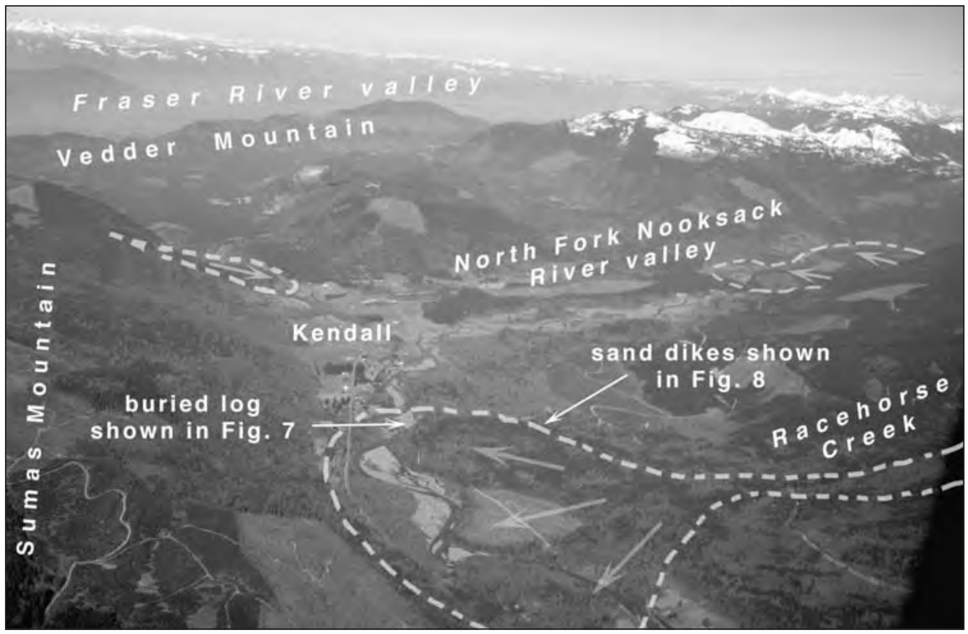

Figure 6. Aerial-oblique view of the Racehorse Creek rock slide–debris avalanche deposit (foreground). View is to the north-northeast. Other ancient rock slides are shown in the upper left and upper right background. Hummocks and large sandstone blocks of the Racehorse slide were found on both sides of the river.

Although a thickness of as much as 2 dm of silt overlies the snag, irregular oxide stains in the silt between the subfossil snag and the overlying landslide deposit indicate that the silt had been disturbed and that the snag probably was a rooted tree that was pushed over by the moving rock slide. Furthermore, although the tree lacked bark, the presence of sapwood indicated that minimal erosion of the tree had occurred before burial (Panshin and de Zeeuw, 1970, p. 493). Western redcedar snags along the Washington coast that died in A.D. 1700 (Yamaguchi and others, 1997) and a population west of Mount Hood that died about A.D. 1800 (Cameron and Pringle, 1987, 1991) had significant erosion of outer wood including most exposed sapwood, probably in large part from mining by wasps. We infer, therefore, that the Racehorse Creek snag noted above, which is aligned in the direction of movement of the rock slide, probably was killed at the time of the event. Alternatively, this snag could have been buried in the silt prior to the rock slide–debris avalanche, and our radiocarbon age could conservatively be interpreted as a maximum age of the Racehorse Creek rock slide–debris avalanche. G. W. Thorsen (geological consultant, oral commun., 1997) noted that the slide had reportedly become reactivated in its upper reaches for a short time in about 1950.

A 2- to 4-cm-thick sand dike and several thin (approx. 1 cm) sills composed of gray andesitic sand intrude sandy flood silts within several meters of the Racehorse Creek rock slide deposit. We exposed these intrusions along North Fork Nooksack River Road about 0.5 km west of where it crosses Racehorse Creek (Fig. 8) in a trench slightly south of the road. Because the sandy silt units, which apparently represent deposition from at least three separate flood events, were not observed in contact with the landslide deposit, we could not determine if they predated or postdated the rock slide–debris avalanche. If they are older than the landslide deposit, the liquefaction that created the sand dikes could have been triggered by movement of the rock slide–debris avalanche. Alternatively, the dikes could have been generated by liquefaction associated with rupture of nearby shallow-crustal faults such as the nearby Macaulay Creek thrust recently described by Dragovich and others (1997b).

DAMNATION CREEK

Riedel and others (in press) have obtained a minimum radiocarbon age of about 7,030 ±60 yr B.P. (Table 1) on a large rock slide–debris avalanche that dammed the Skagit River about 16 km east-northeast of Marblemount near Damnation Creek (Fig. 1). Details of the deposit and of the temporary lake it impounded have been interpreted in that citation.

SLIDE LAKE

Slide Lake (elev. 1,007 m), about 13 km southeast of Marblemount (Fig. 1), was dammed when a rock slide consisting of

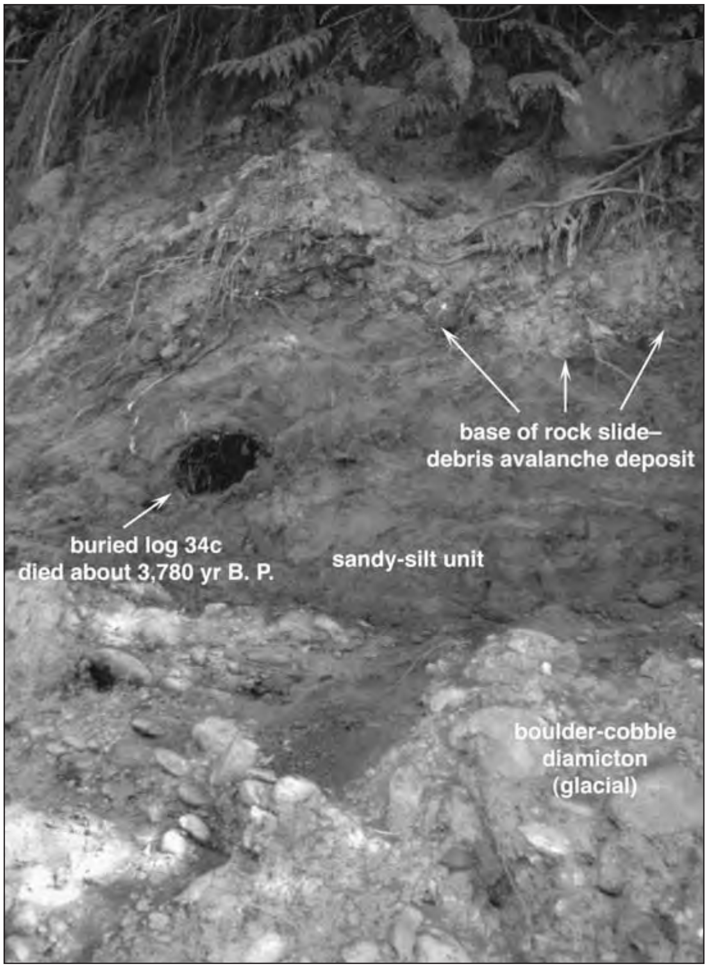

Figure 7. View to the east of a subfossil western redcedar tree exposed under the Racehorse Creek rock slide–debris avalanche deposit. Radiocarbon dating of the tree shows that it died about 3,780 yr B.P. The tree is about 20 cm in diameter. spl, sample.

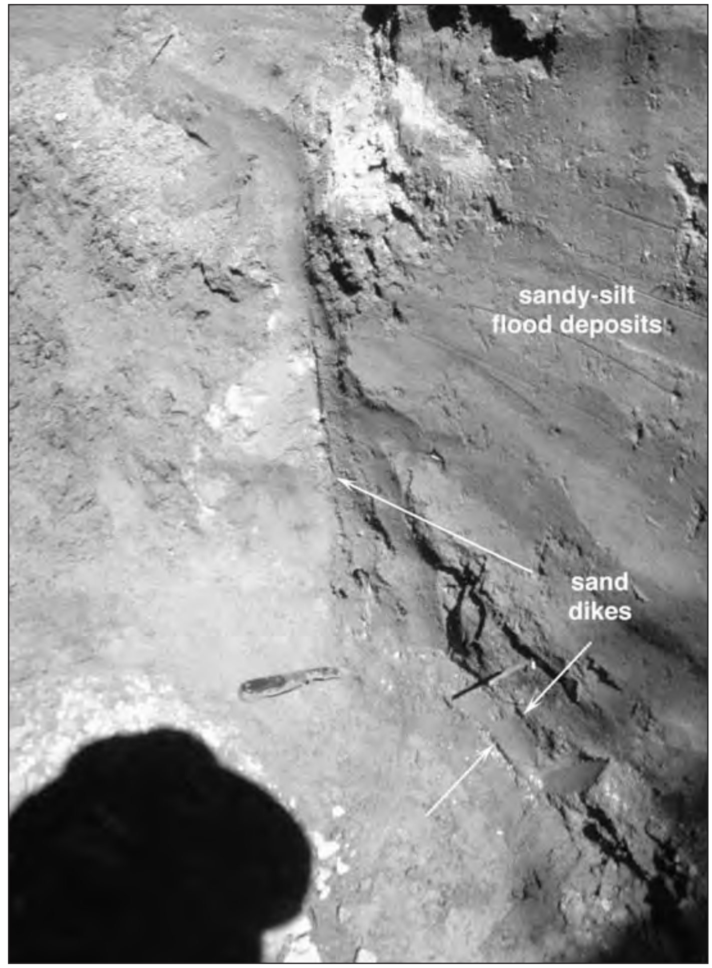

Figure 8. The sand dike cuts sandy flood silt in the flood plain of the North Fork Nooksack River. The site is located adjacent to the Racehorse Creek rock slide–debris avalanche deposit in sec. 10, T5E, R39N. The largest dike shown (near bottom) strikes N70°E and dips 73° to the north-northwest. Pen knife is shown for scale.

tonalite and granodiorite of the Jordan Lakes pluton blocked Otter Creek, a tributary of Illabot Creek. We obtained radiocarbon ages of 450 ±50, 610 ±50, and 390 ±60 yr B.P. on subfossil trees having no bark and rooted below the mean high water line of the lake (Fig. 9; Table 1). Sample SLL-92-1 was taken from the same tree as sample SLL-1; hence, we use the younger of the two sample ages. We infer that the avalanche occurred about 400 radiocarbon years ago, or slightly later, because, although erosion of the tree appeared to be minimal, an unknown number of rings could be missing from the outside of the trees.

DAY LAKE

Day Lake (elev. 487 m) was created when a large rock slide consisting of Darrington Phyllite from Coal Mountain (Tabor and others, 1988) blocked Day Creek, a tributary of the Skagit River (Figs. 1, 10). Tabor and his associates mapped large incipient block slides in the phyllite adjacent to the rock slide deposit on both its northern and southern flanks.

We obtained ^{14}C dates of 1,650 ±60 and 1,850 ±50 yr B.P. from outer rings of western redcedar(?) snags that protruded above the surface of Day Lake. We infer that at least 100 and probably as many as several hundred rings may be missing from the outside of these snags, which would make these ages maximum.

Day Lake is located only 9 km north-northeast of Lake Cavanaugh, where Naugler and others (1996) have inferred postglacial, possibly recent fault rupture(s) and sediment deformation using high-resolution seismic imaging. Naugler and her coauthors thought that the faulting at Lake Cavanaugh could have been associated with the nearby Darrington–Devils Mountain Fault Zone (DDMFZ) (Fig. 1). Indeed, the large size of the Day Lake rock slide and its proximity to the DDMFZ, defined by Tabor and others (1988) and Tabor (1994), and to Lake Cavanaugh indicate that Day Lake may record relatively recent movement on the DDMFZ or another nearby fault. We infer that our radiocarbon age of 1,650 yr B.P. is a reasonable maximum age for the Day Lake rock slide.

PACKWOOD LAKE

Packwood Lake (elev. 871 m) was formed when a large rock slide from Snyder Mountain blocked Lake Creek (Fig. 1). Swanson (1996) noted that the slide consists of volcaniclastic and intrusive rocks of Tertiary age and andesitic lavas from the Pleistocene Goat Rocks volcano. Swanson estimated that the slide covered 5.5 km^2 and may have a volume as great as 1 km^3.

We obtained radiocarbon ages of 970 ±60 and 1,140 ±60 yr B.P. on the wood from the outer parts of two snags protruding above the surface of the lake (Table 1). No bark was observed, so an unknown number of outer rings could be missing from the snags. Thus, we interpret the 970 yr age to represent a maximum age estimate for the Packwood Lake rock slide.

Swanson (1996) mapped a laminated mud deposit upstream of the lake and higher than its present water level. His interpretation is that the muds provide evidence of a higher lake level. Swanson also noted that the landslide "...eventually transformed into a debris flow that doubtless reached the Cowlitz River", about 7 km to the northwest. Alternatively, the debris flow could have been triggered later than the original rock slide when the lake that had been dammed to a higher level breached the dam and cut its channel to a new lower level (now maintained by an engineered dam).

GLACIER LAKE

Glacier Lake (elev. 886 m), about 9 km SE of Packwood and less than 4 km southeast of Packwood Lake, was created by a rock avalanche of volcaniclastic rocks from Angry Mountain (Fig. 1). Swanson (1996) described this landslide and the history of the lake. As at Packwood Lake, Swanson found laminated silts that he thought had been deposited when lake levels were higher than at present.

At a time of low water level, we obtained wood from a snag (GL-2) rooted in the lake bed about 11 m below the maximum annual lake level. The radiocarbon age of the sample was 660 ±60 yr B.P. (Table 1). Because no bark was on the snag and we do not know how many rings could be missing, we regard the 660 yr age as reasonable maximum age of the rock slide avalanche that created Glacier Lake.

Both the Packwood Lake rock slide and the Glacier Lake rock avalanche are located within 20 km of the epicenters of historic earthquakes in the shallow crust including the southern end of the West Rainier seismic zone (Stanley and others, 1996; Moran, 1997) (Fig. 1). These landslides are also fairly close to a diffuse, northeast-trending area of seismicity that Finn and Stanley (1997) described as a stepover from the Saint Helens zone to the West Rainier zone and to northeast-trending faults that were inferred from aeromagnetic lineaments. (See fig. 2 of Finn and Stanley, 1997.) The Packwood Lake and Glacier Lake landslides may record earthquake activity associated with one of these identified active fault zones or on another nearby fault. The similarity of the Glacier Lake radiocarbon age and that of the Electron Mudflow (550 yr B.P.) (Crandell, 1971; Scott and others, 1995; Pringle, unpub. data) from Mount Rainier is intriguing.

DISCUSSION

Accurate estimates of the ages of ancient landslides and earthquakes depend in large part on correct interpretation of the condition of subfossil wood material preserved by the deposits of landslide-dammed lakes. Wood decay is commonly compartmentalized in gymnosperms (Shigo, 1979), and decayed wood can separate or exfoliate along zones of rot that follow growth-ring boundaries. As a result, a subfossil tree that has lost an outer layer or layers can appear as if only the bark had been removed. Likewise, the outer surfaces of drowned trees that have decomposed above the surface of a lake can look as if they were close to bark even after several hundred rings have been removed. For example, we calculated that the outermost slab of wood that had been eroded from the Douglas fir noted above (samples mbr and CMA-92-2) consisted of 276 rings but was only 122 mm thick. Similar problems were encountered in studies by the authors in the Olympic Mountains at Lower Dry Bed Lake, where about 240 rings

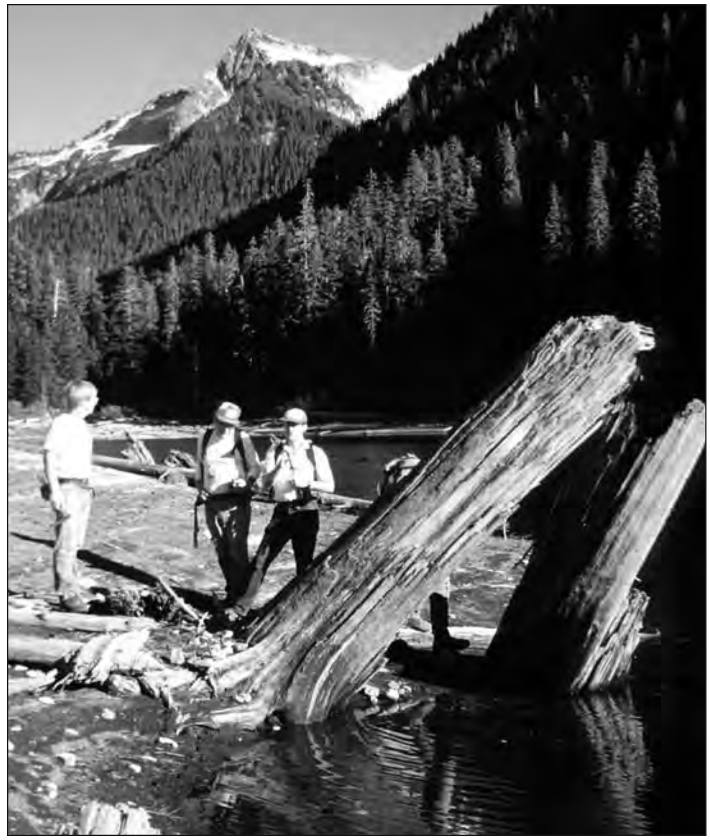

Figure 9. View to the east of two trees sampled for radiocarbon ages at Slide Lake. The tops of both trees are below the mean high water level of the lake. Snowking Mountain is in the distance

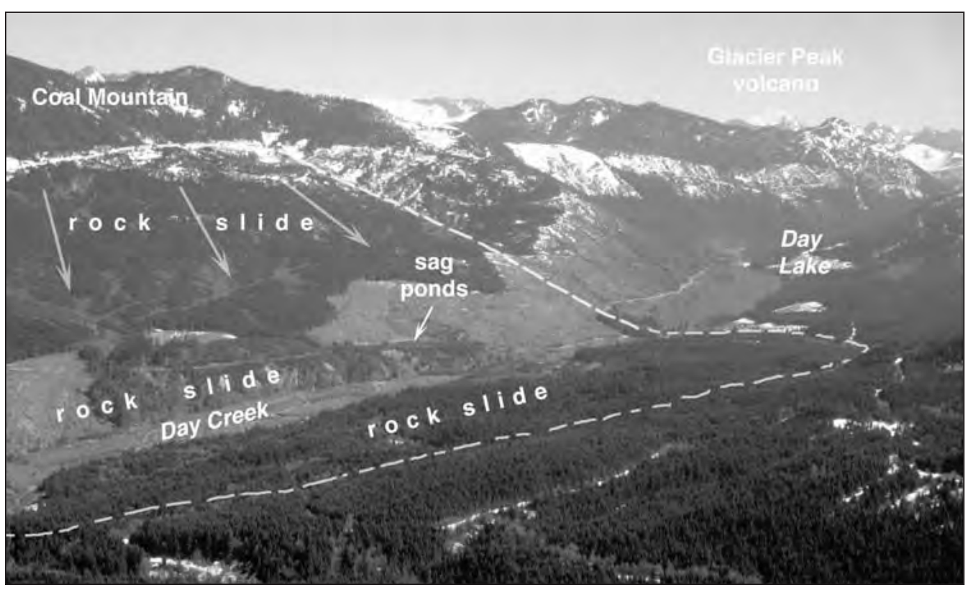

Figure 10. Aerial-oblique view to the southeast of Day Lake rock slide and Day Lake. The boundary of the rock slide is shown by a dashed line. Flow of Day Creek is to the lower left.

(154 mm) were missing from a rooted subfossil tree where it protruded above the mud, and at Lena Lake, where initial radiocarbon ages on protruding snags were more than 200 years "older" than those ages taken from wood adjacent to bark that were exposed at lower lake levels. As a result, care must be taken when seeking radiometric ages of subfossil trees, particularly those buried by energetic debris flows and debris avalanches or those protruding above lakes, in order to find bark and (or) sapwood on the tree if possible. If subfossil wood is not rooted, then its relative state of decay may also be important for determining if the tree was living at the time of the event that killed it.

Carpenter (1993) averaged radiocarbon ages spanning several hundred years for the Church Mountain rock slide–debris avalanche. Carpenter's averaging of samples mbr, mbr2, and gal (Table 1) would be justified only if the wood samples were presumed to be the same age (the same distance from bark on trees killed by the landslide). However, our new radiocarbon data (both 2,340 yr B.P.) for the Church Mountain rock slide–debris avalanche indicate that the wide range in ages noted above is likely caused by sample age disparity, possibly due to the wood decay and (or) exfoliation. In such cases, most confidence should be placed in the youngest sample age instead of averaged values if the standard deviation of the youngest sample(s) constrains the age more effectively.

SUMMARY

Our radiocarbon ages on subfossil trees record the timing of eight probably coseismic major landslides in the Cascade Range. The proximity of these landslides to shallow-crustal faults or seismic zones provides additional evidence that shallow-crustal faults may well have been active during the past few thousand years. Our new age estimate of about 2,340 yr B.P. for the Church Mountain debris avalanche allows more accurate correlation of this landslide with other proxy indicators of seismicity, such as a nearby (but unspecified) rock slide noted by Engebretson and others (1996). Importantly, all of the radiocarbon data presented herein provide age estimates for probable abrupt tectonic displacements in the Cascade Range during the Holocene.

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The Sloth, the President, and the Airport

H. Gregory McDonald
Hagerman Fossil Beds National Monument
Hagerman, ID 83332

I'm probably the only person who flies into SeaTac International Airport and watches the runway closely, wondering if I'm landing on or passing over "The Site" as the plane touches down. The site I'm referring to is at the base of anchor 4B of FAA Approach Lighting System No. 1 at the north end of the airport, so I hope my plane will never actually land right there. But still it's fun to try to spot it as the plane descends.

What makes this particular site of interest to me is the discovery made there in February 1961. While excavating for anchor 4B, Gordon Simmons, an employee of Sellin Construction Company in Seattle, spotted some bones sticking out of the peat in the bottom of the 14-foot hole. Further investigation turned up additional bones, and Stan Mallory of the University of Washington, along with John Lindquist of the Burke Museum and some students, spent seven days recovering most of the skeleton of the animal, which was added to the paleontology collections of the Burke Museum.

Although the skull and jaw were not recovered, examination of the bones—the distinctive basin-shaped pelvis measuring 45 inches across and massive limb bones plus large claws, indicating an animal the size of a small cow—permitted Dr. Mallory to identify the animal as the extinct ground sloth, *Megalonyx jeffersonii*. This was the first and still the only record of *Megalonyx jeffersonii* from Washington, although an earlier ancestral species, *Megalonyx leptostomus*, is known from the largely Pliocene Ringold Formation. Eventually the skeleton was reconstructed and is today on display at the Burke Museum (Fig. 1). Radiocarbon-14 dates of the peat it was entombed in indicate that the animal lived in the area about 12,600 to 12,760 years ago.

What's my interest in this discovery? Actually, I don't enter the picture until 1975 when I was working on the North American ground sloth, *Megalonyx*, as the topic for my master's degree at the University of Florida. I quickly discovered that while many museum collections have individual bones and isolated teeth of this sloth, skeletons, even partial ones, were rare. When I heard there was a partial skeleton of *Megalonyx* at the Burke Museum, it was a must for me to see it as part of my research. During the summer of 1975, I made a sloth road trip, visiting museums for my research, and ended up in Seattle.

Despite the amount of territory covered that summer, I traveled through only a small portion of the North American continent where remains have been found. *Megalonyx* is known from sites as far north as Alaska and the Yukon, as far south as southern Mexico, and from coast to coast—Florida, including the Atlantic continental shelf, to Washington. Like the SeaTac specimen, many remains of *Megalonyx* have been found in peat deposits—in fact, three of the fairly complete skeletons of *Megalonyx* came from peat bogs. But *Megalonyx* remains have been preserved in a variety of situations—tar pits, caves, sinkholes, and sands and gravels. This makes sense when one considers that the widespread distribution of the animal might present opportunities for being preserved in a variety of depositional environments.

The first specimen of *Megalonyx* was found in 1796 during saltpeter mining in a cave in what is now West Virginia. The few bones found—the forearm (ulna and radius) and a few bones of the "hand", including the claws—were sent to Thomas Jefferson. Jefferson was interested in the natural history of Virginia, and in 1797, presented a paper to the American Philosophical Society on the sloth discovery. The large size of the claw impressed Jefferson, so he proposed the name *Megalonyx* (great claw) for the animal. The size of the claw suggested to Jefferson that the remains were of a large cat, perhaps a lion. While Jefferson speculated on the significance of the discovery, the detailed anatomical descriptions of the bones were done by Jefferson's friend Caspar Wistar in an accompanying paper.

Publication of Jefferson's paper was delayed, and during this time, he read about the discovery in Argentina of a huge beast, related to living tree sloths, called *Megatherium*. Jefferson recognized the similarity between his *Megalonyx* and the *Megatherium*, and in a footnote to his paper, finally published in 1799, corrected his original supposition that the bones were of a large lion. Later the specific name *jeffersonii* was proposed by the French paleontologist Desmarest to honor Jefferson's contribution, and we now know the late Pleistocene species as *Megalonyx jeffersonii*.

Although we think of *Megalonyx* as a North American ground sloth, it is actually descended from a group that originated in South America. Sloths, along with their close relatives the anteaters and armadillos, underwent most of their evolutionary history in South America while it was an isolated island continent. The North American part of their history starts about 9 million years ago. At this time the Isthmus of Panama did not exist, but the gap between North and South America was filling with small volcanic islands. Apparently a small ground sloth *Pliometanastes*, the ancestor to *Megalonyx,* was able to island-hop into North America. As far as we know, this was the first species of South American origin to enter the North American continent in the Tertiary. As the islands merged into the Isthmus of Panama, *Megalonyx*, which evolved in North America, was joined by other species, such as opossum, armadillo, porcupine, and other sloths. All of these animals added to the diversity of the North American mammalian fauna, but *Megalonyx* has the longest record, surviving until the wave of Pleistocene extinctions 10,000 to 11,000 years ago.

There is some speculation as to why *Megalonyx* (as well as the other sloths) was so successful. The North American mammalian fauna included lots of herbivores, so one can assume that most niches were filled and the competition was tough. While we will never know with certainty why *Megalonyx* was so successful, as a browser its ecology must have been sufficiently different to allow it to exploit habitats and food not utilized by other herbivores. Although the dung of another ground sloth, *Nothrotheriops*, has been recovered from dry caves in the southwestern United States, we have no such direct evidence for the diet of *Megalonyx*. Examination of the enlarged front teeth indicate that they functioned to cut and crop leaves and twigs. The large claws, which so impressed Jefferson, were probably useful in defense against large predators like saber-toothed cats and dire wolves but, like those of modern tree

Figure 1. The SeaTac sloth, displayed at the Burke Museum in Seattle, stands about 5 feet at the shoulder and was clearly not built for speed. **A**. *(top left)* Skull of this *Megalonyx*, about 1 foot long from front to back. Note the large simple teeth at the front. These are characteristic of the family Megalonychidae and were adapted for grabbing and stripping twigs and leaves from branches that the animal hooked with the big claws and brought to its mouth. **B.** *(top right)* Right front leg. Note the in-turned foot. Ground sloths, like the living giant anteater, supported themselves on the back edge of their front claws. These large claws inspired the generic name "great claw". At the left of this photo are two claws of the right hind foot; the claw on the third toe is the largest. **C.** *(bottom left)* Skeleton from the rear. Note the wide upper leg bone (femur) and the extension of the heel bone (calcaneum), also characteristic of this family. Fusion of the bones of the lower back (sacrum) to the pelvis and of the first few tail vertebrae make up an intricate structure known as the synsacrum, a feature found in all sloths and their relatives, the armadillos and anteaters. The wide pelvis provided an enlarged area for attachment of the hip muscles, which allowed the sloth to sit in an upright position. **D.** *(bottom right)* The sloth is shielded by plexiglass. Behind the skeleton is an artist's concept of how the sloth might have looked when "standing", perhaps in a defensive pose or preparing for a meal.

sloths, were mostly used to hook branches of bushes and small trees during feeding. The preferred habitat seems to have been forests, and while *Megalonyx jeffersonii* was widespread, its remains are more common in the eastern United States, which had extensive forests during the Pleistocene. In sites farther west, such as the Great Plains, it is typically found in deposits associated with river systems. *Megalonyx* may have been inhabiting the gallery forests along the rivers.

Because the Puget Lowland, including what is now SeaTac airport, was under ice 15,000 years ago, our sloth, as well as the rest of the Pleistocene fauna with which it is associated—mammoth, mastodon, musk ox, and bison—must have inhabited the region farther south. As the ice sheet melted and the landscape became habitable, *Megalonyx*, along with other members of the Pleistocene fauna, moved into the area. The melting glaciers produced water to fill the proglacial lakes, such as Lake Russell, that were soon surrounded by trees and other vegetation. The recovery of the SeaTac *Megalonyx* from peat dated to 12,000 years ago certainly indicates that habitat appropriate to support large herbivores existed by this time.

So the next time you fly into SeaTac and are gazing out the window, don't just watch the asphalt runway as it approaches, see if you can spot anchor 4B of FAA Approach Lighting System No. 1. Let your mind wander back 12,000 years and imagine the SeaTac *Megalonyx* pausing from munching leaves to watch you touch down.

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The Iowa Museum of Natural History *Megalonyx* reconstruction can be seen on the Internet at: http://www.museum.state.il.us/exhibits/larson/sloth.html. Hagerman Fossil Beds National Monument can be reached on the Internet at: www.ohwy.com/id/h/hagefbnm.htm.

MAMMOTH IS NOW STATE FOSSIL

The Columbian mammoth (*Mammuthus columbi*) became the official state fossil on March 25 when Gov. Gary Locke signed the bill into law. The mammoth roamed the state more than 10,000 years ago, eating pine cones, pine needles, and grass. Its preserved remains are found from the Palouse to Port Orchard. The herbivore weighed about 7 tons and was 11 to 15 feet tall.

The bill was the brainchild of Chris Pineo, 11, a fifth grader at Windsor Elementary School near Spokane. Four years ago, Chris' second grade class read a book dedicated to a class in Colorado who discovered their state lacked a state fossil, selected one, and got their Legislature to adopt it. Chris figured that if a class in Colorado could do it, so could he and his friends. With the help of their teacher, Sara Aebly, the students researched a suitable fossil after talking to university professors.

Through the third and fourth grades, Chris and his classmates persisted and contacted Rep. Larry Sheahan, R-Spokane, who agreed to introduce a bill in 1997 that would make the fossil official.

Even though Chris testified on behalf of the bill, he and his friends discovered they had competition. An elementary school class in Kent was pushing a bill designating the common green darner dragonfly as the official state insect. The mammoth bill died, but the insect bill was signed into law last year.

But since the bill had already been approved by the House last year, it was a simple matter to resurrect it and send it back to the Senate this year. With backing from Lt. Gov. Brad Owen, the bill was passed and sent to Locke to be signed. Chris and his friends are relieved and gratified.

"It takes a long time," Chris said of the process. "I didn't know how many steps it would have to go through."

Dale Aebly, the students' fifth grade teacher and husband of Sara Aebly, who helped launch the project, said he used student interest in the project as a teaching tool for geology, history, politics, math, and science.

NORTHWEST GEOLOGICAL SOCIETY NEWS

The Northwest Geological Society is an organization of geologists in the public and private sector, professors, students, retirees, and those interested in geology. Membership is $20/year ($5 for students). Mail checks to Donn Charnley, 19344 11th Ave NW, Shoreline, WA 98177-2613.

NWGS meets the second Tuesday of each month from October through May at the University Plaza Hotel, 400 NE 45th St., on the west side of I-5; take the first exit north of the Ship Canal Bridge. Attend the 7:30 p.m. post-dinner speeches free, or come at 5:30 for the social hour and dinner ($17). Reservations for dinner must be sent in by the Thursday preceding the meeting.

NWGS welcomes resumes, literature, and posters by attendees at the meetings. There is display space for these items. The Washington Division of Geology and Earth Resources regularly brings literature for browsing or handouts.

Dave Knoblach, current NWGS president, is a geologist with GeoEngineers. Steve Grupp, the new President-Elect, is project geophysicist at Associated Earth Sciences in Kirkland and part-time professor of Geology at Edmonds Community College.

On May 12, Kathy Troost of Shannon & Wilson will speak on the geology of Tacoma. This will be a joint meeting with the Association of Engineering Geologists (local chapter) and feature a student poster session from area universities/colleges. A $50 award for the best student poster will be presented at the meeting.

NWGS offers field trips (for members only) in June and September.

Volunteers Monitor Puget Sound Beaches

If you enjoy geology, zoology, and beach walks, why not join an organization like the Washington State University-affiliated Beach Watchers of Island County in their efforts to inventory and evaluate beach processes and educate citizens about Puget Sound's coastal environment? There are currently 125 active, trained Beach Watcher volunteers in Island County, with a new class of 22 volunteer trainees preparing to graduate in April 1998. A corps of 48 of these trained Beach Watchers measures beach profiles, makes quantitative analysis of living organisms, takes photographs, and keeps logs of their activities and findings. Twenty-six beach sites are currently monitored. The volunteers are also monitoring erosion rates, a critical but generally missing element in the wise design of residential development along shoreline bluffs. The data they gather at the sites will constitute a long-term information base.

Figure 1. Volunteers learn to deal with one of the hazards of beach work—the wind. At this stop off Libbey Road, the challenge is to measure the distance from a certain point on a large boulder (just out of sight to the left) to a point on the bluff that they can revisit to determine if the bluff is retreating.

Because the coastline is the extension of upland areas, knowledge of processes that are active above the beach is also important. Similarly, understanding the mammals, birds, fish, and invertebrates that live near or on the beach enhances the stewardship function. The Washington State University Extension Education Center offers instruction in, among other topics, aquaculture, bluff erosion, septic systems, geology and glaciation, native plants, and coastal processes. Instructors include master gardeners, consultants, and university and county employees. Some instructors are graduate Beach Watchers or come from the ranks of other organizations, such as the Waste Warriors.

WSU Beach Watcher volunteer trainees attend 100 hours of class and field training to prepare them for basic data-gathering and spreading the message about methods of avoiding damage to or disturbance of the beach habitat.

Field trips give the volunteer monitors hands-on training and experience. A field session last year drew on the expertise of volunteer teachers Jim Johannessen of Coastal Geologic Services, Hugh Shipman of the Washington Department of Ecology, and Gerald Thorsen, a consultant geologist in Port Townsend. Class participants walked several beaches to learn about bluff geology and beach morphology and how they are related, how to measure beach erosion, and what features make good monitoring points (Fig. 1).

Volunteers are checking the east side of Greenbank, the south side of Lagoon Point, and Windmill Heights (south of Bush Point), all in the southern part of Whidbey Island, for bluff erosion. These three sites are just starting to generate information.

Figure 2. The picturesque Beach Watchers headquarters, the lighthouse in Fort Casey State Park.

Among the sites with a more biological focus are the popular Rosario Beach tidepools in Deception Pass State Park. Because 20 school-busloads of students may visit this area in a single day, Beach Watchers explain the fragility of the area before the youngsters and teachers even get to the pools. In 1995, volunteers set up a succession of 30 quarter-meter areas in which they count all species of animals and seaweeds. With three years' worth of these data (from about 300 hours of labor annually) and other information, the park management can determine the effects of trampling and heavy use by visitors and an appropriate level of traffic.

Workshops are held from time to time. On January 31, 1998, more than 200 citizens and volunteers interested in coastal ecology and conservation gathered at the middle school in Coupeville for a full day of courses. Kelley Balcomb-Bartok of the Center for Whale Research in Friday Harbor gave the keynote speech, about orcas. Concurrent sessions led attendees through 15 topics, from slugs to salmon, from estuaries to nature mapping. At other times of the year, evening sessions for Beach Watchers and community members offer opportunities to identify beach species and cover many other subjects as well.

Free services offered by these well prepared volunteers now include talks at schools, on Washington ferries, at state parks, and at the Penn Cove Water Festival in Coupeville on May 9, 1998. Water-quality testing can also be arranged.

The Beach Watchers program is sponsored by Washington State University and administered by Island County's WSU Cooperative Extension Education Center. Funding to date has been through grants from the Department of Ecology and Texaco. Other sponsors are the Washington State Parks and Recreation Commission and the National Oceanic and Atmospheric Administration. Under the new nonprofit umbrella of the Lighthouse Environmental Programs, the Beach Watchers and sister programs are applying for other kinds of grants. Several fundraising events are also planned.

New volunteers for beach monitoring are warmly welcomed by Susan Berta, the program coordinator. The program is housed at the Admiralty Head Lighthouse (Fig. 2; see previous page) in Fort Casey State Park. Susan can be reached at WSU Beach Watchers, PO Box 5000, Coupeville, WA 98239; 360-679-7391, or bertas@wsu.edu. The organization also has a web page at www. island.wsu.edu. A monthly newsletter, Beach Log, goes out to volunteers and other organizations.

With the widespread interest in the natural history of beaches and development of coastal land, other shoreline counties might be interested in starting a similar program and benefit from learning about the evolution of the Beach Watchers. ■

Project Impact

On February 5, Seattle became one of seven cities nationwide to be designated a "disaster-resistant" pilot community. The designation is part of "Project Impact—Building a disaster resistant community", sponsored by the Federal Emergency Management Agency and supported by a grant of $1 million. The tenets of this new project are that mitigation is a local issue, that private-sector involvement is essential, and that mitigation requires long-term effort and investment.

At Phinney community hall, (*from right*) James Lee Witt, Director of FEMA, Robert Freitag, Seattle Project Impact coordinator, and David de Courcy, Regional Director, FEMA Region X, listen as Roger Faris explains how the WellHome program encourages citizens to retrofit their homes using tools borrowed from the Phinney Neighborhood Association's tool library.

Seattle has joined the Contingency Planning and Recovery Management organization in taking advantage of the opportunity to protect city residents and facilities through this FEMA project. Local citizens, neighborhood organizations, businesses such as insurance companies and banks, universities, and state and local government agencies are developing a partnership to undertake home retrofitting and mapping projects to designate areas vulnerable to landslides and earthquake damage.

FEMA Director James Lee Witt and state and local officials gathered at the Burke Museum on the University of Washington campus on February 4 to kick off the project. A meeting was held the following day at the Phinney Neighborhood Association facilities on Dayton Avenue North.

Seattle's Office of Emergency Management will coordinate the project and manage the funding. By the end of January, $6 million had been pledged in matching support for the FEMA grant. About half this amount will likely be spent on schools.

Participants in this project will first develop and then implement an action plan. Components of the plan include:

- Creating and putting into effect a residential retrofitting program through education, financial incentives, and accelerating the permit process.
- Improving school safety by removing nonstructural hazards and investigating advantages of installing automatic gas shutoff valves.
- Undertaking earthquake mapping to identify areas where amplified ground shaking is expected, the distribution of liquefiable materials, and areas of high hazards in Seattle.
- Developing digital hazards maps that can guide efforts to minimize effects of weather-generated threats to the city.

The U.S. Geological Survey will develop the earthquake hazards map. They will be updating the current geologic map of Seattle and continue to collect strong ground motion data, working with the Seattle area's geotechnical businesses to be sure there is information for all local soil types.

The USGS, the Seattle Public Utilities Geographic Systems group, and Shannon and Wilson will inventory the recent (1997 and current) landslide areas, using extensive historical records to create digital files and maps. When these data are combined with rainfall records (particularly return periods) and geotechnical properties of soils, a probabilistic map of landslides can be developed, and perhaps forecasts of probable landslide activity.

Washington's geological survey, the Division of Geology and Earth Resources, is also involved in Project Impact. DGER will prepare earthquake-induced liquefaction susceptibility maps for areas east of Seattle. DGER will also conduct a pilot earthquake loss estimation study of transportation infrastructure in and near the Kent Valley. Additionally, the division will provide technical support for the landslide mapping project and compile bibliographies from its library collection of maps and literature for the region.

Representing Lands Commissioner Jennifer Belcher, Amy Bell, the Department of Natural Resources' Deputy Manager for Resource Protection, signed the agreement on behalf of Commissioner Belcher.

Eric Holdeman (left), manager of King County's Emergency Management Division, looks on as Tim Walsh shows DGER's poster presentation on the causes and impacts of the winter 1996–97 rain-on-snow-triggered landslides in Seattle.

Other signatories included Seattle Mayor Paul Schell, Superintendent of Schools John Stanford, King County Executive Ron Sims, Director of Washington's Emergency Management Division Linda Burton-Ramsey, Director of the Federal Emergency Management Agency James Lee Witt, Coordinator of the U.S. Geological Survey's Earthquake Hazards Program, John Filson, the president of the Cascadia Region Earthquake Workgroup, Jack Bernhardsen, as well as representatives from state and county labor councils, the Red Cross, Master Builders Association, bank and insurance company managers, the executive director of the Seattle Port Authority, and leaders of community councils. ■

KRAKAUER WINS SULLIVAN AWARD

At its December meeting in San Francisco, California, the American Geophysical Union presented the Walter Sullivan Award for Excellence in Science Journalism to Jon Krakauer of Seattle. This award recognizes excellence in science reporting in a single article or radio/television report. Jon was recognized for his article "Geologists worry about the dangers of 'living under the volcano'" that appeared in the July 1996 issue of *Smithsonian* magazine. Excerpts from the citation follow:

Through Jon's acute journalistic vision, we learn of the connection between clumps of reddish brown rock that cling to the spikes of a climber's crampons and the geology of lahars—"flash floods of semiliquid mud, rock and ice that surge down from the heights with terrifying speed and destructive power...." We discover that at least 60 lahars have roared down from Mount Rainier in the past 10,000 years, some carrying massive debris flows all the way to Puget Sound, more than 50 miles from the mountain. We also find that this hydrothermally altered rock is an external expression of a blistering reaction between geothermal aquifers and acidic sulfur-bearing gases that is eroding Mount Rainier from the inside out. In the words of geologist Kevin Scott, "the entire edifice of the mountain is stewing in its own chemical juices and as a consequence it's becoming increasingly rotten and unstable."

Jack Wiley, Jon's editor at *Smithsonia*n, had this to say about Jon's entry. "Starting at the top of the mountain, Jon Krakauer explains what is happening inside Mount Rainier and why it could result in a catastrophe, without the volcano actually erupting. He discusses the lahar that destroyed much of Armero, Colombia, and how an earthquake, a volcanic event, or simply the collapse of a 'rotted' rock could trigger one on Rainier. Geologists and public officials worry about the best ways to protect the 100,000 people living on top of past mud slides. The article is both dramatic science and public service.

Jon learned to climb at the age of eight, and he climbed Mount Rainier for the first time 2 years later. He has climbed Mount Rainier many times since, but "had little idea of the hazards posed by its geologic instability" until *Smithsonian* magazine asked him to write this story. We are indebted to Jon for his ability to weave the human experience together with our current knowledge of geophysics in a highly readable and understandable manner. The story also reminds us of the necessity of conveying our science to public officials and the public so they can take appropriate steps to mitigate future losses from rare but extreme geophysical hazards.

John Sanders, American Geophysical Union, Washington D.C.

In his acceptance speech, Jon said, "I am indebted to the members of the geophysical community who put up with a barrage of stupid questions and generously shared their expertise: Kevin M. Scott, David R. Zimbelman, Thomas W. Sisson, James W. Vallance, Carolyn L. Driedger, Paul Kennard, Patrick T. Pringle [Divn. of Geology and Earth Resources], Stephen D. Malone, Donald A. Swanson, and Jonathan Swinchatt."

Modified from Eos, v. 79, no. 6, p. 71

BOOK REVIEW: Fire, Faults, & Floods—A Road and Trail Guide Exploring the Origins of the Columbia River Basin

by Marge and Ted Mueller, 1997.
Available from University of Idaho Press,
16 Brink Hall, Moscow, ID 83844-1107;
800-847-7377 (order phone); 208-885-9059 (fax);
Paperback, 5½ x 8½ in., 288 p.; $19.95 + $4.00 shipping.

This book is a fine choice for anyone interested in learning more about the geologic features of the Columbia Basin. The book presents the story of the Columbia River Basalt Group and the Spokane (Lake Missoula or Bretz) floods. Although it is designed as a field trip guidebook, it serves well as a basic text. The book is very entertaining and informative whether one takes the field trips or not. The authors are not geologists and have prepared the book for a general audience.

The book is divided into a preface, an introduction, and 10 chapters, each containing several field trips in the same general geographic area, followed by a glossary, a bibliography, and an index. The chapters are titled:

1. The Washington–Oregon–Idaho border, the source dikes and vents for the Columbia River basalt flows
2. Hamilton, Montana, to Sandpoint, Idaho, the basin filled by glacial Lake Missoula
3. Spokane to Pasco, Washington, the Cheney–Pasco scabland corridor
4. Spokane to Ephrata, Washington, the upper Crab Creek flood channel
5. Grand Coulee Dam to Quincy, Washington, the Grand Coulee and other northwest flood channels
6. Quincy to Vantage, Washington, the middle Columbia River drainage
7. Moses Lake to Richland, Washington, lower Crab Creek and the Yakima fold belt
8. North-central Oregon, the Picture Gorge Basalt Subgroup of the Columbia River basalts
9. Biggs to Portland, Oregon, the Columbia River Gorge
10. The Oregon coast, the Columbia River basalt flows meet the ocean.

The preface tells how to use the book and how the authors came to write it. It also provides notes on trail hiking, hazards, and safety, and where to get more maps of various kinds.

In the introduction, the authors present and develop three themes: plate tectonics, the eruption of the Columbia River Basalt Group, and the Spokane floods.

Each chapter begins with a brief description of the field trips and a map showing all of the trip routes and major topographic and cultural features. Each field trip can be run easily in a few hours. Neighboring field trips can be run consecutively if more time is available. Thorough driving instructions and good road maps help make this easy.

Each field trip begins with a few bulleted sentences that tell what geologic features are to be seen on the trip. Then the authors list tourist facilities in the area and give a drive overview. They present the field trip as smoothly flowing text with illustrations, rather than the elapsed-mileage format to which most geologists are accustomed. Maps, photographs, drawings, and copious geographic references in the text make the reader completely comfortable with regard to spatial context. This format is evidence of the careful planning of this book, and is probably the prime reason it is such fun to read.

The glossary, bibliography, and index are all standard and offer no surprises. They, like the rest of the book, are well done. The bibliography is thorough and complete.

Fire, Faults, & Floods is thoroughly and accurately researched, carefully organized, written for the nongeologist but also fun for the geologist, filled with beautiful illustrations (the only thing to wish for is color; except for the cover, the whole book is printed in black and white), and very well edited (for example, J Harlen Bretz' name is written without a period following the "J", as it should be, for he had no first name). This book will make a great addition to the library of anyone who is interested in the natural history of the Pacific Northwest, and it will make you long to take the field trips. Like any good book, if you pick it up, you won't want to put it down.

J. Eric Schuster

EDUCATORS – WE NEED TO HEAR FROM YOU!

The winter issue of *Washington Geology* will focus on geoscience education. We are looking for good materials to include in our teachers' packet. Do you have information about:

- simple demonstrations or projects presented as easily reproduced designs or templates suitable for use in a classroom or for a gathering of adults?
- valuable resources, activity books, or techniques you would like to share?

Your contributions will become the core lists of these resources or articles that we'll publish in this journal or include in our teachers' packet. Please send us short synopses or spare copies of your how-to's and citations for useful resources. Our addresses are on page 2.

EARTH SCIENCE WEEK, OCT. 11–17

The American Geological Institute is sponsoring Earth Science Week, October 11–16, 1998, to:

- Give students new opportunities to discover the earth sciences
- Publicize the message that earth science is all around us
- Encourage stewardship of the Earth
- Share knowledge and enthusiasm about the Earth

Geoscientists will lead field trips, visit classrooms, conduct seminars, create special exhibits, give talks, work with scout and youth groups, and much more.

To obtain an Earth Science Week information kit, contact the American Geological Institute, 4220 King St., Alexandria, VA 22302, 703-379-2480, 703-379-7563 (fax), or visit their website at www.earthsciweek.org.

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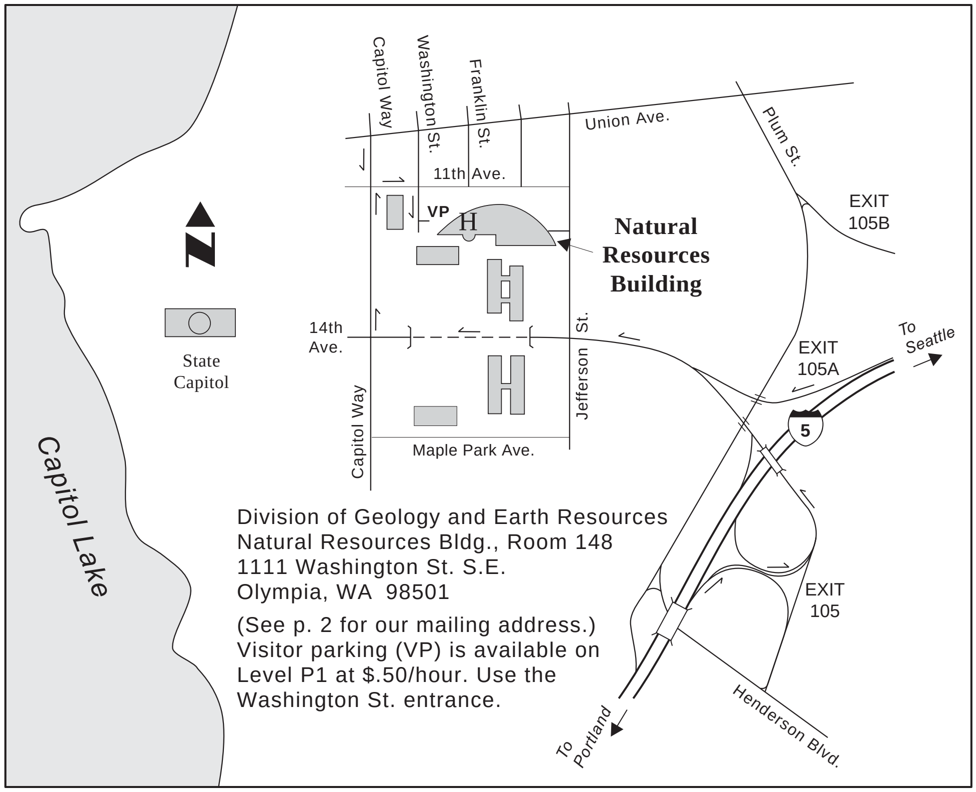
DOGAMI RELEASES TSUNAMI HAZARD MAPS

The Oregon Department of Geology and Mineral Industries has released tsunami hazard maps for these 7.5-minute quadrangles along the Oregon coast:

Astoria quad., Clatsop Co. (O-95-10)
Bandon quad., Coos Co. (O-95-51)

Bill Peak quad., Coos Co. (O-95-52)
Brookings quad., Curry Co. (O-95-65)
Bullards quad., Coos Co. (O-95-49)
Cape Arago quad., Coos Co. (O-95-46)
Cape Blanco quad., Curry Co. (O-95-5)
Cape Sebastian quad., Curry Co. (O-95-61)
Carpenterville quad., Curry Co. (O-95-64)
Cathlamet Bay quad., Clatsop Co. (O-95-11)
Charleston quad., Coos Co. (O-95-47)
Coos Bay quad., Coos Co. (O-95-48)
Depoe Bay quad., Lincoln Co. (O-95-27)
Devils Lake quad., Lincoln Co. (O-95-26)
Empire quad., Coos Co. (O-95-44)
Floras Lake quad., Curry Co. (O-95-53)
Florence quad., Lane Co. (O-95-37)
Gearhart quad., Clatsop Co. (O-95-13)
Gold Beach quad., Curry Co. (O-95-59)
Goose Pasteur quad., Lane Co. (O-95-36)
Heceta Head quad., Lane Co. (O-95-34)
Knappa quad., Clatsop Co. (O-95-12)
Lakeside quad., Coos and Douglas Co. (O-95-43)
Langlois quad., Curry and Coos Co. (O-95-54)
Lincoln City quad., Lincoln Co. (O-95-25)
Mack Point quad., Curry Co. (O-95-63)
Mercer Lake quad., Lane Co. (O-95-35)
Mount Emily quad., Curry Co. (O-95-66)
Nehalem quad., Tillamook Co. (O-95-17)
Neskowin quad., Tillamook and Lincoln Co. (O-95-24)
Newport North quad., Lincoln Co. (O-95-28)
Newport South quad., Lincoln Co. (O-95-29)
North Bend quad., Coos Co. (O-95-45)
Olney quad., Clatsop Co. (O-95-14)
Ophir quad., Curry Co. (O-95-58)
Port Orford quad., Curry Co. (O-95-57)
Reedsport quad., Douglas Co. (O-95-32)
Riverton quad., Coos Co. (O-95-50)
Signal Buttes quad., Curry Co. (O-95-60)
Sixes quad., Curry Co. (O-95-56)
Sundown Mountain quad., Curry Co. (O-95-62)
Tahkenitch Creek quad., Douglas and Lane Co. (O-95-38)
Tidewater quad., Lincoln Co. (O-95-32)
Toledo South quad., Lincoln Co. (O-95-30)
Waldport quad., Lincoln Co. (O-95-31)
Warrenton quad., Clatsop Co. (O-95-09)
Winchester Bay quad., Douglas Co. (O-95-31)
Yachats quad., Lincoln/Lane Co. (O-95-33) ■

HOW TO FIND OUR MAIN OFFICE



NEW PRICES FOR REPRINTS OF BULLETIN 37 AND IC 60

Jon Gladwell has had to raise the price of these two documents.

Bulletin 37 (Inventory of Washington minerals—Part II, Metallic minerals): $45.95 unbound, $53.95 comb-bound, postage $5 per copy.

Information Circular 60 (The St. Helens and Washougal mining districts of the southern Cascades of Washington): $9.95 unbound (not available bound), postage $3 per copy. (Note: In our last issue this was incorrectly listed as Information Circular 61.)

Orders should be sent to Myrddin Emrys Limited, 3235 SE 56th Ave., Portland, OR 97206-2007; 503-771-4123; -3769 (fax); myrddin@zephyr.net.

FOOD FOR YOUNG MINDS *Continued from p. 2*

wires from the Highland Bell mine, British Columbia, were substituted as a precious metal, one of 33 elements and minerals used to build a computer. Then the hunt was on through the newspaper advertisements for a good picture of a computer. While looking for that, she could not help but notice all the Valentine's Day jewelry pictures. Garnet was featured by many merchants, and so a picture of a garnet-encrusted heart was matched with a red garnet crystal. Her birthday is in April, so she asked about diamonds, her birthstone. We found a chart in a book about industrial minerals, and we talked about all the uses of diamonds other than as gems. We traded questions about a candle, plastic, and other petroleum derivatives, but she decided there was no practical non-messy way to put actual oil on the poster board. And so it went.

Finally, I asked her, "How do you want to present the information?" She came up with the idea she had seen used in other exercises in her school, that is, to make up a list of sources, a list of products, and link the lists. She chose to make this a game to hand out her schoolmates to see how many they could match up correctly.

As geologists, we should constantly seek ways to help our young children learn about the world we live in. The everyday objects that surround us are starting points on the road to understanding why the Earth is so important to us. Take those opportunities to help fill curious minds. ■

DIVISION PUBLICATIONS

New Releases

Quaternary Stratigraphy and Cross Sections, Nooksack, Columbia, and Saar Creek Valleys, Kendall and Deming 7.5-minute Quadrangles, Western Whatcom County, Washington, Open File Report 97-4, by J. D. Dragovich, Andrew Dunn, K. T. Parkinson, and S. C. Kahle. 8 plates and text. $3.71 + .29 tax (for WA residents only) = $4.00. This report is based on interpretations of numerous well logs.

Geologic and Geophysical Mapping of Washington, 1984 through 1997, and Theses on the Geology of Washington, 1986 through 1997, Open File Report 98-1, compiled by C. J. Manson. 55 pages, 9 plates. Listed are 264 geologic or geophysical maps and 508 theses. This report supersedes (by updating) Open File Report 96-1; no similar report was released in 1997. $1.39 + .11 = $1.50.

Preliminary Bibliography and Index of the Geology and Mineral Resources of Washington, 1997, Open File Report 98-2, compiled by Connie Manson. In press.

Landslides of the Puget Lowland—A selective bibliography, Open File Report 98-3, compiled by C. J. Manson. 35 p., current through 1997. $.92 + .08 = $1.00.

GEOLOGIC MAPS AVAILABLE IN ARC/INFO

Arc/Info versions are available for the following 1:100,000 geologic maps: Astoria, Centralia, Chehalis River, Hood River, Ilwaco, Mount Baker, Mount St. Helens, Port Townsend, Priest Rapids, Richland, Sauk River, Seattle, Skykomish River, Snoqualmie, Spokane, Tacoma (south half), Vancouver, Westport.

We are distributing copies free on 8-mm tape. We provide the tape and ask that you send us a blank tape in return. Contact Carl Harris at 360-902-1453 for details.

We'd appreciate your giving us credit as the source of the data. The work was supported by the U.S. Geological Survey STATEMAP program, agreement 1434-HQ-96-AG-01523. More quadrangles, prepared with similar support, will be ready mid-year.

Bibliographies of Geology and Mineral Resources are now available for all Washington counties. Thirty of these are updates through 1997; nine are new compilations. They are still free in paper version (with the $1 postage and handling charge) or as WordPerfect 5.1 (DOS) files on *your* IBM formatted disc. Call us for information about file size. For addresses, see p. 2.

Best Management Practices for Reclaiming Surface Mines in Washington and Oregon, Open File Report 96-2 (revised December 1997), by D. K. Norman, P. J. Wampler, A. H. Throop, E. F. Schnitzer, and J. M. Roloff. 128 p. This second edition incorporates the suggestions of many readers, including several new diagrams and topics, and new information has been added on native plants for erosion control and slope stabilization.

Available Again. We have a small supply of the AEG Bulletin article about the geology of Seattle, thanks to the generosity of its authors, Dick Galster and Bill Laprade. If you would like a copy, send us $1 for postage and handling.

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