WASHINGTON GEOLOGY

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A retaining wall of boulders (or a rockery) under construction in the Seattle area. See related article on p. 3. Photo supplied by Associated Rockery Contractors.

WASHINGTON GEOLOGY

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Word Processing Specialist		J. Renee Christensen
Clerical Staff	Naomi Hall	Shelley Reisher Kelli Ristine
Regulatory Clerical Staff		Mary Ann Shawver

Main Office
Department of Natural Resources
Division of Geology and Earth Resources
P.O. Box 47007
Olympia, WA 98504-7007
Phone: 206/459-6372
FAX: 206/459-6380

(See map inside back cover for office location.)

Field Office
Department of Natural Resources
Division of Geology and Earth Resources
Spokane County Agricultural Center
N. 222 Havana
Spokane, WA 99202-4776
Phone: 509/533-2484
FAX: 509/533-2087

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Budget Reductions Fiscal Years 92–93

by
Raymond Lasmanis

With the slowdown of the state's economy, all activities that were normally paid for by the state's general fund have been cut back by 10 percent for the current biennium. This budget reduction applies to the geologic and regulatory programs of the Division of Geology and Earth Resources. Because discretionary expense items (such as portions of our printing and travel budgets) were removed from our budget during an earlier belt-tightening period, the current reduction is now more severely affecting staff salaries and benefits. The legislature has also instructed agencies to further reduce expenses for equipment, personal services contracts, travel, and printing by 25 percent. Cumulatively, this is having a major impact on our activity levels.

Despite these budget cuts, our long-term priorities remain unchanged. We will continue to work toward our goal of producing up-to-date geologic maps of the state at scales of 1:100,000 and 1:250,000; it is the Division's intent to preserve the highly talented state geologic map team. In addition to this ongoing geologic work, the Growth Management Act, forest practices activities, surface-mining conflicts, urban growth issues, increasing earthquake awareness, and many other related issues add to our workload while funding is being reduced.

In order to make all this possible, at least in the short term, the reduction in the level of general-fund support for salaries and benefits will have to be offset by grants and contracts. Staff members are actively seeking funding from numerous sources, from the federal government and within the state. It appears that we will be successful in this endeavor.

Wherever possible, we are seeking out contracts that will not only meet the needs of the funding organization, but will at the same time advance our state map program. However, these opportunities will be limited. As staff time is transferred to preparing products for the grants and contracts, less time can be devoted to work on the components of the map of the state's northwest quadrant. This translates into a delay in completion of this last (northwest) segment of the state geologic map.

We are cutting back at least temporarily on some of our normal functions—for example, we will publish fewer formal publications. During the next legislative session, we will be seeking increased funding for important Division programs. Despite the significant budget reductions, we remain committed to meeting our obligations, to serving our clients, and making geologic information available. ■

Building and Decorative Stone Production in Washington

by Charles W. Gulick

> *...our bountifully endowed commonwealth, rich in everything, is wealthy in the possession of the finest building, dimension, and rubble stone of nearly every known variety from the finest of marbles to the sturdiest of granites and sandstones.*
>
> *George A. Bethune, State Geologist, report for 1890 (1891, p. 97)*

The preceding statement by Washington's first state geologist is no less true today than it was 102 years ago. The variety of high-quality raw materials in Washington is impressive, and the reserves are seemingly inexhaustible. Over the years, changes in the industrial minerals business, such as more efficient transportation, have facilitated production. New or enlarged market segments for crushed and large landscaping stone, rockery (Fig. 1A), and exposed aggregates (Fig. 1B) suggest greater opportunities in the near future.

While these markets have expanded, however, production of traditional building stone has all but ceased. As recently as 1964 there were at least 50 producers of dimension stone or rough construction stone, whereas in 1992 there are fewer than ten. Nonetheless, if Bethune were alive today, he would be witnessing an active building and decorative stone industry and might be heartened to find that the Evergreen State's dolomite chips are a component of the terrazzo floors at Denver's Stapleton airport and the new United Airlines terminal at Chicago's O'Hare airport.

While such far-flung applications do exist, most of the business of 1992 producers is closer to home. Healthy demand exists from both residential and commercial construction projects throughout the populous high-growth corridor along the major highways of western Washington and elsewhere in the Pacific Northwest. Andesite, basalt, cinders, diorite, granite, dolomite, limestone, marble, pumice, quartzite, and sandstone are currently quarried for building stone and landscape rock products.

Not surprisingly, the distribution of raw materials and production is not uniform. Igneous rock varieties, while present essentially statewide, are quarried chiefly in western and central Washington. Sedimentary and metamorphic rock (dolomite, marble, and quartzite) production occurs primarily in northeastern Washington.

Figure 1A. A rock wall (rockery) being constructed. Photo courtesy of Fred Hackney, Alpine Rockeries, Woodinville.

CLASSIFICATION OF BUILDING STONE

Building stone can be defined as any rock type that is suitable for construction purposes because it has acceptable durability and attractiveness and can be economically produced. Building stone includes hearthstone, rubble, moss-covered rock, river rock, large landscaping rock, fieldstone, flagstone, curbing/paving blocks, and rough, natural construction stone. Building stone also consists of crushed stone products such as landscaping rock, exposed aggregate, dry dash stucco (finely ground material that acts as micro-exposed-aggregate and may be used to color the product), terrazzo, and roofing granules. Lastly, building stone comprises cut or dressed stone such as ashlar (Fig. 2), roofing slate, and some monuments. Some classifications include manufactured stone, such as cultured marble, reconstituted stone, and manmade stone as forms of building stone. Even though stone sculptures have a decorative function and have been considered building stone, many carvings and *objets d'art* are more commonly classified as gems.

Classifications of building stone (Moen, 1967; Power, 1983) typically place dimension stone in a separate category because it has unique properties. Dimension stone for buildings and monuments/tombstones is quarried in regularly shaped blocks, cut to specific sizes, and, for most uses, polished, honed, or flame finished. In some buildings, dimension stone plays a structural role, in others, stone is purely decorative. Quarrying of dimension stone in Washington is currently idle but has yielded blocks of granite and Chuckanut, Tenino, and Wilkeson sandstones that have been used in

Figure 1B. Two-inch-diameter river rock aggregate is exposed on the face of these "tilt-up" prefabricated walls.

Figure 2. A sandstone wall consisting of rectangular blocks of ashlar laid randomly in courses.

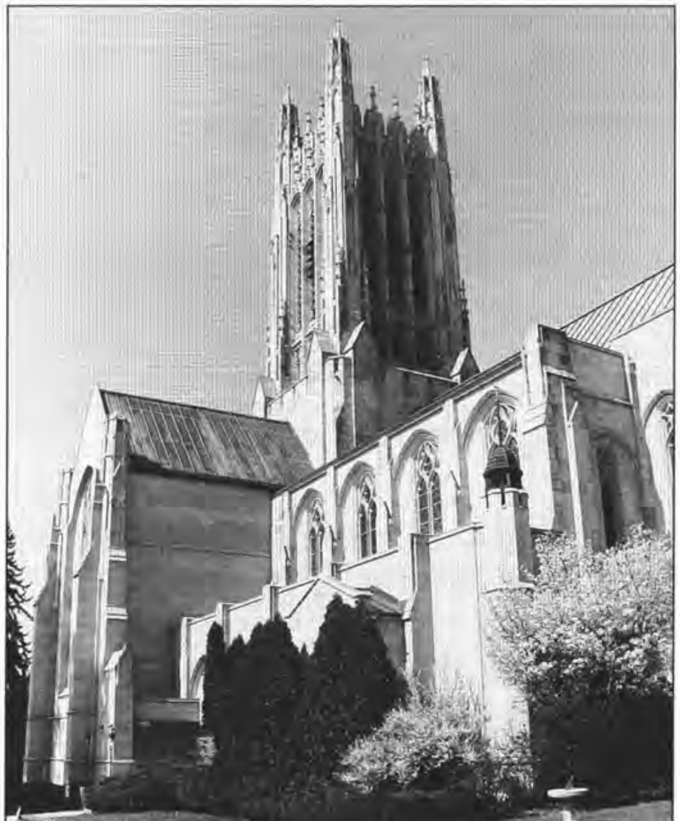

Figure 3. The exterior of the Episcopal Cathedral of St. John the Evangelist in Spokane was constructed from dimension stone cut from sandstone near Wilkeson. Each stone was cut for its particular place and was numbered accordingly. This gothic building, built in the shape of a cross, took 12½ years to complete, but there was a long hiatus before, during, and after World War II. The cathedral interior contains Boise Sandstone and Indiana limestone.

grand buildings such as the Cathedral of St. John the Evangelist in Spokane (Fig. 3), the Legislative Building and the Old State Capitol in Olympia, and many others throughout the state and region. Monumental™ Miniatures of Wilkeson quarries minor amounts of sandstone to make a series of small-scale models including an arcade (Fig. 4), arch and pier, temple facade, and a megalithic ring (such as Stonehenge).

In contrast to Washington's dimension stone industry, production of several other types of decorative building stone in the state is active. This article describes the major sources and applications of this economically significant geologic resource. Table 1 lists companies that produce building stone in Washington.

BUILDING STONE QUALITY

Rock or cut stone used for pavements, rockery, building foundations, or riprap and jettystone breakwaters must remain sound over time. Knowing what minerals make up a rock can be important in predicting its long-term behavior: certain minerals weather rapidly, whereas others may dissolve when exposed to fresh or salt water. Foliation and schistosity may weaken a rock intended to support a heavy load. Tiny fractures and pores can promote mechanical disintegration because these can become saturated and expand when trapped water is frozen.

Engineers have found that comprehensive testing can avoid rock failure by determining which materials meet specific quality criteria. For example, because large rocks may contain more fractures than smaller ones and thus hold more water, the U.S. Army Corps of Engineers recommends that samples of rock to be used in permanent structures be subjected to repeated freezing and thawing to determine susceptibility to breakage in these conditions. Certain rocks, "especially andesites and foliated metamorphic rock, have a history of sudden and significant deterioration even after as many as 15 yr of satisfactory field use" (Lepp and Flowers, 1989, p. 34). The Corps also found that measuring specific

Figure 4. The Monumental™ Miniatures arcade, made of sawed and hand-ground blocks of Wilkeson sandstone. When set up as shown, the dimensions are 11 x 26 x 2". The set is packaged in two cedar crates.

Table 1. Producers of decorative stone in Washington

Operator	Products	Quarry name	Rock type	County	Location
410 Quarry Inc. 31818 Highway 410 Enumclaw, WA 98022	crushed landscape rock, rockery	410	basalt (gray to tan)	King	sec. 20, 20N, 7E
AAA Monroe Rock Corp. 15421 166th St. S.E. Snohomish, WA 98290	rockery, crushed landscape rock	Monroe Rock	basalt (charcoal)	Snohomish	sec. 10, 27N, 6E
		AAA Diorite	diorite (light gray)	Snohomish	sec. 23, 28N, 7E
Allied Minerals, Inc. Star Route Springdale, WA 99173	crushed landscape rock	Gehrke	dolomite (white)	Stevens	sec. 2, 29N, 39E
Alpine Rockeries Inc. 23711 63rd Ave. S.E. Woodinville, WA 98072	rockery	Miller Lime	limestone (white)	Snohomish	secs. 15, 16, 27N, 9E
Bishop Red Rock Inc. P.O. Box 34 Goldendale, WA 98620	crushed landscape rock	Red Rock (Lorena Butte)	cinder (red)	Klickitat	sec. 27, 4N, 16E
Blue Silver Mining HCR 11, P.O. Box 28 Davenport, WA 99122	crushed landscape rock	Blue Silver	dolomite (white)	Lincoln	sec. 21, 28N, 36E
Cadman Rock Co. Inc. P.O. Box 790 Monroe, WA 98272	rockery	Cadman Rock	basalt (gray-brown)	Snohomish	sec. 19, 27N, 7E
Enumclaw Quarry Inc. 27407 S.E. 416th Enumclaw, WA 98022	rockery, landscape boulders	Enumclaw	andesite (gray)	King	sec. 1, 20N, 6E
Raymond Fosback Masonry P.O. Box 108 Kettle Falls, WA 99141	veneer	Kifer	quartzite (white)	Ferry	sec. 2, 36N, 37E
Gaylor's Construction P.O. Box 820 Camas, WA 98607	veneer, landscape boulders	Fisher	andesite (light gray)	Clark	sec. 8, 1N, 3E
General Construction Co. P.O. Box 24506 Seattle, WA 98124	rockery	Mats Mats	Crescent Formation basalt	Jefferson	sec. 33, 29N, 1E
Gilbert Western Corp. P.O. Box 1016 Camas, WA 98607	rockery, landscape boulders	Fisher	andesite (light gray)	Clark	sec. 8, 1N, 3E
Heatherstone Inc. P.O. Box 88626 Steilacoom, WA 98388	veneer, ashlar	Snow Queen	felsite (gray with specks)	Yakima	sec. 36, 14N, 11E
Interstate Rock Products Inc. MP 0.70 R Wantland Rd. Washougal, WA 98671	veneer, landscape boulders	Fisher	andesite (light gray)	Clark	sec. 8, 1N, 3E
Iron Mountain Quarry P.O. Box 55099 Seattle, WA 98155	rockery	Iron Mountain	andesite	Snohomish	sec. 17, 30N, 7E
Island Frontier Landscape Construction Co. P.O. Box 1278 Anacortes, WA 98221	rubble, landscape boulders	unnamed	andesite (bluish green)	Skagit	sec. 13, 34N, 1E
Jones Quarry 2840 C Black Lake Rd. Olympia, WA 98502	rockery, landscape boulders	Jones	Crescent Formation basalt (greenish)	Thurston	sec. 29, 18N, 2W

Table 1. Producers of decorative stone in Washington *(Continued)*

Operator	Products	Quarry name	Rock type	County	Location
Juanita Trucking 36621 132nd St. S.E. Sultan, WA 98294	crushed landscape rock	Chikamin	pumice (buff)	Chelan	sec. 22, 29N, 17E
D. M. Layman Inc. P.O. Box 208 Goldendale, WA 98620	crushed landscape rock	Blockhouse	cinder (reddish brown)	Klickitat	secs. 5, 8, 9, 4N, 15E
Manufacturers Mineral Co. 1215 Monster Rd. Renton, WA 98055	exposed aggregate, crushed landscape rock	unnamed	granite	King	sec. 22, 22N, 10E
Marenakos, Inc. 30250 S.E. Highpoint Way Issaquah, WA 98027	landscape boulders, moss rock	various	various	---	---
Meridian Aggregates Co. P.O. Box 839 Granite Falls, WA 98252	rockery, crushed landscape rock, landscape boulders	Granite Falls	andesite (brown)	Snohomish	sec. 8, 30N, 7E
		Pacific	diorite (light gray)	Skagit	sec. 33, 34N, 4E
Monumental™ Miniatures P.O. Box 63 Wilkeson, WA 98396	models (dimension stone)	Wilkeson	sandstone (gray)	Pierce	sec. 27, 19N, 6E
Nanome Aggregates P.O. Box 296 Valley, WA 99181	terrazzo, crushed landscape rock	nine quarries	dolomite (various colors)	Stevens	---
Northwest Marble Products 1403 Highway 9 Chewelah, WA 99109	terrazzo, crushed landscape rock	White; various	dolomite (white, various colors)	Stevens	sec. 19, 38N, 38E
Randles Sand and Gravel Inc. 19209 Canyon Rd. E. Puyallup, WA 98373	crushed landscape rock	Lynch Creek	basalt (bluish gray)	Pierce	sec. 13, 16N, 4E
Rockeries Inc. 1911 S.W. Campus Dr. Federal Way, WA 98023	rockery, landscape boulders	Wilkeson	sandstone (gray)	Pierce	sec. 27, 19N, 6E
Twin Rivers Quarry P.O. Box 1090 Monroe, WA 98272	rockery	Twin Rivers	basalt with clay	Snohomish	sec. 9, 27N, 6E
Universal Land Construction Co. P.O. Box 329 Woodinville, WA	rockery, crushed landscape rock, landscape boulders	Hazen	basalt (grayish green)	King	sec. 6, 23N, 6E
		Mandan	basalt (black)	Snohomish	sec. 12, 30N, 6E
Washington Rock Quarries Inc. 29104 Camp 1 Rd. E. Orting, WA 98360	crushed landscape rock	Buckley	basalt (black)	Pierce	sec. 7, 19N, 7E
	crushed landscape rock, rockery, veneer	Kapowsin	basalt (various colors), andesite (blue)	Pierce	sec. 8, 17N, 5E
Whatcom Skagit Quarry 4189 Chance Rd. Bellingham, WA 98226	flagstone, rubble, landscape boulders	Whatcom and Skagit	Darrington Phyllite	Skagit	sec. 6, 36N, 4E
Whitestone Company P.O. Box 498 Chewelah, WA 99109	veneer, crushed landscape rock	Moonlight	dolomite (white)	Stevens	sec. 24, 38N, 37E
	veneer	Whitestone	marble (beige)	Stevens	sec. 34, 39N, 38E
	veneer	unnamed	strip basalt	Spokane, Douglas	two locations
	veneer	near Kifer quarry	quartzite	Ferry	sec. 2, 36N, 37E

gravity and percent absorption, as well as a test that accelerates expansion in any fissure, are useful in predicting future performance. Other tests such as "Los Angeles" abrasion and those for sand equivalent, degradation, and soundness are routinely required for crushed stone that will be used in roadway construction. Because rock in quarries is not uniform, and one section of a quarry may be suitable for one use, while that elsewhere in the quarry can fit other needs, continual testing can assure that materials have characteristics appropriate to their use. (See discussions by Lepp and Flowers, 1989, and Koloski and others, 1989.)

BUILDING STONE PRODUCTS

Washington producers currently quarry or collect natural stone for the following products or uses, listed in approximate descending order of economic importance:

- crushed stone
    - landscaping stone
    - exposed aggregates
    - terrazzo
- rockery
- large landscaping rock
    - crushed rock
    - moss rock
    - river rock
    - fieldstone
- rough construction stone
    - rubble
    - veneer
    - flagstone
    - hearthstone
    - ashlar

Crushed Stone

Decorative crushed stone is probably the largest market segment for building stone in the state. Andesite, basalt, cinders, diorite, dolomite, marble, and pumice are currently produced for use in landscaping. While some producers are wholly dedicated to these landscaping products, virtually every producer of crushed rock or aggregate for construction purposes sells incidental amounts of material for purely decorative purposes.

Crushed andesite and basalt are widely sold throughout western and central Washington by major aggregate companies and smaller companies that cater to the decorative landscape and rockery markets. Two andesite quarriers also produce and market "diorite", a trade name that does not reflect the chemical composition of these typically meta-igneous and altered rocks.

Cinder or scoria landscape rock is produced by two companies that mine cinder cones near Goldendale (Klickitat County). Cinder products known by the trade names "Red Rock" and "Golden Shale" are marketed primarily in the Spokane, Portland, Seattle, and Richland/Pasco/Kennewick areas. In addition to popular landscape rock sizes (½–1 in., 1–2 in.), the cinder producers market smaller (5/16 in.) material for horticultural hobbyist products such as bonsai mixes. Still finer fractions of cinders are locally used for traction sand. Unlike their nearest competitors in Bend, Oregon, the Washington producers wash all cinders except for those few applications in which contained clay is desirable, such as sand for track and field arenas.

Pumice for horticultural and landscaping rock uses is produced seasonally in the Chiwawa River area north of Lake Wenatchee and marketed by Juanita Trucking of Sultan (Snohomish County). This material is mined at several sites in the extensive pumice and pumicite deposits that were derived from eruptions of Glacier Peak.

Dolomite (or magnesite) and marble are mined by two Stevens County firms whose primary product is landscaping rock. As for producers of andesite and basalt, there are other incidental producers of carbonates for decorative rock applications in both Stevens and Okanogan counties.

Crushed stone is typically produced by blasting, crushing, and screening. Many western Washington aggregate producers market both crushed rock and larger uncrushed material from a single quarry. The largest and most competent blocks of four-, five-, and six-man rock (terms derived from the number of men required to budge them; see tabulation below) are sold for jetty stone and riprap. More moderately sized one-, two-, and three-man rocks and other aesthetically pleasing materials are sorted for landscape boulders and rockery applications. The smaller boulders that are not suitable for rockery are commonly crushed and screened for landscaping rock, aggregates, and gabion walls. Gabion walls are retaining walls comprised of 4- to 8-in. crushed rock that is enclosed by cyclone fence or other wire mesh. Gabion walls have been used, for example, along parts of the east- and westbound lanes of Interstate Highway 90 west of Snoqualmie Pass, where they stabilize the toe of slopes that are prone to slides.

Rock size	Rock weight (pounds)	Average dimension (inches)
one man	50–200	12–18
two man	200–700	18–28
three man	700–2000	28–36
four man	2000–4000	36–48
five man	4000–6000	48–54
six man	6000–8000	54–60

Gabion rock, riprap, and jetty stone are strictly functional construction materials, and producers are not listed in Table 1. Strong markets for riprap are a consequence of intense flooding in northwestern Washington during the past several years. The Kendall and Silver Lake limestone quarries in Whatcom County traditionally served portland cement, pulp and paper, and lime markets. Today, however, these quarries primarily produce riprap for flood control, and the previously active limestone markets are largely supplied with raw material from Texada Island, B.C., which has the advantage of low-cost barge transportation.

Crushed stone chips for exposed aggregate (including dry dash stucco) and terrazzo flooring are produced in Washington by three companies. Nanome Aggregates operates nine dolomite or marble quarries near their Valley plant in Stevens County. They produce 14 naturally colored decorative aggregate products. Northwest Marble Products of Chewelah also produces various colors of exposed aggregate and terrazzo chips from deposits in Stevens County. Much of their output is marketed by Manufacturers Mineral Co. of Renton (King County), a major distributor and producer of other

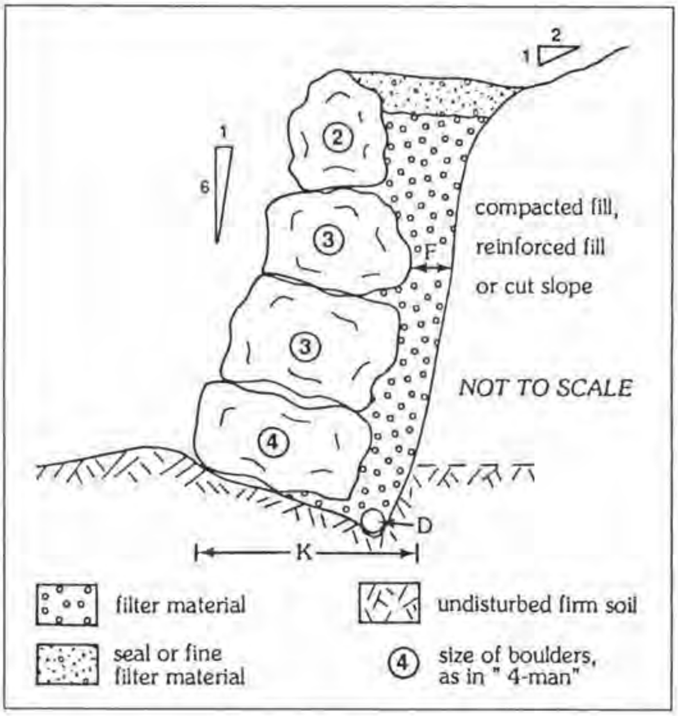

Figure 5. Diagrammatic cross section of a rockery. The keyline is dug about a foot deep the length of the face to be supported and so that it slopes toward the cut slope face. Keyline width (K) is the sum of the width of the basal boulders and the coarse (4–8-in. diameter) filter (F) material placed between the boulders and the cut slope. A slotted or perforated drain (D) at the back of this excavation carries water away from the rockery. Boulders, which decrease in size upward in the rockery, are placed so that they are tipped toward the cut slope; interstices between boulders are packed with coarse rock, but the main support is boulder-on-boulder. Boulder dimensions are described in a table on p. 7. Behind the top of the last course of boulders is a finer grained fill to seal the coarse filter material or limit drainage through the filter. The slope of the face of the finished rockery should be about 6 feet vertical for each foot horizontal, and the slope of the ground above the rockery should be about 2 feet horizontal for every foot vertical. Rockeries should be inspected periodically and maintained for proper performance. See cover photo and Figure 1A. (Redrawn from a series of proposed standards, Associated Rockery Contractors, 1992).

decorative aggregates. One item in Manufacturers' product line is "Grey Granite" from the North Bend area. This is the only decorative granite currently quarried in the state despite the existence of as many as 22 formerly active granite quarries in Washington (Moen, 1967).

Rockery

Another active segment of Washington's building stone industry is the construction of rockery. A rockery is defined as a wall of unmortared, interlocking courses of boulders (Figs. 1A and 5). Rockery sources are primarily volcanic rocks, and most of the Eocene or younger andesites and basalts selected for rockery are produced in western Washington. Fast-paced urban growth has created a shortage of flat building sites; therefore, cut and fill is a common means of preparing sites on the west side of the state. Rockeries provide an effective and aesthetic means of retaining glacial sediments, fill, colluvium, or soil along cut banks, and the cost of rockery walls is typically about half that of reinforced concrete walls.

As noted, physical integrity of the stone is of paramount importance in rockeries and construction of retaining walls, bulkheads, and creek- and seawalls. Because many rockeries are also decorative, color is another major consideration. Basalts are typically dark gray or brown, and some andesites are green or gray. Tan or white andesites, often referred to as felsites and commonly quarried in the past, are not widely produced today. Chloritization and iron staining create some of the most popular green and brown varieties of andesite and basalt.

The proliferation of rockeries, a term that now includes companies that produce and install these hand-picked stones, can be confirmed by scanning the Seattle Yellow Pages under "Rock". Some rockeries lease multiple quarries or acquire materials from several sources in order to retail a range of materials. Other rockeries specialize in installation and repair. A western Washington trade association, Associated Rockery Contractors, sets industry standards and has identified unacceptable raw material sources through documented failures of walls. According to association president J. D. Rinker, 11 of the approximately 18 rockery contractors throughout King, Pierce, and Snohomish Counties are active in the association. The rockery market in western Washington alone has been estimated at 120,000 tons per annum (David Piper, Meridian Aggregates Co., oral commun., 1991).

Landscape Boulders

In addition to rockery, significant tonnages of boulders are chosen for use in gardens and other landscaped environments. Blasted andesite and basalt quarry rock is the most common product for this market. Many of the rockery contractors also sell these landscaping materials. An unusual definition of the term "outcroppings" is used by some landscaping rock retailers to mean an installation of selected boulders with intervening space, which may be large, filled with plants, shrubs, or trees.

Several producers of large landscaping rock concentrate on naturally occurring varieties known as moss rock and alpine rock. These are handpicked, naturally broken boulders, preferably at least partly covered with lichen or moss. The term "alpine" rock is used by rockeries and landscape rock retailers to describe these lichen-covered varieties from mountain talus sources. Lichens in alpine rock encrust the host rock so tenaciously that they can withstand considerable handling—in contrast to the easily stripped green "blanket" mosses that grow on wet rocks in wooded areas. Most of the alpine rock sources are high in the Cascade Range. Because they are uncommon and in demand, moss rock and alpine rock varieties have higher value relative to quarried landscaping rocks.

Columnar basalt is a popular landscaping rock product in Washington. It is quarried by Interstate Rock Products Inc. in the Washougal River valley (Clark County), and there is intermittent production from sites in Lincoln and Spokane

Counties. Use of the smooth-sided vertical columns can create striking effects (Fig. 6). The concave conchoidally fractured tops of some columns allow a second use—as birdbaths.

River Rock

River rock is another natural landscaping product commonly sold in the state. Much of the "river rock" in Washington is actually obtained from glacial deposits, erratics, and the like. A large demand exists for screened river rock in smaller (pebble) sizes for use in exposed aggregate walls (Fig. 1B) and walkways. Some pebble varieties are imported from great distances: Manufacturers Mineral Company's "Roan River" rock comes from Michigan. Flat "pancake rock", a type of river rock used in some masonry applications, is imported from the Fraser River in British Columbia. Both river rock and large blasted and/or crushed rock have many additional functional uses, such as in ditch liners for erosion control.

Rough Stone

Rough construction stone products, variously referred to as rubble, hearthstone, ashlar, veneer, or flagstone, are obtained from numerous andesite, basalt, marble, and quartzite sources in Washington. Rough construction stone, like dimension stone, is not widely used in modern construction. Several factors are responsible for this decline, including high cost, contractor reluctance to use unfamiliar materials, lack of qualified masons to set the stone, and limited selection. However, a few determined producers of attractive stone are still active in Washington.

Basalt is the rock type most frequently used in rough stone applications. The most common products are typical of the Columbia River Basalt Group as a whole. These are the dark-brown to black, vesicular, subround to angular boulders, fieldstones, and blasted quarry rocks that are set in mortared walls or fireplaces, for example (Fig. 7). The second variety is a far less common type known as strip basalt (also termed needle rock or liver rock). These are elongate, dense, non-vesicular black basalt blocks that are set horizontally in walls (Fig. 8). These large slivers, as much as 4 feet long, have smooth sides that reflect the conchoidal fracture pattern of glassy basalt flows. Strip basalt is quarried near Bridgeport (Douglas County) and near Cheney at Williams Lake (Spokane County). Whereas common basalt rough stone wholesales for approximately $60/ton, strip basalt sells for approximately $125/ton.

Andesite is the other common rough stone that has been widely developed in

Figure 6. Columnar basalt landscape boulders surround the Ecology Goat at Spokane's Riverfront Park. The goat is a vacuum system for disposing of trash.

Figure 7. This mortared fieldstone wall composed of vesicular basalt boulders is an example of a common use of building stone in Washington.

Figure 8. Palletized elongate pieces of "strip basalt" (also known as needle rock or liver rock) await installation as horizontal elements in a rock wall.

Figure 9. Camas Gray used as veneer in part of a sign. This rock is also known as Camas Gray Basalt. Photo courtesy of Tracy Lambert, Gilbert Western Corp.

Figure 10. Andesitic "Heatherstone" forms striking ashlar walls at this apartment complex. These apartments were named for the trade name of the building stone.

Figure 11. A rubble wall that consists of irregular pieces of marble, each of which has one essentially flat face.

Washington. Much of the historic production has been the gray, green, and maroon varieties. This andesite is intrinsically platy, flaggy, or blocky, and thus readily split for ashlar, flagstone, and rubble.

Gray andesite known as Camas Gray is quarried by Gilbert Western Corp. near Camas (Clark County). Near-vent gas bubble entrainment appears to create zones in this rock that can be split to create 1- to 4-in.-thick slabs (Fig. 9). These slabs are hand-split for flagstones or veneers by Interstate Rock Products Inc. and Gaylor's Construction from selected areas of a flow that elsewhere yields massive blocks of jetty stone, riprap, and rock for crushed aggregates. This veneer adorns the entrance to the Portland, Oregon, airport and the Skamania County courthouse in Stevenson.

Heatherstone Inc., a family-owned andesite producer in Steilacoom, has continuously supplied andesite veneers and ashlar (known by the trade name Heatherstone) for more than 25 years. This reddish-brown to gray, black-speckled andesitic felsite (Fig. 10) is seasonally quarried near White Pass. Heatherstone is currently being prepared for use in an oriental landscape at Nike's World Campus in Beaverton, Oregon. Formerly popular greenish andesite products such as "Shuksan Stone" from the Mount Baker area are no longer quarried.

White quartzite flagstones for veneer are quarried on a limited basis at and adjacent to the Kifer quarry, west of Kettle Falls near Barney's Junction (Ferry County).

Brilliant white dolomite is being produced for rubble, hearthstone, landscaping rock, and roofing granules east of Barstow in the Glasgo Lakes area of Ferry County by the Whitestone Company. Whitestone also markets white to beige marble that is produced near China Bend on the Columbia River mostly for rubble walls (Fig. 11).

Metamorphic rock production for rough construction stone appears to be limited to green-, black-, and purple-streaked Darrington Phyllite. Whatcom Skagit Quarry mines the phyllite near the common border of these counties. Highly graphitic zones now exposed in their quarry may necessitate new development work because graphite is soft and renders the stone unacceptable for most applications.

There is no current confirmed production of slate in the state, although there is purported slate production in the Longview area of Cowlitz County. Some of the most suitable slate (argillite?) near Bead Lake north of Newport (Pend Oreille County) has been withdrawn from active production by timber company landowners. Production of argillite flagstone known as "Desert Dream" from the Colville National Forest (sec. 2, T37N, R36E) was recently discontinued.

One former (1956) eastern Washington slate producer, the Waterman-Symington Slate Co. operation near Waitts Lake in Stevens County (NW¼ sec. 19, T31N, R33E), developed a slate resource that was not resistant to the repeated winter freeze-thaw conditions of eastern Washington. Consideration of the potential attrition due to freeze-thaw cycles is important for any building or decorative stone that will be used in colder climates.

A wide variety of green (nickel- and/or chromium-stained) silica carbonate rocks, most of which are associated with serpentinites, is available. However, only the Germaine property on Diobsud Creek near Marblemount (Skagit County) has a record of commercial production for this variety of stone (Moen, 1967).

Sculpture

Stone carvings and *objets d'art* are frequently classified as gems and are prepared from gemstones; these are not normally considered building or decorative stone. The principal ornamental rock types that are worked by artisans for bookends, pen stands, and other decorative purposes are petrified wood and picture rock. In addition, marble, serpentine, brucite, and soapstone are popular raw materials for a small community of sculptors.

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Editor's note: If readers have additions or corrections to Table 1, please notify the Division at P.O. Box 47007, Olympia, WA 98504-7007 [phone: 206/459-6372] *or* N. 222 Havana, Spokane, WA 99202-4776 [phone: 509/533-2484]. ■

The Washington Division of Geology and Earth Resources prepared background information for a chapter on decorative stone that will appear in the 6th edition of Industrial Minerals and Rocks, to be published by the Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc. (AIME).

Share Your Enthusiasm With the Next Generation

Geologists have many opportunities to influence their communities, but one of the most important and rewarding connections they can make is through schools. Joining the educational process in the classroom not only gives students some firsthand exposure to geological topics, but a student's face-to-face contact with an enthusiastic professional may be the inspiration for a career.

Several professional organizations have rosters of geologists willing to become involved with K–12 students. One such group is the Washington State Section of the Association of Engineering Geologists (AEG). The Section is looking for persons who will volunteer to make guest presentations and demonstrations. In addition, AEG coordinators are offering their services to school districts to help school science coordinators find appropriate classroom help with geologic subject matter. Contact Bill Laprade at Shannon & Wilson, Inc., 206/632-8020, if you would like to get involved as a volunteer or coordinator or if you want help in finding a geologist to come to your class.

Teachers are encouraged to contact other professional societies for lists of potential guest presenters for their classes.

Bellingham Woman Honored As Earth Science Teacher

Ann L. Babcock has been selected as the Pacific Northwest Section's Outstanding Earth Science Teacher by the National Association of Geology Teachers. Ann teaches at Whatcom Middle School in Bellingham. According to her principal, "Her lessons consistently involve the use of hands-on experiences that promote a high degree of student task commitment. She does a superb job of building upon basic skills to lead students to apply higher-order thinking skills. In meeting student needs she is both innovative and creative. She very skillfully builds student self-esteem as she leads her students to practice the skills needed to be independent learners. Students like her and know that she enjoys teaching them."

Confirming this appraisal, Ann has also been selected as the "Teacher of the Year" by the Washington Science Teachers Association and has received Woodring College of Education's "Excellence in Education" award. She has been selected as Woodring's "Teacher on Sabbatical" and during the next year she will collaborate with faculty, local school districts, and the OSPI in developing more effective programs for science education in Washington State.

As a participant in the "Adventures in Arts and Sciences" program at Eastern Washington University, Ann created a class called "Summit to Shoreline", which had middle-school students eagerly scrambling up mountains looking for specimens to compete in "Crystal Olympics." They snacked on "inclusion cookies" and created their own rocks in an experiment that simulates the rock cycle.

For the elementary-school level, Ann developed a program called "Crystal Creations", which one parent called "the kind of class I would gladly go back to school for."

Ann has also written lesson plans for the University of Washington's SET program on climatic change and a unit called "Dirt Work" on the engineering properties of soils. She not only develops imaginative programs but goes the additional step of promulgating her ideas through publication in appropriate journals. Anne has published eight articles since 1985.

Modified from the *Journal of Geological Education*, March 1992, v. 40, no. 2, p. 158-159.

Shallow Explosion-like Seismicity and Steam-and-Ash Emissions at Mount St. Helens, August 1989–June 1991

by Larry G. Mastin and Bobbie Myers
U.S. Geological Survey, Cascades Volcano Observatory
5400 MacArthur Boulevard, Vancouver, WA 98661

Introduction

On a clear summer evening on August 24, 1989, nearly 34 months after its most recent magmatic eruption, Mount St. Helens was rocked by a shallow, explosion-like seismic event that marked the beginning of a new phase in the volcano's recent activity. The record began abruptly with a high-amplitude signal captured by stations in the crater (Fig. 1). The activity continued for almost an hour and was followed over the next two hours by a series of discrete, small earthquakes, at the rate of a few per minute to one every few minutes. The long duration, high amplitude, and characteristic sequence of these small earthquakes in the latter part of the record distinguished this event from the rumbling of a rock fall, the buffeting of the stations by wind, or the sharp arrivals and rapid logarithmic decay (within seconds) of earthquakes that typify the Mount St. Helens magmatic system (Jonientz-Trisler and others, 1991). The fact that strong shaking was chiefly confined to the crater suggested that the source was shallow, and the sustained level of activity was reminiscent of events in the mid-1980s that had accompanied explosive emissions of gas and ash from the lava dome.

The August event occurred after dark (2227 PDT) when no workers were on the mountain and the crater could not be observed. A similar but weaker signal occurred at 0918 PDT the next morning, however, and observers north of the mountain reported no visible changes to the dome or crater. A third event, at 1758 PDT on August 30, produced, at best, ambiguous evidence of ash or steam clouds when the crater was examined through a slow-scan video camera mounted 8 km north of the mountain.

Over the next 22 months, shallow, explosion-like seismicity of this type continued. Some produced plumes of steam that rose as high as 7½ km in altitude (5½ km above the lava dome), ash clouds that were blown as far as 140 km from the mountain, showers of ballistically ejected blocks as large as 2 m in diameter that covered the crater floor, and small debris flows that travelled down the Toutle River valley. All emissions of ash and steam during these events were small in comparison with pyroclastic eruptions of the early 1980s, and none has produced evidence of any new juvenile magma. Their occurrence was nevertheless the cause of some concern about future eruptions on the mountain. This article is a summary of these events and a discussion of their possible causes.

Chronology of the Events

Although weak seismic events may have been masked by the frequent, low-level shaking that accompanies rock fall, storms, and avalanches in the crater, no more strong signals were recorded until early December, 1989 (Table 1). Then, on December 7 at 1609 PST, a tremor began sharply with a higher amplitude than that of the August events, and it continued with the characteristic short, sharp quakes in the latter part of the record (Fig. 2). This event was followed by a smaller one at 0601 PST on December 9. Staff members of the U.S. Geological Survey's Cascades Volcano Observatory (CVO) entered the crater on December 11 and found two fresh ash layers, each several millimeters thick and separated by snow, on the north side of the lava dome. These layers thinned to a few millimeters several hundred meters north of the base of the dome. USGS staff geologists inferred that the younger and thicker of the two deposits was caused by the event on December 7. (The older deposit has not been assigned to an identified event and may have been produced by a small tremor that was obscured by seismic noise). There was no obvious source vent for the deposits, and it was assumed that the conduit was one of the numerous fractures on the dome. The ejected debris was primarily crystal-lithic ash consisting of small fragments of dacite from the lava dome. No fresh glass shards with bubble-wall textures were found that might suggest new juvenile magma.

Although the December ash deposits recorded the first surface emissions since 1986, their small volume and the lack of ash transport beyond the summit crater caused little concern. The level of concern increased significantly when a larger blast rocked the crater at 0537 PST on January 6, 1990. This signal occurred on a Saturday morning during a lull in the largest storm in southern Washington in recent years. No one was on duty in the observatory, and the USGS learned of the event later in the day through reports of light ash fall at Toppenish, 140 km east of the volcano. USGS scientists subsequently found evidence that a north-directed blast, coinciding with one or perhaps two rock avalanches,

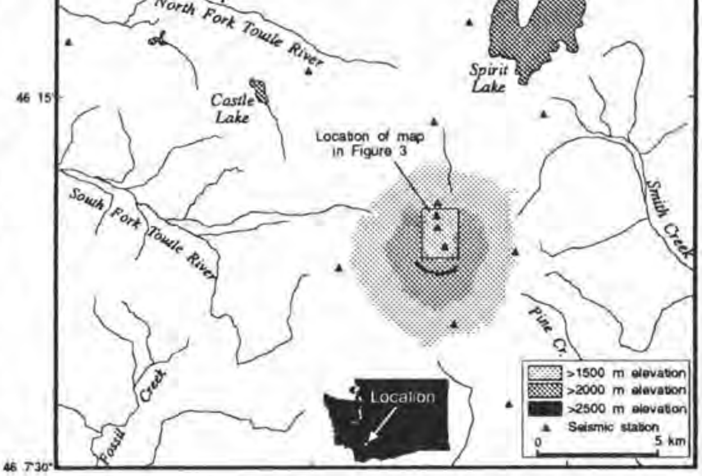

Figure 1. General map of the Mount St. Helens area.

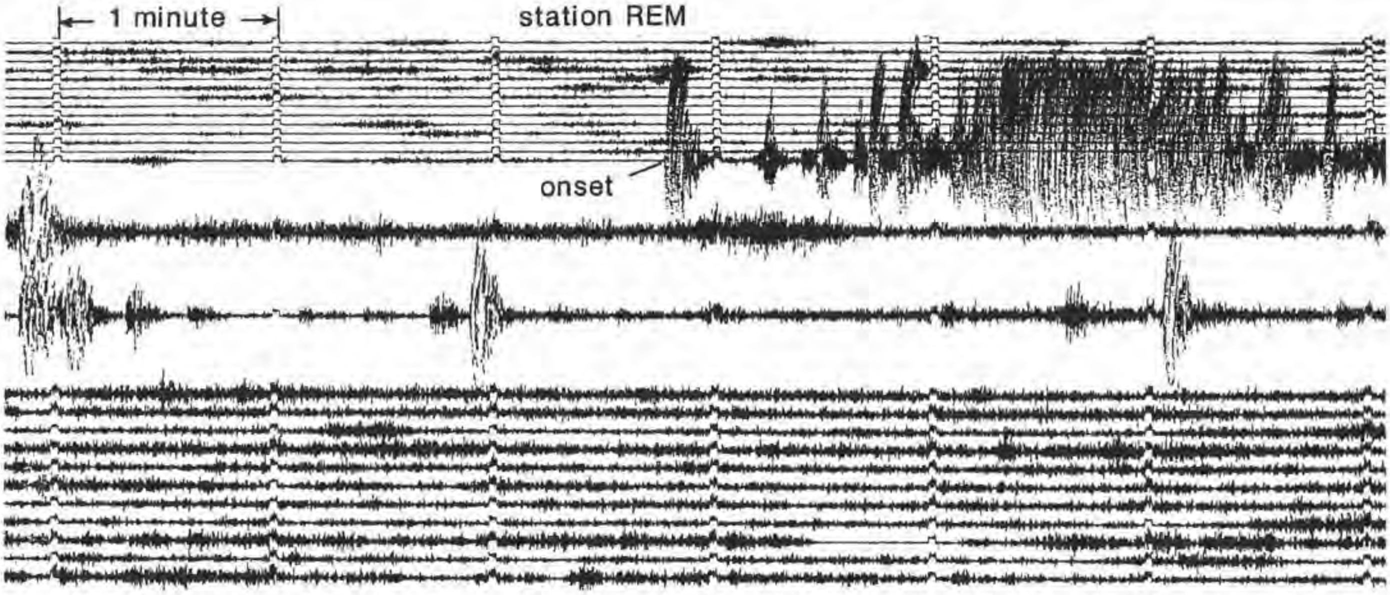

Figure 2. A portion of the seismogram from December 7, 1989, as recorded on the station Rembrandt (REM), just east of the top of the lava dome; see Figure 3. The time period between each trace is 15 minutes.

Table 1. Summary of shallow, explosion-like seismic events and steam-and-ash emissions, August 1989–June 1991. >, signal dies out too gradually to estimate exact duration; N, confirmed, no steam or ash emission; T, recognized tephra deposit; P, visible plume; F, flowage deposit; B, ballistic blocks; ?, evidence of steam or ash emission inconclusive

Date	Time of onset	Approximate duration of sustained shaking	Emissive activity
08/24/89	2227 PDT	1 hr	?
08/25/89	0918 PDT	1 hr	N
08/30/89	1758 PDT	35 min	?
12/07/89	1609 PST	5 hr	T
12/09/89	0601 PST	2 min	?
01/06/90	0537 PST	2 hr	T,F,B
03/02/90	0034 PST	1 min	?
03/02/90	1101 PST	3 min	?
04/05/90	0156 PDT	2 min	?
04/25/90	0126 PDT	3 hr	?
05/08/90	0912 PDT	2 min	?
06/07/90	2251 PDT	1 hr	?
09/14/90	1950 PDT	3 min	?
09/24/90	1652 PDT	>3 hr	N
10/15/90	1224 PDT	4 min	?
10/25/90	0639 PST	>3 hr	?
10/26/90	0003 PST	4 hr	?
11/05/90	0207 PST	1 hr	P,T,F,B
11/14/90	2341 PST	4 min	?
11/20/90	1058 PST	2 min	?
11/25/90	1245 PST	2 min	?
11/28/90	1921 PST	2 min	?
12/20/90	1259 PST	3 hr	P,T
12/23/90	1115 PST	1 hr	N
01/05/91	2146 PST	3 min	?
02/05/91	0747 PST	40 min	P,T,F,B
02/14/91	0524 PST	4 hr	T,F
06/18/91	0608 PDT	5 min	N

had issued from the north shoulder of the lava dome (Fig. 3). A new, talus-filled crater there lay within an arcuate pull-apart zone that resembles a smile, or more appropriately (because the feature is convex upward) a frown, on a golf ball. The blast deposit consisted of boulder- to sand-size lithic debris that mantled the north side of the dome and the crater floor north of the dome. Most of the ash deposit was confined to the Mount St. Helens crater, and the dispersal of trace amounts of ash as far away as Toppenish was due more to strong winds than to a high eruption column. As with the deposits from the December events, the January 6 deposit was composed of lithic dacite from the dome, with a small amount (<1%) of dark, glassy, high-silica andesite or low-silica dacite that may represent an unusual phase of the early (1981) dome rock or 1981-vintage material from the conduit (Pallister and others, 1992). Again, there was no evidence of juvenile glass.

Nevertheless, the transport of ash outside the crater posed a potential public hazard. Concern for the dangers posed by this ash (heightened by the near-tragic engine failure on a commercial jet near Alaska's Mount Redoubt three weeks earlier (Brantley, 1991)) motivated USGS personnel to install a beeper-operated system that would alert scientists in the event of strong, localized seismic activity in the Mount St. Helens crater (Myers and Theisen, 1991).

At least 11 shallow, explosion-like seismic events occurred in the next ten months (Table 1). Of these, five lasted for hours and were comparable in duration to the events on August 24, December 7, and January 6. One, on September 24, 1990, occurred when workers were near the mountain and could verify that no ash or steam emission had occurred. The others occurred at night, during bad weather, or under other conditions when the crater could not be observed. Scientists who visited the crater days to weeks afterward found no new deposits or evidence of eruptive activity (though in those intervening periods some evidence could have been destroyed).

From November 5, 1990, through February 14, 1991, ten shallow, explosion-like seismic tremors and four confirmed steam-and-ash emissions were recorded. For these events we have significantly more observational data than for the preceding ones. The first (and one of the best documented) occurred at 0207 PST on November 5, 1990. The seismic record for this event (Fig. 4), as obtained from station Yellow Rock (YEL) about 460 m north of the dome (Fig. 3), grew gradually in amplitude over about 10 sec, diminished to low-level tremor that lasted about 1.5 min, then increased and maintained a constant, high amplitude for about a minute before the seismograph was destroyed (as was determined by later field observations) by the impact of a lithic pyroclastic flow. Sixteen seconds before destruction of the Yellow Rock seismograph, a seismograph at Garden Rock (GDN) at the north base of the dome (Fig. 3) was also destroyed, probably by the same pyroclastic flow, giving a velocity for the flow of about 29 m/sec.

Because of the gradual increase in seismic amplitude at the onset of the November 5, 1990, event, its source location (which must be obtained by accurate determination of the arrival times of the signal at several different stations) could not be ascertained. However, two small jolts that occurred 51 min and 2 hr 32 min after the onset of shaking were located at 1.2 and 1.5 km depth, respectively, below the dome (with a standard error of ±0.1 km for each event). In plan view, their epicentral positions (with standard errors of ±0.5 and ±0.3 km, respectively) were both within a few hundred meters of the center of the dome.

Airline pilots reported that the November 5 ash plume rose about 5½ km above the dome, and a trace of ash fall was reported in north-central Oregon. Later in the day, USGS personnel found that the explosion had generated a north-directed shower of dacite blocks that extended several hundred meters from the vent (Fig. 3). This had been followed by a pyroclastic flow of hot lithic fragments, the deposit of which was about a meter thick near the base of the dome and extended at least half a kilometer north and northwest onto the crater floor (Figs. 3, 5). Much of the hot deposit melted old snow on the ground surface to produce watery floods and debris flows that coursed down braided gullies to the north. Another flood originated on the northwest side of the dome as a result of melting and mass failure of thick firn and avalanche deposits. It cut a channel (f, Fig. 5) through the new hot lithic deposit at the north base of the dome. Although snow had lightly dusted the ground surface in the hours after debris was ejected, the deposit was hot enough (because most of it came from within the hot dome) to melt this snow. Increased flow in the North Fork of the Toutle River as a result of this event raised the water level by 0.6 m at Elk Rock, about 18 km downstream from the crater, but it increased the height of water residing behind the sediment retention structure, 50 km downstream, by only a few centimeters.

Following the November 5 event, the pattern of ash and debris on the ground surface indicated they had been ejected from the same vent on the north side of the dome as the ash from the January 6, 1990, emission. Field observations and aerial photography between January and November documented changes in the morphology of the vent area over this 11-month period. The vent area was described in January as a frown-shaped pull-apart zone containing a closed, talus-filled crater at its center. By September, aerial photographs indicate that the area had acquired the shape of an amphitheater approximately 90 m in diameter and 20 m deep, that drained to the northwest, slightly oblique to the dome's north-trending fall line. Erosion of debris from the amphitheater had produced a small new talus apron near the north base of the dome. Within this amphitheater, the November 5 event produced a crater about 30 m in diameter and 5–10 m deep that, according to field observers, steamed vigorously following its creation.

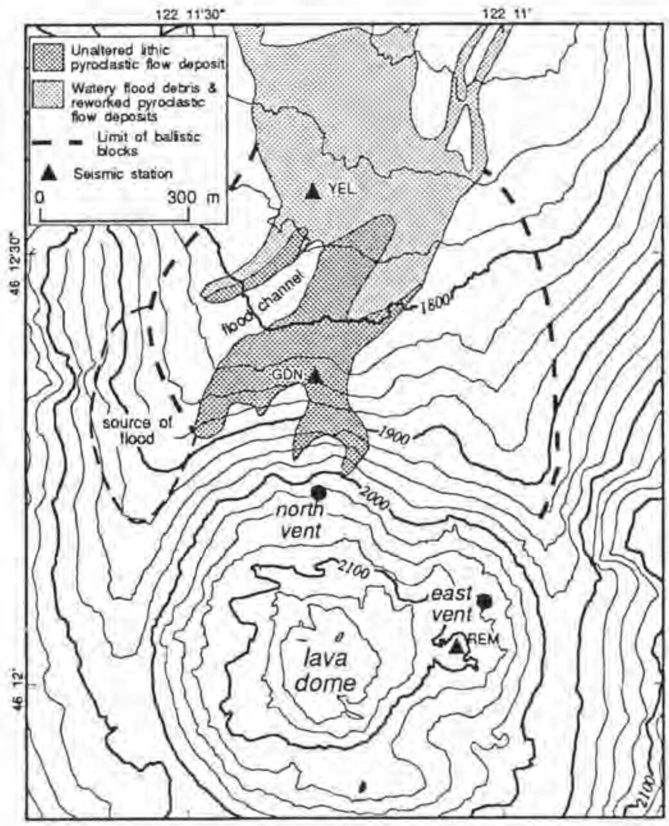

Figure 3. Map of the Mount St. Helens crater showing locations of vents, seismic stations, and deposits of the November 5, 1990, steam-and-ash emission event. Deposits mapped by E. W. Wolfe, R. B. Waitt, and D. Dzurisin (USGS).

The next confirmed steam-and-ash emission, on December 20, 1990, was unlike the others in two significant respects. First, debris was expelled from a new, smaller vent on the dome's northeast shoulder (east vent, Fig. 3). Second, several hundred small to tiny earthquakes, located below or just north of the dome, continued for more than two weeks following this event. Although those occurring in the first few days were all at depths of less than 3 km, later ones ranged to more than 5 km (S. C. Moran, Univ. of Wash., written commun., 1992). In contrast, earthquakes that had followed previous shallow, explosion-like seismic events had stopped within a few hours after the onset of the signal and were located within about 3 km of the surface.

The December 20, 1990, event began at 1259 PST and increased gradually in amplitude over nearly a minute, then continued for a few hours before diminishing to near-background levels. Commercial airline pilots flying over the crater observed a plume with a height of about 3 km above the

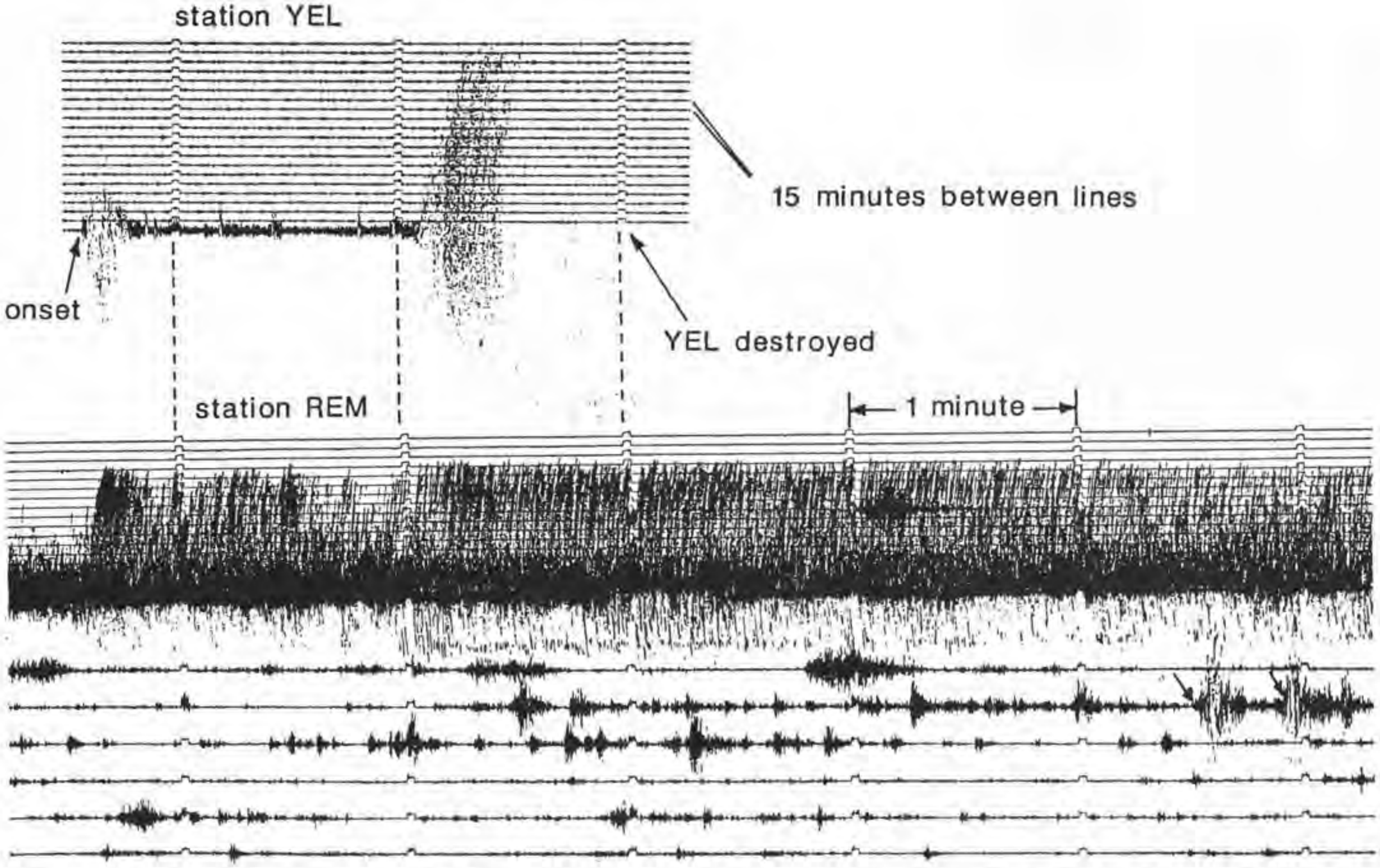

Figure 4. Part of the seismograms of the November 5, 1990, event from the stations Yellow Rock (YEL) and Rembrandt (REM).

dome at 1308 PST; reports at 1325 PST indicated that the plume had drifted south-southwest and risen to about 5 km above the vent. Scientists who flew over the crater later that afternoon observed a light dusting of ash that covered the ground surface within about 200 m of the vent and extended about 50 m up the east crater wall. A small amount of ash was blown over the crater rim and at least several kilometers to the southwest. Unlike the event on November 5, however, there was no evidence of pyroclastic flows, floods in the crater, or of significant increases in stream flow in the Toutle River (which was partly frozen at that time).

When the next steam-and-ash emission event began, at 0747 PST on February 5, ground observers on the south side of the mountain noted a white plume of steam which shot up to about 2 km above the crater, turned black with ash 2 to 3 min later, and wafted to an elevation about 1½ km higher. A trace of ash was later reported in Trout Lake, 50 km east of the volcano. USGS staff members who visited the crater later that day reported that ash was concentrated around both the north and east vents (Fig. 6) and that both vents were steaming profusely. The distribution of debris indicates that the north vent was the source of most ejecta, and stratigraphic relations document that emissions from this vent began when a ballistic shower threw large blocks of dome rock (b, Fig. 6) as far as 1 km to the north. Accompanying or perhaps following this shower was a surge of lithic ash (ac, Fig. 6) that swept down to and across the crater floor and about 100 m up the northeast crater wall. North of the north vent, ash and slushy snow were mobilized into a debris flow (df, Fig. 6) that overrode the newly deposited ash and continued north toward the mouth of the crater.

The final steam-and-ash emission, on February 14, 1991, was similar to the previous one but expelled material only from the north vent. Only one small explosion-like seismic event, on June 18, 1991, has been recorded since that time.

Summary of the Events and their Impact

In all, 28 shallow, explosion-like seismic events have been recorded since August, 1989; additional minor ones may have been obscured by other signals or lost when seismic stations were out of service. Of the 28 events recorded, six are known to have produced emissions of steam and ash; an additional four were observed and produced no visible emissions. Information about the remainder is insufficient to determine whether ash or steam was produced. Of the six confirmed emission events, four vented from the north shoulder of the dome; one (Dec. 20, 1990) vented from the northeast shoulder, and one (Feb. 5, 1991) appears to have vented from both locations simultaneously.

Most of the locatable earthquakes that occurred during these events were bursts of activity within minutes or hours after the onset of shaking. The depths of most were 1 to 3 km below the crater floor. In plan view, their epicenters were scattered throughout the main crater, with a modest concentration below the dome and below the west crater wall.

Because these events were far smaller than the pyroclastic eruptions that occurred in the early and mid-1980s, their

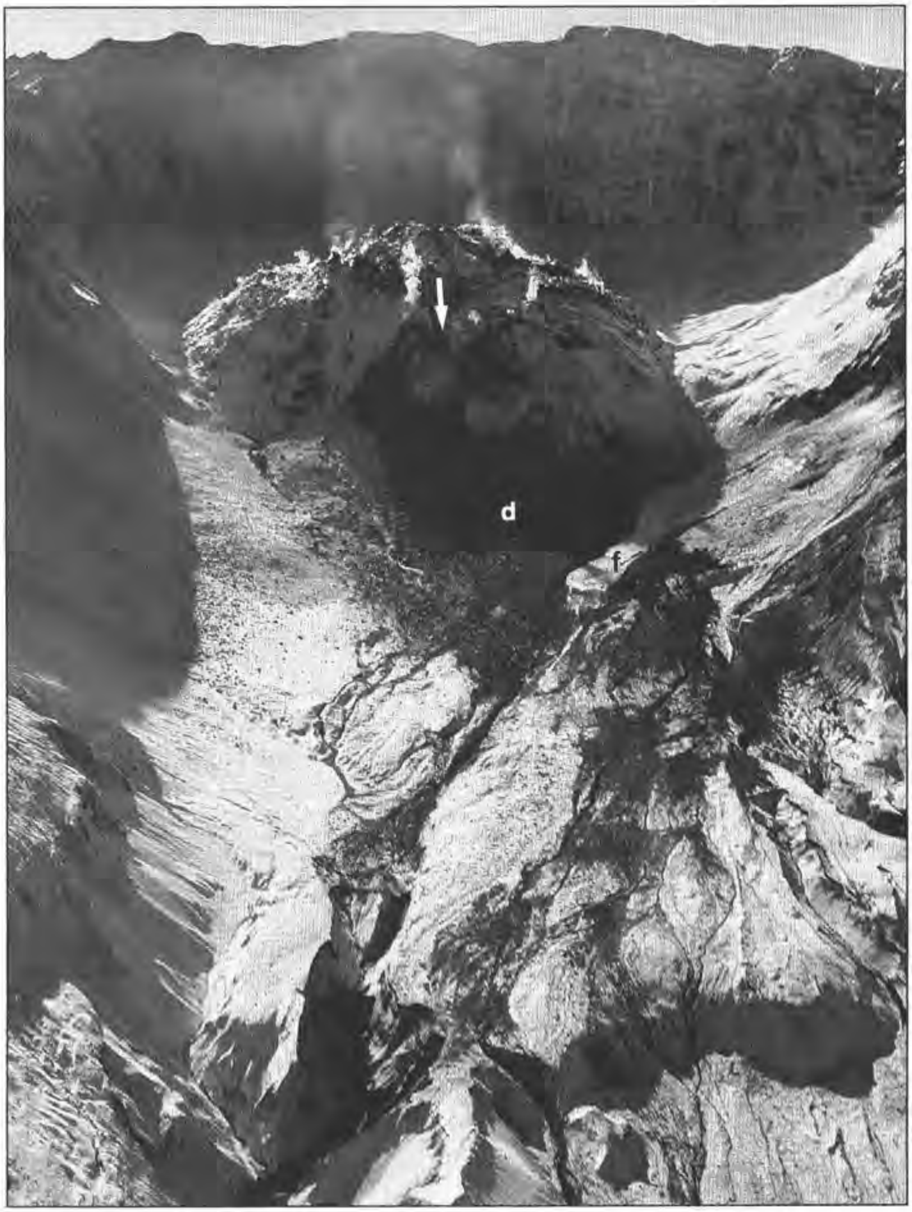

Figure 5. Mount St. Helens lava dome with light dusting of snow after the November 5, 1990, steam-and-ash emission event. The dark deposit on the north side of dome (d) resulted from a lithic-pyroclastic flow down the north side of the dome from the main vent (white arrow). Melting and mobilization of snow on the northwest side of the dome caused a flood that eroded a channel (f) through the pyroclastic-flow deposit. Snow, which fell lightly in the hours following the emission, remained on the ground in the flood channel but melted where it fell on the warm pyroclastic-flow deposit. Photo by R. B. Waitt, USGS, on November 5, 1990.

impact on local residents and structures was relatively minor. Public access to the crater has been controlled by the U.S. Forest Service since 1980; thus no one was in the immediate area during any event. Ash, which travelled as much as 140 km from the crater, was deposited only in trace amounts beyond the flanks of the mountain. Though reports of ash during the December 20, 1990, event motivated one commercial airline carrier to cancel flights downwind from the mountain that afternoon, no other significant changes in flight plans were made. The primary effect of these events has been to remind us that Mount St. Helens could return to life at any time.

Cause of Recent Activity

Steam-and-ash emission events on an active volcano such as Mount St. Helens are not unusual. Between 1975 and 1985, more than 80 eruptions of steam and non-juvenile ash occurred on active volcanoes throughout the world (McClelland and others, 1989). Experiences at Mount Lassen in 1915 (Day and Allen, 1925) and Mount St. Helens in 1980 (Lipman and Mullineaux, 1981) tell us that eruptions of steam and non-juvenile ash may precede more violent magmatic eruptions in the Cascades. Because of these reports, there was initially some concern for a possible escalation in activity during the 1989–1991 events on Mount St. Helens. On the other hand, other Cascades volcanoes, particularly Mount Baker in 1975 (Frank and others, 1977), have occasionally ejected steam and non-juvenile ash with no evidence of accompanying intrusions and no subsequent magmatic eruptions. This was evidence that the events at Mount St. Helens did not necessarily presage a return to magmatic activity. The lack of juvenile ejecta in the recent ash deposits at Mount St. Helens, and the absence of geodetic signs of inflation of the volcano or seismic evidence of magma movement, indicate that the recent events were not accompanied by intrusive activity (at least not within the uppermost few kilometers). Nevertheless, their occurrence, following 2.8 years of no eruptions, is somewhat puzzling. The recent activity may have been caused in part by a combination of two factors (1) the release of magmatic gas from the conduit or the magma chamber; or (2) meteoric water that infiltrated into hot cracks in the lava dome. There is some evidence for each factor.

Evidence for the first factor is that seismic activity at 4 to 8 km depth, which had been sparse since 1982, increased significantly in early 1989, several months before the first shallow, explosion-like seismic event (Fig. 7). Focal mechanisms of some of these events suggest that the magma chamber was repressurizing (Moran and others, 1991). Intermediate-depth seismicity then diminished near the end of 1990, a few months before the last shallow, explosion-like seismic event (Moran and others, 1991). The 1- to 3-km-deep earthquakes that accompanied the shallow, explosion-like seismicity and the occurrence of some quakes to depths of 5 km or more following the December 20, 1990, event may also suggest a source of gas below the dome and possibly a connection through the conduit to the magma chamber. (On

Figure 6. Mount St. Helens lava dome after the emission of February 5, 1991. Debris was apparently ejected from both the north vent (long white arrow) and east vent (short white arrow). Large ballistic blocks (b) and ash cloud deposits (ac) were ejected from the north vent; flood and debris-flow deposits (df) originated from the area around the north vent. Photo by R. B. Waitt, USGS, February 5, 1991.

the other hand, some such quakes may have been simply readjustments in the volcano following shaking that was initiated within the dome.)

The evidence for the second factor comes from a remarkable correlation between the timing of steam-and-ash emissions and the ends of major storms. For the six confirmed steam-and-ash emissions, the average rainfall (2.56±0.36 in.) at nearby Spirit Lake in the four days preceding each event was more than five standard deviations greater than the average (0.18 in.) in any given four-day period (Mastin and Myers, 1991). The probability that such a coincidence is fortuitous is tiny—about one in 100,000 (Mastin and Myers, 1991). Moreover, all of the confirmed ash-emission events occurred within three days after major storms (Fig. 8), and four of the six occurred less than 24 hours after the end of a storm. Many of the other events also coincide with the ends of storms, though several (including large ones on Aug. 24, 1989, and Sept. 24, 1990) occurred during fair weather.

The temporal association between the storms and ash emissions suggests that meteoric activity was partly responsible for their occurrence. What specific role it played is still unclear. If rainwater infiltrated into the dome and flashed to steam to cause the explosions, it must have been confined and pressurized under some set of conditions about which we can only speculate. Moreover, conditions within the dome that could have produced such explosive events must have been only occasionally present, because many

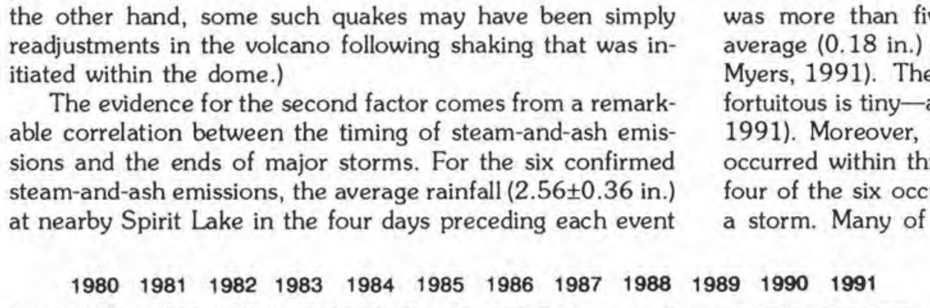

Figure 7. Depth of earthquakes under Mount St. Helens since 1980. Data and plot provided by the University of Washington.

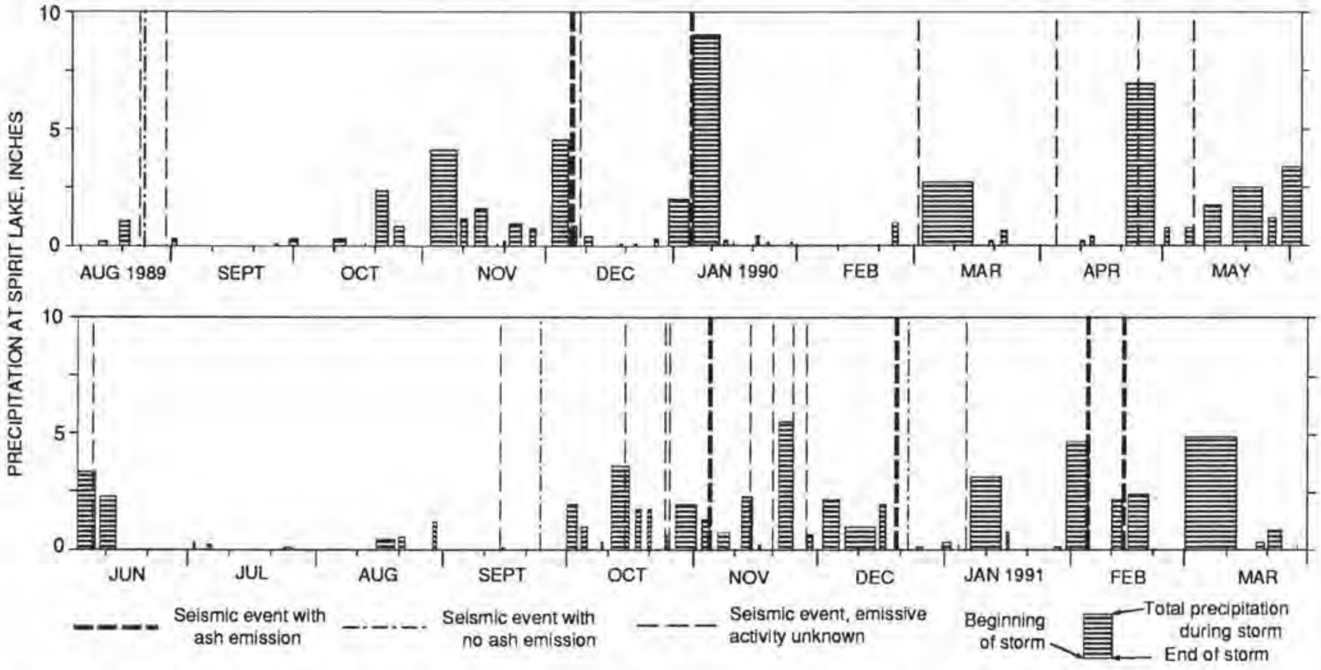

Figure 8. Timing of storms at Spirit Lake, 8 km NNE of the crater, and of shallow, explosion-like seismic events from August 5, 1989, through March 30, 1991. Small tick marks on the horizontal axis represent the 10th and 20th day of each month.

storms were not followed by explosions. A somewhat more likely role that meteoric water might have played is helping to cool the dome, thereby accelerating the growth of cooling fractures. These cooling fractures may then have intersected pockets of pressurized, exsolved gases within or below the dome. Recent deep magmatic activity could conceivably have contributed the gas for such a mechanism.

Although the specific cause of these events in the dome area has not been identified, their occurrence demonstrates that Mount St. Helens, the most active volcano in the conterminous United States, is still capable of unpredictable and sometimes violent behavior. Scientists at CVO and the University of Washington's Geophysics Program are prepared to monitor future events, if and when they occur.

Acknowledgments

Information contained in this report was collected by many workers at the USGS CVO and the Geophysics Program, University of Washington. Many field observations were provided by Richard Waitt, Edward Wolfe, Donald Swanson, Daniel Dzurisin, and Jack Kleinman. The identification of the shallow, explosion-like seismic events was made jointly by this paper's second author and by Chris Jonientz-Trisler (with help from others at the Univ. of Wash.). Earthquake locations were determined at CVO by Gloria Smith, and helpful reviews of the manuscript of this paper were made by Waitt and Jonientz-Trisler. Funding for this research has been provided by the U.S. Geological Survey's Volcano Hazards Program.

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Recent Pacific Northwest Earthquake Information

Compiled by Timothy J. Walsh

Recent research on the earthquake hazards of the Pacific Northwest, primarily in western Oregon and western Washington, is being compiled and prepared for publication by editors Al Rogers and Bill Kockelman, U.S. Geological Survey (USGS), Tim Walsh, Washington Division of Geology and Earth Resources, and George Priest, Oregon Department of Geology and Mineral Industries. Subject to Director's approval, these papers will appear collectively as USGS Professional Paper 1560, now tentatively titled "Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest".

The research represents the efforts of USGS, state geological surveys, university, and industry scientists in response to USGS initiatives under the National Earthquake Hazards Reduction Program, commonly known by its acronym, NEHRP.

The USGS open-file series is occasionally used to release selected information in a timely manner and before publication in the formal report series. Most papers destined for Professional Paper 1560 have already been released as open-file reports. An additional open-file report will contain several abstracts not yet released.

The papers to be included in Professional Paper 1560, in approximate order of presentation are:

Introduction

Rogers, A. M.; Walsh, T. J.; Kockelman, W. J.; Priest, G. R., 1992, Earthquake hazards in the Pacific Northwest—An overview: U.S. Geological Survey Open-File Report 91-441-O, 74 p.

Tectonic Setting

Paleoseismicity

Adams, John, Great earthquakes recorded by turbidites off the Oregon–Washington margin.

Atwater, B. F., Coastal evidence for great earthquakes in western Washington.

Nelson, A. R.; Personius, S. F., 1991, The potential for great earthquakes in Oregon and Washington—An overview of recent coastal geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia subduction zone: U.S. Geological Survey Open-File Report 91-441-A, 29 p.

Peterson, C. D.; Darienzo, M. E., in press, Discrimination of climatic, oceanic, and tectonic forcing of marsh burial events from Alsea Bay, Oregon, U.S.A.: U.S. Geological Survey Open-File Report 91-441-C.

Tectonics/Geophysics

Goldfinger, C.; Kulm, L. D.; Yeats, R. S.; Applegate, B.; Mackay, M.; Cochrane, G., in press, Active strike-slip faulting and folding in the Cascadia plate boundary and forearc in central and northern Oregon: U.S. Geological Survey Open-File Report 91-441-S.

Ma, Li; Crosson, R. S.; Ludwin, R. S., 1991, Focal mechanisms of western Washington earthquakes and their relationship to regional tectonic stress: U.S. Geological Survey Open-File Report 91-441-D, 38 p.

Weaver, C. S.; Shedlock, K. M., 1991, Estimates of seismic source regions from considerations of the earthquake distribution and regional tectonics: U.S. Geological Survey Open-File Report 91-441-R, 25 p.

Yeats, R. S.; Graven, E. P.; Werner, K. S.; Goldfinger, C; Popowski, T. A., 1991, Tectonic setting of the Willamette Valley, Oregon: U.S. Geological Survey Open-File Report 91-441-P, 47 p.

Earthquake Hazards

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Cohee, B. P.; Sommerville, P. G.; Abramson, N. A., 1991, Ground motions from simulated M_w=8 Cascadia earthquakes: U.S. Geological Survey Open-File Report 91-441-N, 35 p.

King, K. W.; Carver, D. L.; Williams, R. A.; Worley, D. M., 1991, Site response studies in west and south Seattle, Washington: U.S. Geological Survey Open-File Report 91-441-Q, 16 p.

Madin, I. P., in press, Earthquake-hazard geology maps of the Portland metropolitan area, Oregon: U.S. Geological Survey Open-File Report 91-441.

Silva, W. J.; Wong, I. G.; Darragh, R. B., 1991, Engineering characterization of strong ground motions with applications to the Pacific Northwest: U.S. Geological Survey Open-File Report 91-441-H, 24 p.

Ground Failure

Chleborad, A. F.; Schuster, R. L., 1990, Earthquake-induced ground failure associated with the April 13, 1949, and April 29, 1965, Puget Sound area, Washington, earthquakes: U.S. Geological Survey Open-File Report 90-687, 136 p.

Grant, W. P.; Perkins, W. J.; Youd, L., in press, Liquefaction susceptibility maps for Seattle, Washington North and South quadrangles: U.S. Geological Survey Open-File Report 91-441.

Earthquake Risk Assessment

Wang, L. R. L.; Wang, J. C. C.; Ishibashi, Isao, 1991, GIS applications in seismic loss estimation model for Portland, Oregon water and sewer systems: U.S. Geological Survey Open-File Report 91-441-F, 71 p.

Implementation

Kockelman, W. J., 1991, Techniques for reducing earthquake hazards—An introduction: U.S. Geological Survey Open-File Report 91-441-L, 24 p.

Booth, D. B.; Bethel, J. P., 1991, Approaches for seismic hazard mitigation by local governments—An example from King County, Washington: U.S. Geological Survey Open-File Report 91-441-G, 8 p.

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Current Research on Eocene Conifers at Republic, Washington

by

Wesley C. Wehr
The Burke Museum
University of Washington
Seattle, WA 98195

and

Howard E. Schorn
Museum of Paleontology
University of California
Berkeley, CA 94720

The fossil beds in and near Republic, in western Ferry County, are known for their superbly preserved leaves, flowers, fish, and insects. (See *Washington Geologic Newsletter*, v. 14, no. 4; *Washington Geology*, v. 19, no. 3.) These middle Eocene deposits also contain a remarkably diverse assemblage of fossil conifers. Many of these forms are the 49-m.y.-old ancestors of conifers that are now native only to China and Japan.

The fossils of the Republic upland forest include many of the earliest and best-documented records of *Abies* (true fir), *Picea* (spruce), *Tsuga* (hemlock), *Thuja* (arborvitae), and *Chamaecyparis* (false cedar), as well as such currently exotic conifers as *Amentotaxus* (Chinese yew), *Sciadopitys* (umbrella pine), and *Pseudolarix* (Chinese golden larch). The last three Asian genera are now extinct in North America. Five families of conifers occur in the Republic flora: Ginkgoaceae (ginkgo), Taxaceae (yew), Taxodiaceae (redwood), Pinaceae (pine), and Cupressaceae (cypress). A multivariate analysis of leaves (dicotyledonous plants) led Wolfe and Wehr (1991) to conclude that the average mean annual temperature was about 10°C, which falls within a climate termed microthermal, that is, where the mean annual temperature is less than 13°C.

In contrast, fossils of somewhat older forests in the Puget Lowland record only two conifer families: redwood and cypress. The Eocene Chuckanut Formation contains remains of three genera of the redwood family, *Metasequoia* (dawn redwood), *Sequoia* (redwood), and *Glyptostrobus* (Chinese water pine). The cypress family is represented by only one genus, *Mesocyparis*, which is extinct. Also present in this coastal forest, recorded in the Chuckanut Formation near Bellingham and in the approximately contemporaneous Swauk Formation near Blewett Pass, are palm fronds and fossil ferns representing genera (*Danae, Pteris, Cyathea*, and *Athyrium*) (Pabst, 1968) that are today confined to Central America and the Southern Hemisphere. None of these fern or palm taxa is known in the Republic flora.

The fossil record is beginning to show that at least some conifer genera first evolved in paleoclimates similar to those in which they live today. The geologic history of *Abies* suggests that since its early appearance in the microthermal forests of the Okanogan Highlands (at Republic and at Princeton, B.C.), it has had continuous confinement to upland temperate forests. The macroscopic fossil records for *Tsuga* and *Picea* suggest a similarly restricted climatic history. On the other hand, among the other pinaceous genera, *Pinus*, *Keteleeria*, and *Pseudolarix* have well-documented pre-middle Eocene histories in wider climatic ranges. *Pseudolarix* is known from older sedimentary rocks, the late Paleocene–early Eocene Golden Valley Formation of North Dakota, where it appears to have been part of a lowland flora that was subtropical (Gooch, 1992). Additionally, in contrast to its present restriction to 2,000- to 7,000-ft elevations from Alaska to northern California, *Chamaecyparis* is well documented in Eocene lowland/coastal subtropical forests.

One troublesome aspect of conifer studies is the fact that fossil pinaceous seeds are easily misidentified, particularly if they are not well preserved or if only the non-seed-bearing side is exposed. Small winged seeds of *Pinus* are commonly confused with those of *Picea*. The winged seeds of *Tsuga*, *Larix*, *Pseudotsuga*, and *Pseudolarix* are often mistaken for each other. Because distinguishing conifer seeds is so difficult, the literature contains many instances of misassignments (e.g., Axelrod, 1987). This can lead to naming more genera or species than might be justifiable if the gradations of winged seed features within a population were known. (See examples of seeds, Plate 1.)

Only recently has a detailed and more satisfactory key to pinaceous winged seeds been available (Wolfe and Schorn, 1990). The many specimens of these seeds in the Republic lakebed strata promise to help clarify affinities and allow refinement of generic or specific characters.

Fossil foliage of the cypress family has traditionally been hard to sort out. An historic example of the problem created by reliance on fossil cypress foliage is the story of *Mesocyparis*, which is found in the Chuckanut Formation. Newberry (1868) and later Pabst (1968), using the foliage characters, put this fossil in two different genera, but examination of the distinctive cones (which are commonly attached to the foliage) shows that these fossils actually belong to a third,

Plate 1. **A,B**, *Picea* spp. winged seeds, x1.2. **C,D**, *Pseudolarix* sp.; **C**, winged seed, x2.5; **D**, foliage, x1.2. **E**, *Tsuga* sp. winged seed (below leaf fragment), x1.2. **F–K**, *Pinus* spp.; **F**, two-needle foliage, x1.2; **G**, four-needle foliage, x1; **H**, five-needle foliage, x1; **I**, cone, x.6; **J**, pollen cone, x1.2; **K**, hard pine seed wing, x1.75. **L,M**, *Chamaecyparis* sp. foliage, x1.4. **N,O**, *Thuja* sp.; **N**, foliage, x1.3; **O**, cones, x2. Photos by Alan Yen, scale approximate.

PLATE 1

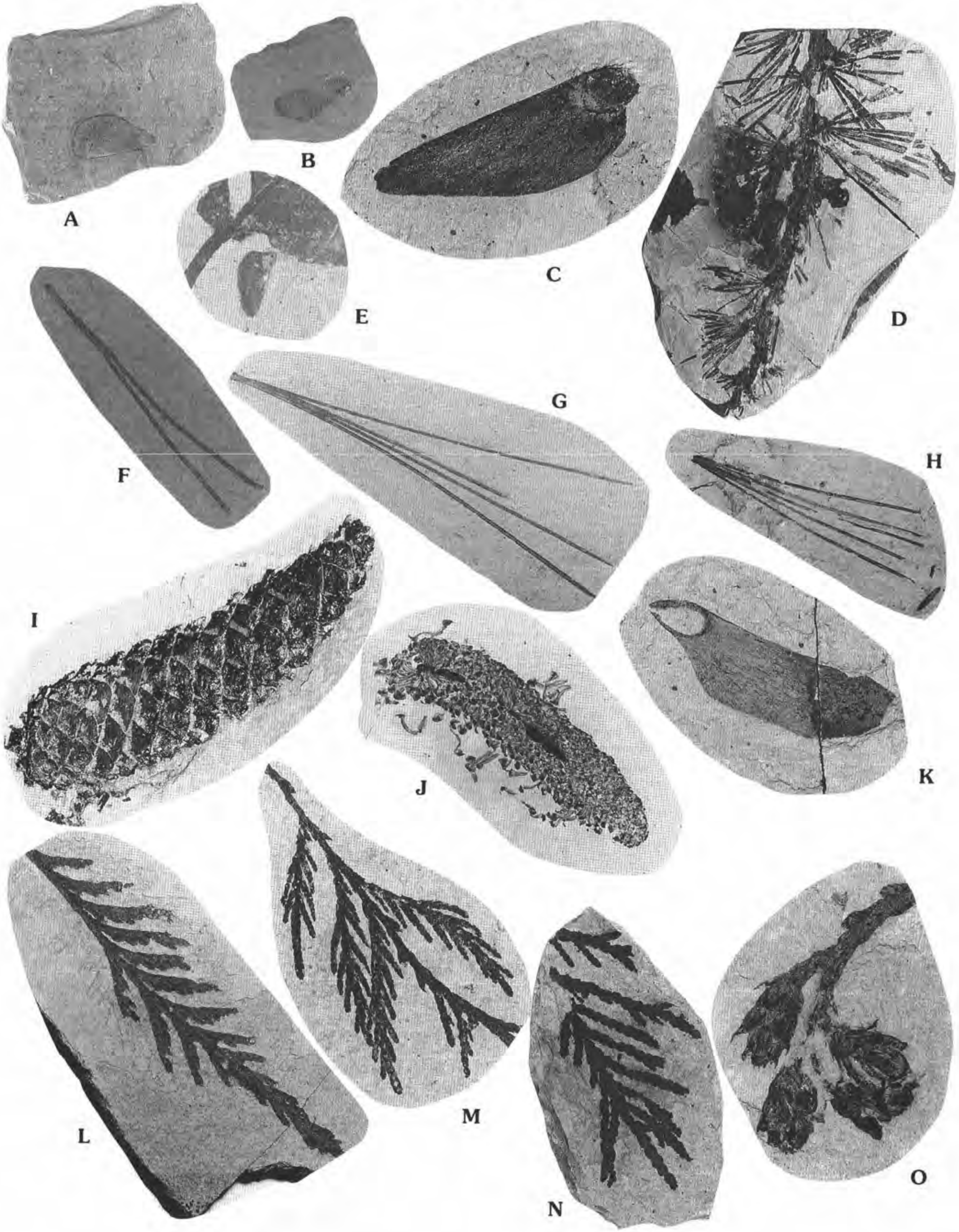
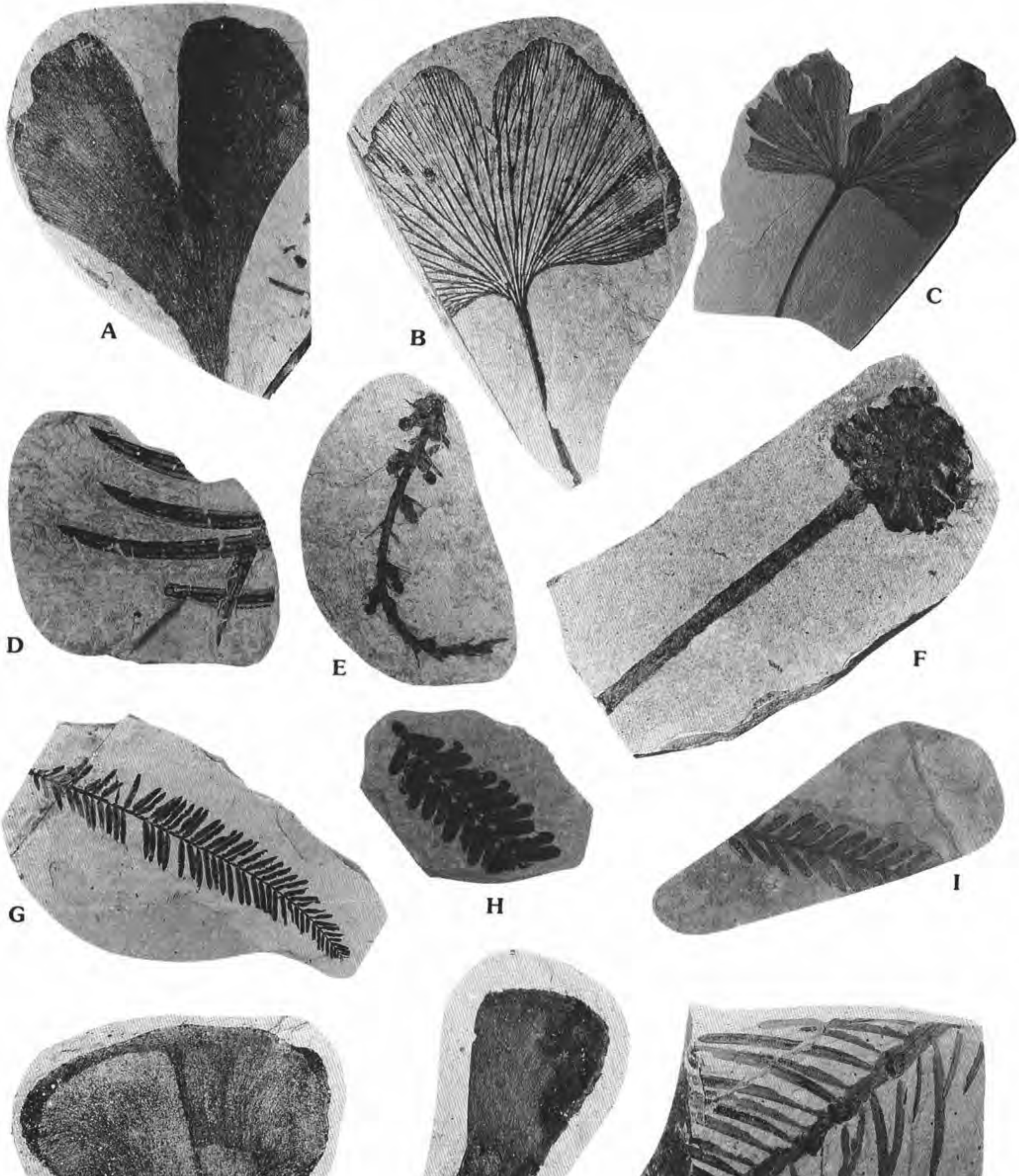


PLATE 2



then new, genus (McIver and Basinger, 1987). Republic's fossil cones are providing helpful keys to the conifer taxonomic puzzle. A *Thuja* cone found in 1977 confirms that arborvitae-like foliage in the fossil flora can safely be assigned to that genus. (Compare foliage and cones, Plate 2.)

Nancy Gooch of the Museum of Paleontology at the University of California, Berkeley, is studying a fossil conifer first found at Republic in 1937 by Roland Brown (U.S. Geological Survey). At that time Brown identified it as *Picea*, but three years later, he determined that the form is *Pseudolarix*. The winged seeds and cone scales of this genus were particularly important to correctly identifying its Eocene representative. This find became the first recognized fossil occurrence of the golden larch. Although the tree is now known from other localities, including Princeton, B.C., Republic has yielded more specimens of winged seeds and cone scales of this taxon than any other site in the world, providing a rare opportunity for examination of intraspecific variation (Gooch, 1992).

A multidisciplinary approach to the geologic history of *Tsuga* is under way by University of Washington palynologist Estella Leopold, her students Cindy Updegrave and Katie Maier, and paleobotanists Wehr and Schorn. Work to date on the pollen and winged seeds suggests that this genus may have originated in the Eocene Okanogan highlands. The *Thuja* cone also assists in determining what some of the poorly preserved *Thuja*-like pollen might have come from. Samples from a locality known as One Mile Creek, in the Allenby Formation in British Columbia, which is of the same age as the Republic rocks, are yielding some well-preserved pollen that is confirming the presence of genera identified by macrofossils as well as hinting at others not yet found. These samples are also helping the work at Republic by offering excellent material for comparison.

Republic's fossils are also helping to change an old paleobotanical practice of identifying ancient plants to fit a preconceived paleoenvironment. Berry (1935) noted "It seems that *Thuja* fits into my picture of the environmental conditions better than *Libocedrus*." This thinking has led to some strained reconstructions of fossil forest floras, such as Chaney's redwood forest (Chaney, 1925), which consisted of trees assigned to genera that would be found in an equivalent modern forest. The "redwood" was actually *Metasequoia*, whose foliage and cones are easily distinguished from *Sequoia*, and the paleoecological models based on this erroneous identification were therefore flawed. The amount of material available to Berry and Chaney was significantly less than is now known, and diagnostic techniques seem primitive in comparison to what is possible today. Work on the Republic material is directed toward refining both taxonomy and techniques.

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To visit the Republic site, first check in with the Stonerose Interpretive Center, just downhill from the site near the city park. After registering at the Center, visitors can dig at the site Tuesday–Sunday, 10:00 a.m.–5:00 p.m. Bring a cold chisel and hammer. Take your finds to the Center for identification. A seminar led by Wes Wehr will be held at the site September 17–20; for more information, contact Northwest Interpretive Association, 83 S. King St., Suite 212, Seattle, WA 98104.

Plate 2. **A**,**B**,**C**, a coniferophyte, *Ginkgo* sp., x1.2. **D**, *Amentotaxus* sp. foliage, x1.2. **E–H**, *Metasequoia* sp.; **E**, pollen cones, x1.2; **F**, seed (female) cone x2; **G**,**H**, foliage, x1.2, x2 respectively. **I**, *Sequoia* sp. foliage, x1.2. **J**,**K**, *Abies milleri*; **J**, cone scale, x3; **K**, winged seed, x2. **L**, stem with needles, x1.5. Photos by Alan Yen; scale approximate.

Washington Framework for Seismic Risk Reduction

by Timothy J. Walsh

In 1990, the Washington State legislature enacted House Bill 2929, the Growth Management Act (GMA). The GMA required the largest and fastest growing counties and all of their included cities to adopt comprehensive plans and to make zoning consistent with the plan. Planning is required to consider geologic hazards (among other things). The 1991 legislature extended the requirement to identify and protect critical areas (including geologically hazardous areas) to all 39 counties and their included cities.

The basic approach of most jurisdictions for regulations that relate to seismic risk is the mapping of liquefaction susceptibility coupled with a requirement that applicants for building permits within potentially hazardous areas must demonstrate the safety of the proposed project.

Some other jurisdictions are also attempting to zone areas of amplification, but historic intensity and shear-wave velocity data are generally not available outside the Seattle-to-Olympia corridor.

The legislature also created a temporary Seismic Safety Advisory Committee to make recommendations for improving the state's earthquake preparedness. The implementing legislation narrowly failed in the 1992 legislature but will be reintroduced in the 1993 legislature. The committee recommended, among other things:

- That the state of Washington support a strong motion instrumentation program as outlined in U.S. Geological Survey (USGS) Open-File Report 89-374. As an initial effort, the Washington Department of Natural Resources (DNR), Division of Geology and Earth Resources (DGER), is sharing with the USGS the cost of instrumenting DNR's new headquarters building in Olympia.
- That the seismic zonation for western Washington be re-evaluated (in conjunction with the state of Oregon, which is attempting to upgrade western Oregon to seismic zone 3). The application to amend the Uniform Building Code is in preparation and will be sent to the International Conference of Building Officials in June 1992. The seismic zone map is not yet complete but will put all of western Washington into zone 3.
- That DNR, in conjunction with the USGS, support and coordinate geologic mapping of sensitive areas, at least in part to achieve the goals of the GMA. DGER is currently preparing a new state geologic map. The full-color map is at a scale of 1:250,000 and is supported by a more detailed set of open-file maps at a scale of 1:100,000. We are also investigating liquefaction, both in sets of liquefaction-susceptibility quadrangle maps that aid land-use planning and in geotechnical investigations of historic liquefaction events, such as the numerous sand blows induced by the 1949 Puget Sound earthquake. These studies have suggested that moderately to well-sorted, liquefiable sand can be deposited in valley bottoms as distal facies of volcanic eruptions or debris flows. These sands can be much thicker than sand deposited by normal fluvial processes. Studies are continuing to determine the sedimentary processes responsible for the deposition of these liquefiable sands and to map them in other drainages. ■

Proclamation of the State of Washington

Whereas, *the state of Washington has experienced significant earthquakes in the past, and scientific evidence indicates that Washington will experience earthquakes in the future; and*

Whereas, *the state Seismic Safety Advisory Committee presented its report to the Legislature in December 1991 recognizing the need for greater public awareness and preparedness for earthquakes; and*

Whereas, *the loss of life and property damage can be greatly reduced if appropriate earthquake preparedness measures are taken before, during and after a damaging quake; and*

Whereas, *state agencies should be prepared at their facilities, and state workers prepared in their homes, so they can continue ongoing public services after a quake, and support the state's disaster-response mission; and*

Whereas, *the citizens of our state need to be prepared to be self-sufficient for 72 hours in the event of an earthquake; and*

Whereas, *lifesaving preparedness procedures will be highlighted during April as the State Department of Community Development and city and county emergency-services programs raise awareness of earthquake safety with the theme of "Earthquake Safety at Home";*

Now, therefore, *I, Booth Gardner, Governor of the State of Washington, do hereby proclaim April 27–May 1, 1992, as*

Earthquake Awareness Week

in the State of Washington, and I urge all citizens to become prepared for this destructive force of nature.

Signed, this 23rd day of March, 1992, by Governor Booth Gardner

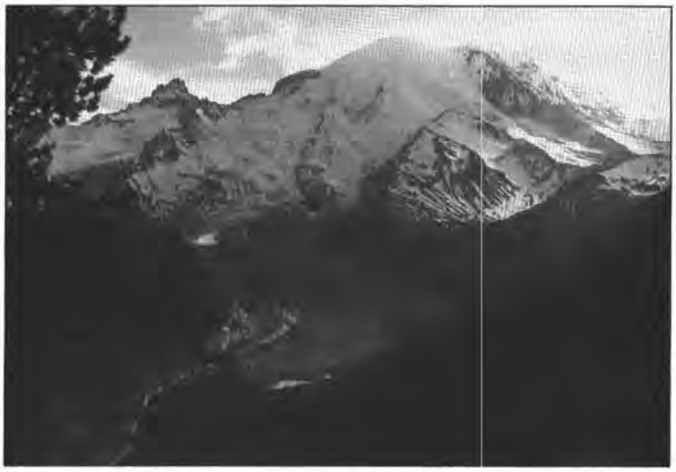
Taken verbatim from the Governor's proclamation

Uzbek Scientists Visit Olympia. On May 13, Deputy Supervisor Stan Biles and State Geologist Ray Lasmanis attended a meeting between a delegation from the Republic of Uzbekistan, C.I.S., and the Governor of Washington. Makhmud Salakhitdinov, President of the Uzbek Academy of Sciences expressed the desire to develop closer ties with Washington State institutions and the private sector. He said he would also like to see a branch of American University established in Tashkent. From the left: Askar G. Khalmuradov, Vice President, Uzbek Academy of Sciences; Ilse D. Cirtautas, Chair, Near Eastern Languages and Civilization, University of Washington; Governor Booth Gardner; Makhmud S. Salakhitdinov, Parliamentarian and President, Uzbek Academy of Sciences; Bekhzad S. Yuldashev, Director, Institute of Nuclear Physics, Uzbek Academy of Sciences. ■

Mt. Rainier Selected as "Decade Volcano"

In 1989, a task group set up by the International Association of Volcanology and Chemistry of the Earth's Interior was selected to work with the International Decade for Natural Hazard Reduction. The group has chosen several volcanoes for focused study during the remainder of this decade. Criteria for selection of a volcano are: that it present one or more volcanic hazards; that it be geologically active; and that it be in a populated area. Mount Rainier amply qualifies on all counts. Deposits of tephra, lava, and pyroclastic materials are well documented, as are voluminous mudflows that contain hydrothermally altered material. There is more snow on ice on Rainier than any other volcano in the conterminous states; melting of large volumes of ice during an eruption could produce heavy floods through major population centers—the mountain is only about 40 miles from Tacoma. Mount Rainier last erupted about 150 years ago, and a variety of signals have been recorded in the last two decades. The significance of recent seismic activity concentrated near the summit is not yet understood.

An article in the April 21, 1992, edition of Eos (Transactions of the American Geophysical Union) details planned and current studies attempting to determine why Mount Rainier has been the site of intrusive magmatism and eruptions, what kinds of hazards exist, and what mitigation strategies might be effective.



West view of Mount Rainier from Emmons Vista at Sunrise. Snow-covered Columbia Cone fills the large crater created by the 3 km^3 Osceola Mudflow about 5,000 years ago. An eruption about 150 years ago produced pumice.

Division of Geology and Earth Resources geologists Eric Schuster and Patrick Pringle were instrumental in preparing the documentation that led to the selection of Mount Rainier as a Decade Volcano. ■

Selected Additions to the Library of the Division of Geology and Earth Resources

February 1992 through April 1992

THESES

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U.S. GEOLOGICAL SURVEY REPORTS

Published Reports

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GEOLOGY AND MINERAL RESOURCES OF WASHINGTON

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Slemmons, D. B.; Engdahl, E. R.; Zoback, M. D.; Blackwell, D. D., editors, 1991, Neotectonics of North America: Geological Society of America DNAG Decade Map Volume 1, 498 p.

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Bobrowsky, P. T.; Giles, T.; Jackaman, W., 1992, Surficial geology map index of British Columbia: British Columbia Geological Survey Branch Open File Report 1992-13, 1 v.

Bullen, K. E.; Bolt, B. A., 1985, An introduction to the theory of seismology; 4th ed.: Cambridge University Press, 499 p.

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McMillan, W. J.; Höy, T.; MacIntyre, D. G.; and others, 1992, Ore deposits, tectonics and metallogeny in the Canadian Cordillera: British Columbia Geological Survey Branch Paper 1991-4, 276 p.

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1992 Geological Projects, Washington Colleges and Universities

This list is taken from material submitted by press time by the geology departments of the state's colleges and universities. Names in parentheses with the faculty projects are student collaborators unless otherwise noted; with student projects, they are faculty collaborators unless otherwise noted. Affiliations other than with the pertinent college or university are bracketed. Some projects involve areas outside Washington.

EASTERN WASHINGTON UNIVERSITY

Faculty projects

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

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

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

Formulation of a finite-difference computer model (MODFLOW) for the Spokane Valley aquifer system, Spokane County, Washington—*John P. Buchanan*

Delineation of aquifer recharge areas for the Wanapum aquifer, Lincoln County, Washington—*John P. Buchanan*

Hydrogeology of Long Lake, Spokane and Stevens Counties, Washington—*John P. Buchanan*

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

Radon gas distribution in cave systems near Ely, Nevada—*John P. Buchanan*

Survey of karst features in the Pryor Mountains, Montana—*John P. Buchanan*

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

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

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

Chemical analysis of ultrapure electronic materials—*Mohammed Ikramuddin*

Development of new analytical methods by inductively coupled argon plasma and electrothermal atomic absorption—*Mohammed Ikramuddin*

Distribution of immobile trace elements in hydrothermally altered rocks associated with various types of gold deposits—*Mohammed Ikramuddin*

Geochemistry of sediment-hosted precious metals deposits—*Mohammed Ikramuddin*

Geochemistry of volcanic rocks and its relationship to gold-silver mineralization—*Mohammed Ikramuddin*

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

Rare earth element geochemistry of gold deposits—*Mohammed Ikramuddin*

Reconnaissance lithogeochemical survey of northwest Pakistan—*Mohammed Ikramuddin*

Study of toxic elements in environmental samples—*Mohammed Ikramuddin*

Thallium—A potential guide to mineral deposits—*Mohammed Ikramuddin*

Trace element geochemistry of stream sediments and waters affected by mining—*Mohammed Ikramuddin*

Use of cesium and boron as a guide to mineral deposits—*Mohammed Ikramuddin*

Geology of national parks—*Eugene P. Kiver*

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

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

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

Stratigraphy, sedimentology, and paleontology of the Cambrian System of the Great Basin—*Linda B. McCollum*

Structure and stratigraphy of the Middle Paleozoic Antler Orogen in northwestern Nevada—*Linda B. McCollum*

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

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

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

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

Petrology of the Quartz Hill molybdenum deposit, Alaska—*James R. Snook*

Styolites in igneous rocks—*James R. Snook*

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

Mechanism of acquisition of remanent magnetization by air-fall ash—*William K. Steele*

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

Student projects

Computer exercises in pattern recognition applied to exploration for mineral deposits related to igneous rocks—*Glen R. Carter*

Origin and mineralization of Colorado Plateau uranium-copper-bearing breccia pipes—*J. Michael Faurote*

Characterization of alunite in the Gold Quarry mine, Eureka County, Nevada—*Dean G. Heitt*

Hydrology of Long Lake, Spokane and Stevens Counties, Washington—*Michael S. Johnson*

Hydrogeology of the Haripur Plain, Pakistan—*Christopher T. Jones*

Rare earth element geochemistry of volcanic-hosted gold deposits—*Calvin A. Landrus*

Hydrochemical characteristics of an unconsolidated aquifer down-gradient from an oxidized, sulfidic mine tailings impoundment—*Robert H. Lambeth*

Biogeochemical methods of exploration for Archean gold deposits—*Richard B. Lestina*

Abundance and behavior of cesium and selected trace elements in rock, soil, and water samples from the Republic area, northeast Washington—*Wilfred H. Little*

Fenestrate bryozoans of the Toroweap Formation, Clark County, Nevada—*Miriam E. McColloch*

Platinum-group elements in alkaline igneous rocks—*Thomas C. Mooney*

Formulation of a finite-difference ground-water flow model for the Spokane Valley aquifer—*Iain A. Olness*

Gallium in Carlin-type gold deposits—*Phillip A. Owens*

Geochemistry of igneous rocks from Newport and adjacent areas, northeastern Washington—*L. Christine Russell*

Ground-water geochemistry down-gradient from a uranium mill tailings pond—*Ronald A. Stone*

WASHINGTON STATE UNIVERSITY

Faculty projects

Age and distribution of Cascade tephras in the Pacific Northwest—*F. F. Foit, Jr.*

Crystal chemistry of the tourmaline group—*F. F. Foit, Jr.*

Eolian morphology, sedimentology, and paleoclimatic significance, Hanford site, Washington—*David R. Gaylord*

Geologic and geohydrologic site characterization studies, Hanford site, Washington—*David R. Gaylord and Eileen P. Poeter [Colorado School of Mines and Technology]*

Sedimentology and stratigraphy of middle Eocene volcanogenic deposits, northeastern Washington and southern British Columbia—*David R. Gaylord*

Deformation along the Olympic/Wallowa Lineament, Oregon and Washington—*Peter R. Hooper*

The Columbia River basalts in the Lewiston Basin and along the Blue Mountains uplift (Oregon and Washington)—*Peter R. Hooper*

Deccan basalts—*(John E. Beane), Peter R. Hooper, and John Mahoney [University of Hawaii]*

Fifes Peak volcanic rocks of the western Cascades, south Washington—*Paul Hammond [Portland State University] and Peter R. Hooper*

Karoo basalts—*Peter R. Hooper, Robert A. Duncan [Oregon State University], Andy R. Duncan [University of Cape Town, South Africa], and Julian Marsh [Rhodes University, South Africa]*

Paleomagnetism of volcanic rocks in the Pacific Northwest—*Peter R. Hooper, William K. Steele [Eastern Washington University], (David G. Bailey), (Richard M. Conrey), (Kevin M. Urbanczyk), and (Sandra P. Lilligren)*

Primitive basalt flows in the Pacific Northwest—*(David G. Bailey), (Richard M. Conrey), and Peter Hooper*

Prineville Basalt—*Peter R. Hooper, (Richard M. Conrey), (David G. Bailey), (Kevin M. Urbanczyk), William K. Steele [Eastern Washington University], Terry L. Tolan [Portland State University], and Gary Smith [University of New Mexico]*

Age-dating dissolved inorganic carbon and dissolved organic carbon in ground waters—*C. Kent Keller*

Carbon cycling in ancient terrestrial environments—*C. Kent Keller*

Oxygen isotope investigations of igneous rocks, northeastern Washington—*Peter B. Larson*

Water–rock interaction in the Rico hydrothermal system, Colorado—*Peter B. Larson*

Exploration targets for the next century—Metals in the metasomatic environment—*Lawrence D. Meinert*

High-temperature gold-quartz veins in distal portions of porphyry copper districts—*Lawrence D. Meinert and (John Link)*

Isotopic tracking of mineralizing fluids in skarn deposits—*Lawrence D. Meinert and (Brian Zimmerman)*

Analysis of topography using automated computer methods and application to petroleum exploration problems in southeastern New Mexico—*Richard L. Thiessen*

Automated fracture analysis of the Nevada Test Site using digital topography—*Richard L. Thiessen and Michael G. Foley*

Computer-aided techniques for the delineation of lineaments on image, topographic, and geophysical databases—*Richard L. Thiessen*

Geophysical investigations of the cratonic margin in the Pacific Northwest—*Richard L. Thiessen*

Integration of three-dimensional computer databases for the delineation of active fault and fracture systems in the Puget Sound—*Richard L. Thiessen*

Refold analysis of multiply deformed mines and mining districts—*Richard L. Thiessen and A. John Watkinson*

Structural analysis of the central Columbia Plateau utilizing radar, Landsat, digital topography, and magnetic databases—*Richard L. Thiessen*

The significance of orogen-parallel lineations—*A. John Watkinson*

Structural evolution of metamorphic core complexes, northeast Washington—*A. John Watkinson*

Annotated bibliography of Carboniferous conodonts—*Gary D. Webster with Carl B. Rexroad [Indiana Geological Survey]*

Bibliography and index of Paleozoic crinoids—*Gary D. Webster*

Biostratigraphic analysis of three potential mid-Carboniferous boundary stratotypes in the Great Basin—*Gary D. Webster and Larry E. Davis*

Early Carboniferous crinoid faunas of the western United States (includes materials of Kinderhookian and Osagean age from Montana, Utah, Idaho and Nevada)—*Gary D. Webster*

Permian crinoids of Western Australia—*Gary D. Webster*

Refold geometries observed in the Loch Monar region, Scotland—*A. John Watkinson*

Student projects

Provenance of the Ringold Formation on the southern part of the Hanford site, Washington—*Michael G. Bednar*

Geology and geochemistry of gold skarn mineralization in the McCoy mining district, Lander County, Nevada—*Jeffrey W. Brooks*

Kinematics and strain in the Lincoln gneiss dome, northeast Washington—*Jay P. Busch and (A. John Watkinson)*

Dissolved organic carbon in vadose-zone pore water—*Richard Crum and (C. Kent Keller)*

Foraminifera and conodont biostratigraphy and carbonate microfacies of Early Carboniferous shelf to basin sediments, north-central Wyoming to southeastern Idaho—*Aram M. Derewetzky, Chen Xiaobing, and (Gary D. Webster)*

Rhyolitic flows in the Toroda Creek graben, northeastern Washington—*Thomas C. Ellifritz and (Peter R. Hooper)*

Bulk gas-phase diffusion coefficients in unsaturated loess—*Diane M. Foster and (C. Kent Keller)*

The Eckler Mountain Member [revision of status], Columbia River Basalt Group in Oregon, Washington, and Idaho—*Beth A. Gillespie and (Peter R. Hooper)*

Carbon mass fluxes in vadose zones—*Diana J. Holford and (C. Kent Keller)*

Fracture patterns and fold-related strain using examples from the Yakima Fold Belt, Washington, and the Montana fold and thrust belt—*Sarah M. Koerber and (A. John Watkinson)*

Relation between volcanism and tectonics in the Vale area, eastern Oregon—*Kate Lees, [Chris Hawkesworth, Open University, U.K.], and (Peter R. Hooper)*

Geochemical distribution of elements at the Overlook deposit and their lithologic and structural relationships—*Christopher H. Lowe (Peter B. Larson)*

Stratigraphy and sedimentology of the O'Brien Creek Formation, northeastern Washington and southern British Columbia—*Jeffrey M. Matthews*

Northern part of the Colville batholith, northeastern Washington—*George A. Morris and (Peter R. Hooper)*

Gold skarn mineralization in the Fortitude deposit, Lander County, Nevada—*Greg L. Myers*

Identification of range-front fault scarps using digital topography databases and application to the Wasatch Front, Utah—*Douglas S. Neves*

Distribution of environmental tritium and ground-water recharge in the Palouse Formation—*Rachel O'Brien and (C. Kent Keller)*

Weiser basalts, west-central Idaho—*Jakub Rehacek and (Peter R. Hooper)*

Determination of the three-dimensional orientation and location of the Cascadia subduction zone, Washington, using earthquake foci—*Eric R. Rieken*

Analysis of the spatial distribution of the Loma Prieta, California, aftershock sequence—*Eric R. Rieken*

Geology of the Tillicum gold skarn camp, British Columbia—*Dean M. Peterson*

Detailed structural analysis and mineral/vein paragenesis of Barrick Gold Strike Mines property, Carlin trend, Nevada—*Thomas R. Sampson (Peter B. Larson)*

Syenites around the Idaho batholith, Idaho—*D. Kate Schalck*

Sedimentology and geoarchaeology of eolian deposits on the Hanford site, Washington—*Grant D. Smith*

Analysis of geophysical databases for the Pasco Basin—*Stanley M. Sobczyk*

Geophysical parameters and tectonic structure of the Columbia Plateau—*Stanley M. Sobczyk and (Peter R. Hooper)*

Sedimentology, stratigraphy, and paleoclimatic implications of eolian deposits on the Hanford site, Washington—*Larry D. Stetler*

Regional stratigraphy and sedimentology of the upper Sanpoil Volcanics and Klondike Mountain Formation in the Republic, First Thought, and Toroda Creek grabens, Washington and southern British Columbia—*James D. Suydam*

Geochemical study of the Copper Vein, Sunshine Mine, Kellogg, Idaho—*Carl B. Trachte (Peter B. Larson)*

The volcanic rocks of the eastern Clarno, north-central Oregon—*Kevin M. Urbanczyk, Sandra P. Lilligren, and (Peter R. Hooper)*

Colville batholith and Sanpoil Volcanics—*Laureen J. Wagoner and (Peter R. Hooper)*

Gold skarn mineralization in clastic host rocks, Beal mine, Montana—*Kurt M. Wilkie*

WESTERN WASHINGTON UNIVERSITY

Faculty projects

Petrology and geochemistry of the Hannegan and Swift Creek volcanic rocks, north Cascades Range—*Scott R. Babcock (with Julie Thompson)*

Petrology, geochemistry, and structure of the Crescent basalts and related rocks—*Scott R. Babcock*

Argon-laser chronology of Pleistocene sediments in the Pacific Northwest—Alderton, Stuck, Double Bluff, and Possession stratigraphic units and Whidbey Formation—*Don J. Easterbrook*

Causes of debris torrents and extreme flooding in northwest Washington—*Don J. Easterbrook*

Holocene fluctuations of glaciers on Mount Baker—Radiocarbon dating of a forest buried in lateral moraines and dating of late Holocene moraines by tree coring—*Don J. Easterbrook*

Investigation of mega-landslides in Whatcom County—*Don J. Easterbrook*

Thermoluminescence dating of Quaternary sediments—Double Bluff, Whidbey, and Possession stratigraphic units—*Don J. Easterbrook (with Glenn Berger)*

Relationships among Tertiary sedimentary rocks overlying the Crescent Formation, northern Olympic Peninsula—*Christopher A. Suczek*

Student project

Petrography of the Miocene–Pliocene Ringold Formation in the southern Pasco Basin, southcentral Washington State [Master of Science thesis]—*Shannon Goodwin*

YAKIMA VALLEY COMMUNITY COLLEGE

Faculty projects

Late Cenozoic faulting in the Columbia Basin—*Newell P. Campbell*

Sub-basalt stratigraphy in the Columbia Basin—*Newell P. Campbell* ■

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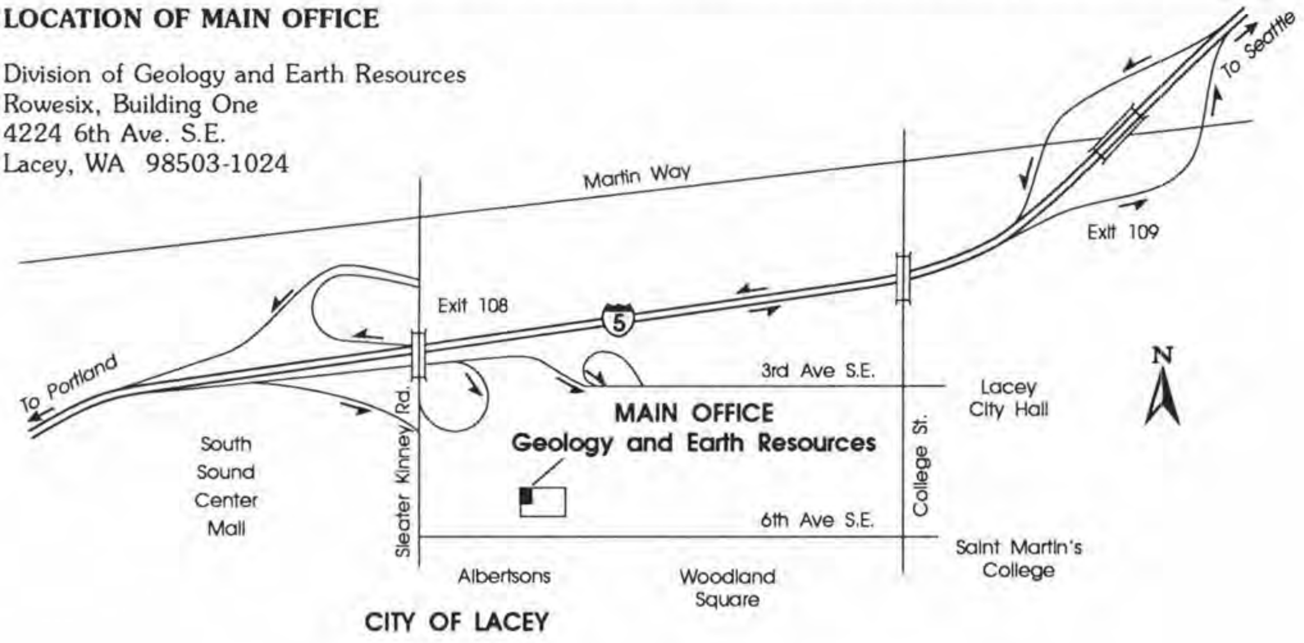

New Division Releases

Geology of the Naches Ranger District, Wenatchee National Forest, Kittitas and Yakima Counties, Washington, Open File Report 92-3, by Newell P. Campbell and Daryl Gusey. This compilation was prepared primarily for U.S. Forest Service use. The text accompanies one oversize 1:62,500-scale geologic map and a correlation chart. $2.30 + .20 tax (WA residents only) = $2.50.

Preliminary bibliography and index of the geology and mineral resources of Washington, 1991, Open File Report 92-4, compiled by Connie J. Manson. This 104-page report continues the series of these products. $3.70 + .30 tax (WA residents only) = $4.00.

Surface mining in Washington: Some regulatory responsibilities of various federal, state, and local government agencies, 1992, Open File Report 92-5, compiled by David K. Norman. This report lists mining-related laws, regulations, and ordinances administered by state, federal, and local agencies. Free.

Paleontology and stratigraphy of Eocene rocks at Pulali Point, Jefferson County, eastern Olympic Peninsula, Washington, Report of Investigations 31, by Richard L. Squires, James L. Goedert, and Keith L. Kaler. This report describes the Crescent Formation and the overlying unit at this location. 25 pages, 3 plates. $1.85 + .15 tax (WA residents only) = $2.00.

Note: **Index to geologic and geophysical mapping of Washington, 1899–1983, Information Circular 77** is now out of print. However, Open File Report 92-1 provides information on geologic and geophysical mapping from 1984 through 1991. $3.23 + .27 tax (WA residents only) = $3.50.

Publications of the Washington Division of Geology and Earth Resources, a list of Division publications and their prices current to December 1991, is available upon request. A slip sheet describes publications released in 1992.

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The Mining Industry and Food Production in the U.S.

The mining industry produces the basic raw materials for manufacture of farm machinery, food processing machinery, food containers, and vehicles for transport of the food from the farm to the consumer. More than this, the bountiful food supply in the United States is dependent upon the following each year directly from the mining industry:

- About 20,000,000 tons of processed phosphate rock for manufacture of fertilizer for direct application to the soil. This amount of material would occupy a string of railroad hopper cars stretched from Seattle, WA, to Louisville, KY. There are no known substitutes for phosphorus requirements in agriculture.
- About 1,000,000 tons of processed phosphate rock for direct feeding to livestock and fowls as a food supplement. There are no known substitutes for phosphorus for this use. About 6,000,000 tons of refined potassium chloride for direct application to the soil. There are no known substitutes for potassium requirements in agriculture.
- About 40,000,000 tons of limestone for direct application to the soil. Any substitutes would be more expensive and would also require mining.
- About 1,500,000 tons of gypsum for direct application to the soil. There are no known substitutes for gypsum for agricultural purposes.
- About 6,000,000 tons of sulfur per year for the manufacture of fertilizer for direct application to the soil.
- About 1,500,000 tons of sodium minerals for direct application or manufacture of chemicals for direct application to the soil.
- About 50,000 tons of vermiculite for direct application to the soil. Substitute materials could be peat and perlite (also mined), and sawdust.
- About 30,000 tons of boron chemicals for direct application as an essential plant nutrient or as a weed exterminator. There are no known substitutes for use as a plant nutrient.
- Quantities of iron, copper, zinc, and other metal compounds as essential plant nutrients.

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by F. T. Davis, SME Western Regional Vice President.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Division of Geology and Earth Resources
P.O. Box 47007
Olympia, WA 98504-7007

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