# OREGON GEOLOGY

published by the
Oregon Department of Geology and Mineral Industries

VOLUME 55, NUMBER 6 NOVEMBER 1993

**IN THIS ISSUE:**

Klamath Falls Earthquakes, September 20, 1993

and

Modeled Strong Ground Shaking in the Portland Metropolitan Area

# OREGON GEOLOGY

(ISSN 0164-3304)

**VOLUME 55, NUMBER 6 NOVEMBER 1993**

Published bimonthly in January, March, May, July, September, and November by the Oregon Department of Geology and Mineral Industries. (Volumes 1 through 40 were entitled *The Ore Bin*.)





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The style to be followed is generally that of U.S. Geological Survey publications. (See the USGS manual *Suggestions to Authors*, 7th ed., 1991, or recent issues of *Oregon Geology*.) The bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Names of reviewers should be included in the acknowledgments.

Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, news, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office of the Oregon Department of Geology and Mineral Industries.

## Cover photo

Damage caused by the Klamath Falls earthquakes of September 20, 1993. This bridge on Oregon Highway 140 across Howard Bay shows left-lateral displacement across joints in the bridge deck, probably as a result of slumping and settling that caused the bridge deck to rotate. Report on the earthquake begins on next page.

# OIL AND GAS NEWS

### Drilling at Mist Gas Field

Nahama and Weagant Energy Co. of Bakersfield, California, continues the multiple-well drilling program at Mist Gas Field in Columbia County. Of the first six wells for the year, two have been completed as gas producers, one is suspended, and three are plugged and abandoned. A seventh well, LF 31-36-65, was drilled to a total depth of 3,987 ft and is suspended. Next, the well CC 24-19-65 reached a total depth of 3,044 ft, was plugged and redrilled to a total depth of 2,882 ft, and is now suspended. The last well drilled to date, LF 43-32-65, reached a total depth of 1,909 ft and is suspended.

### Northwest Petroleum Association symposium

The NWPA held its 10th annual symposium in Bend during September. Some 70 people were in attendance, heard speakers, and attended a poster session dealing with energy issues in the Northwest. A field trip for this meeting went to the Newberry Volcanic Monument. For more information, including the monthly luncheon program, contact the NWPA, P.O. Box 6679, Portland, OR 97228.

### Carbon Energy commences drilling

Carbon Energy International of Kent, Washington, has commenced drilling operations on the Coos County Forest 7-1 well, SE¼ sec. 7, T. 27 S., R. 13 W., Coos County, Oregon. The proposed total depth for this well is 4,250 ft. It is located in the Coos Basin about 10 mi south of Coos Bay. The wildcat well is being drilled for coal-bed methane gas, which may be generated and trapped within coal beds, and this method of extracting methane gas is known as coal degasification. Carbon Energy has one other drilling permit for the WNS-Menasha 32-1 well, SW¼ sec. 32, T. 26 S., R. 13 W., with a proposed total depth of 1,600 ft.

### Natural gas pipeline to serve Northwest and California

Pacific Gas Transmission Company will soon complete construction of a 42-in. natural-gas pipeline that stretches over 805 mi from Canada to California, crossing Oregon approximately parallel to State Highway 97, through Biggs, Bend, and Klamath Falls. The $1.7 billion project will increase supply capacity by approximately 900 million cubic feet per day, about 16 percent of it for the Oregon market. Statistics show that during the last ten years Oregon's consumption of natural gas has more than doubled. Much of the pipeline crosses lands managed by the U.S. Bureau of Land Management (BLM), so BLM's Prineville District has taken the lead in ensuring minimal environmental impact and proper restoration of the land disturbed by the pipeline and its construction.

### Recent permits

| Permit no. | Operator, well, API number | Location | Status, proposed total depth (ft) |
|---|---|---|---|
| 494 | Nahama and Weagant<br>Hemeon 13-14-65<br>36-009-00316 | SW¼ sec. 14<br>T. 6 N., R. 5 W.<br>Columbia County | Permit issued;<br>2,800. |
| 495 | Nahama and Weagant<br>Johnston 11-30-65<br>36-009-00317 | NW¼ sec. 30<br>T. 6 N., R. 5 W.<br>Columbia County | Permit issued;<br>2,700. |
| 496 | Nahama and Weagant<br>LF 21-32-75<br>36-009-00318 | NW¼ sec. 32<br>T. 7 N., R. 5 W.<br>Columbia County | Permit issued;<br>2,500. |
| 497 | Nahama and Weagant<br>Libel 32-15-65<br>36-009-00319 | NE¼ sec. 15<br>T. 6 N., R. 5 W.<br>Columbia County | Permit issued;<br>2,800. |

□

# Klamath Falls earthquakes, September 20, 1993—including the strongest quake ever measured in Oregon

*by Thomas J. Wiley[1], David R. Sherrod[2], David K. Keefer[3], Anthony Qamar[4], Robert L. Schuster[5], James W. Dewey[5], Matthew A. Mabey[6], Gerald L. Black[6], and Ray E. Wells[3]*

## INTRODUCTION

Earthquakes struck the Klamath Falls area on Monday night, September 20, 1993, resulting in two deaths and extensive damage. The quakes were felt as far away as Coos Bay to the west, Eugene to the north, Lakeview to the east, and Chico, California, to the south.

A foreshock recorded at 8:16 p.m. had a Richter magnitude of 3.9. The first of two main shocks, measuring 5.9 on the Richter scale, rumbled through Klamath Falls at 8:28 p.m. Following 16 smaller jolts with magnitudes between 2.2 and 3.8, the largest quake struck at 10:45 p.m. This earthquake, measuring 6.0 on the Richter scale, is the largest to hit Oregon since the 1873 Port Orford/Crescent City earthquake (Jacobson, 1986). Oregon has been shaken by stronger quakes, but those quakes originated beneath the Pacific Ocean west of Port Orford.

## NATURE OF THE EARTHQUAKES

The epicenters of the Klamath Falls earthquakes clustered around an area near lat 42°20′N. and long 122°05′W. (T. 37 S., R. 2 W.), within the Mountain Lakes Wilderness, 26 km (16 mi) west-northwest of Klamath Falls, in Klamath County, Oregon (Figures 1 and 2). The magnitude 5.9 main shock that occurred at 8:28 p.m. was located at lat 42°18.94′N. and long 122°03.30′W. at a depth of approximately 12 km (7.5 mi). The magnitude 6.0 main shock that occurred at 10:45 p.m. was located about 6 km (3.7 mi) farther to the northwest (lat 42°21.31′N., long 122°06.61′W.) and at a depth of approximately 12 km (7.5 mi). More than400 aftershocks with magnitudes greater than 1.5 had been recorded by October 12 (Figure 3); the 10 largest had magnitudes ranging from 3.0 to 4.3. Hypocentral depths range from 0–12 km (0–7.5 mi), with the best located aftershocks occurring at depths of 5–12 km (3–7.5 mi).

Initially, individual earthquake hypocenters were poorly located due to a lack of permanent seismographs in the area. However, 20 portable seismographs were rapidly deployed by teams from Oregon State University, U.S. Geological Survey, and University of Oregon.

The first records obtained from portable seismographs showed aftershocks occurring at a rate of one per minute on September 21, most of them too small to be detected except by the portable seismographs. By the end of September, this rate had fallen off dramatically.

During the first week of October, the U.S. Geological Survey installed four permanent seismographs in the epicentral region. Data from these instruments are now telemetered to the University of Washington (UW), where they are recorded as part of the UW seismic network. The UW is now able to precisely locate aftershocks as small as magnitude 0.3.

Analysis of the shock waves was used to determine the orientation of the fault plane and the direction of slip in what is known as a fault-plane solution. One fault-plane solution for the magnitude 6.0 main shock at 10:45 p.m. is shown on Figure 4 and is interpreted to represent a northwest- to north-northwest-striking (N. 38° W.), east-dipping (56°) normal fault with a very small component of left-lateral motion.

**Hypocenter** ("hypo" = "under") is the point within the Earth where the earthquake actually originates.
**Epicenter** ("epi" = "upon") is the point on the Earth's surface that lies directly above the hypocenter.

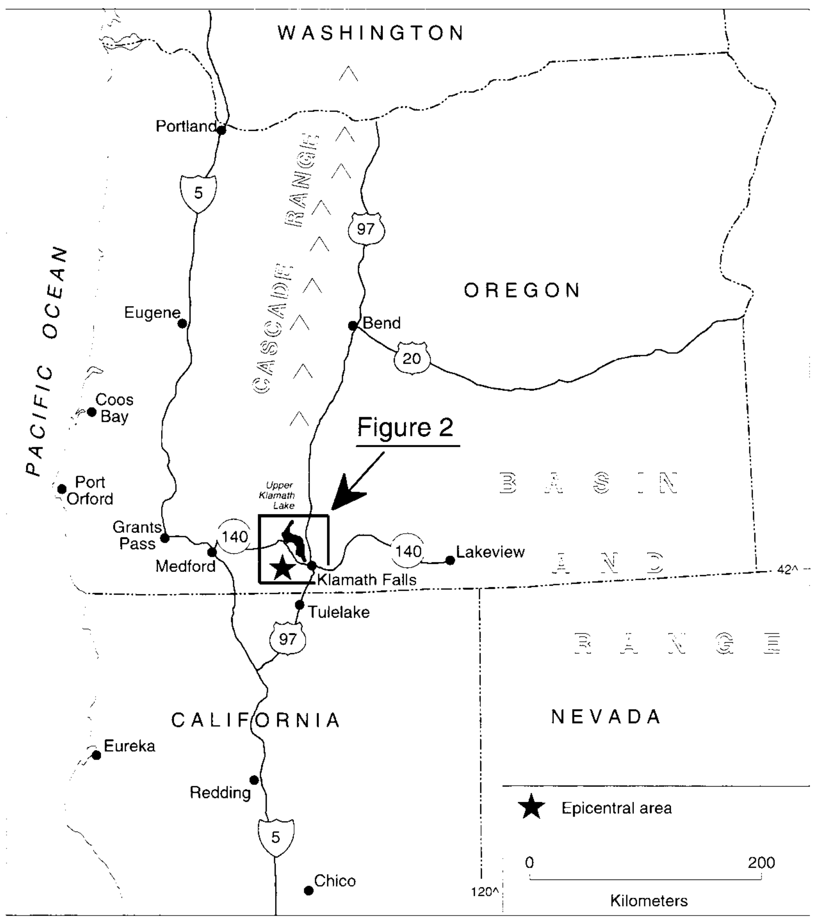


*Figure 1. Location map.*

[1] *Oregon Department of Geology and Mineral Industries, Grants Pass, Oregon.*
[2] *U.S. Geological Survey, Vancouver, Washington.*
[3] *U.S. Geological Survey, Menlo Park, California.*
[4] *University of Washington, Seattle, Washington.*
[5] *U.S. Geological Survey, Golden, Colorado.*
[6] *Oregon Department of Geology and Mineral Industries, Portland, Oregon.*

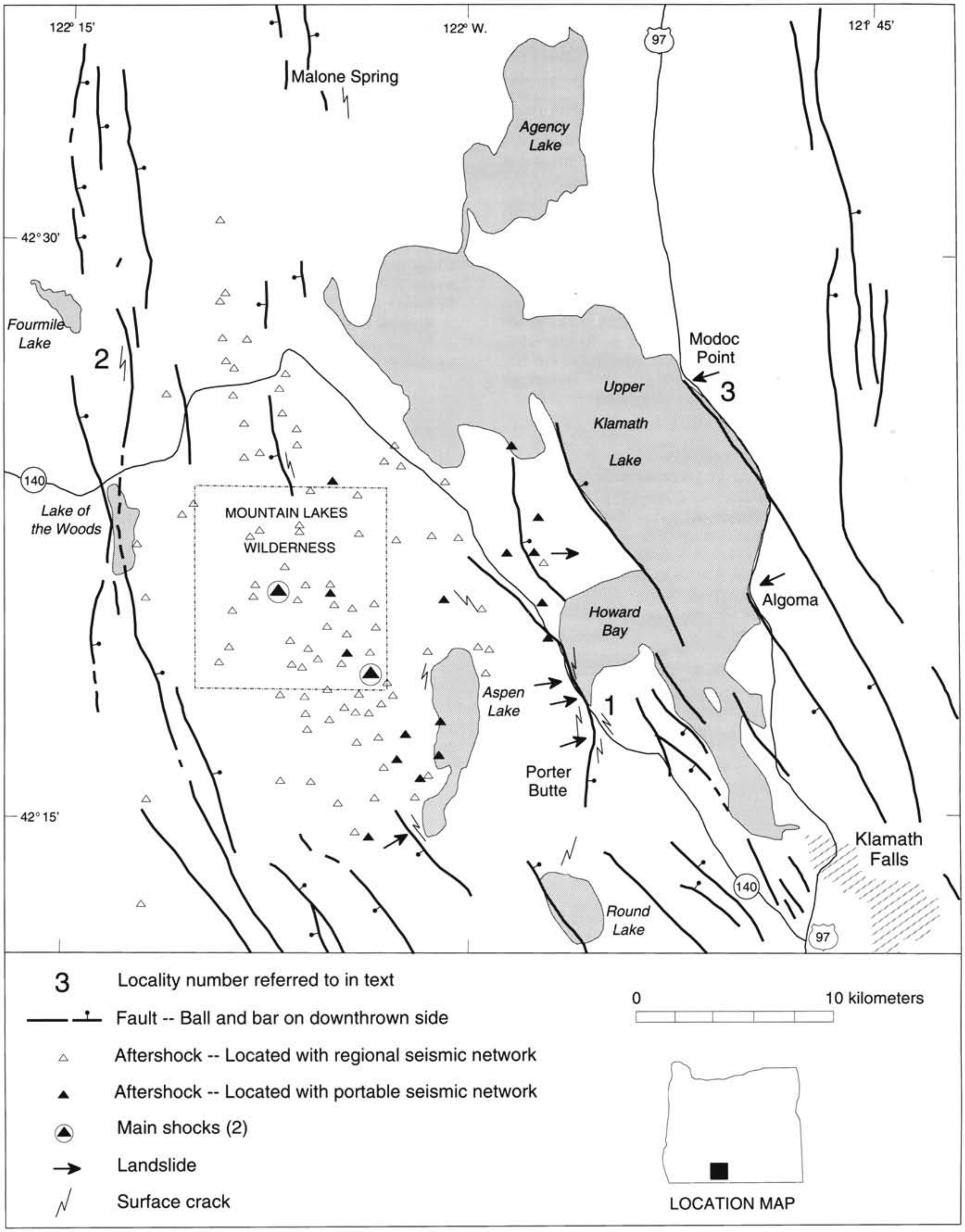


*Figure 2. Map showing location of the two main shocks, aftershocks, surface deformation, mapped faults, and localities discussed in text.*

## SURFACE DEFORMATION

After the earthquake, a search for newly formed fault scarps, newly formed ground cracks, new and reactivated landslides, liquefaction, and related effects was conducted through aerial observation from a small, fixed-wing aircraft and traverses by automobile and on foot. The aerial search was carried out to epicentral distances of about 40 km (25 mi), whereas automobile and foot traverses extended more than 135 km (84 mi) from the epicenter. Neither newly formed ground rupture nor evidence of liquefaction was found. Ground cracks and landslides were the only surface geologic effects that could reliably be attributed to the Klamath Falls earthquakes.

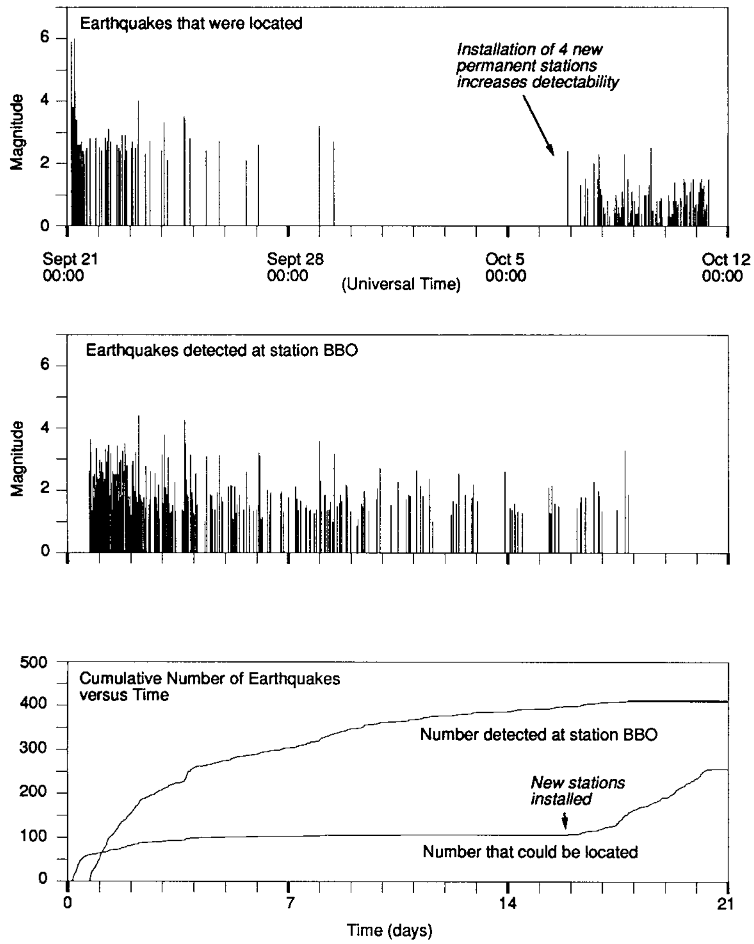


*Figure 3. Plots showing earthquake magnitude versus time during first three weeks of earthquake activity. (a) Earthquakes located by University of Washington (UW) seismic network. (b) Earthquakes detected by closest permanent seismograph at station BBO (see Figure 11). (c) Total number of located and detected events. With the addition of the new stations now being recorded at UW, 780 earthquakes had been located by October 22.*

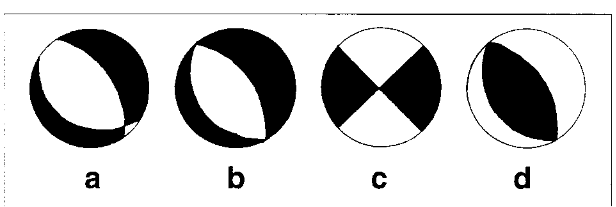


*Figure 4. (a) Fault-plane solution for magnitude ($M_C$) 6.0 main shock at 10:45 p.m. on September 20, 1993 (lower hemisphere stereographic plot). The two planes defined by the boundaries between black (compression) and white (dilation) zones indicate fault orientations that could have produced this earthquake. The N. 38° W. plane dipping 56° NE. parallels many of the known faults in area. (b) Idealized normal-fault solution. (c) Idealized strike-slip-fault solution. (d) Idealized thrust-fault solution.*

### Ground cracks

Newly formed cracks were typically confined to artificial fill, chiefly in roadways where cinders and crushed rock had been used to elevate roads 30–60 cm (1–2 ft) above the surrounding ground. Newly formed or enlarged cracks were located as far west as Fourmile Lake, as far north as Malone Spring, as far south as Round Lake, and as far east as Howard Bay (Figure 2). Cracking was sparse near the main shock epicenters. Most cracking occurred in an area 3–8 km (2–5 mi) southwest of the epicenters, between Aspen Lake, Howard Bay, and Round Lake. A north-south linear zone with the greatest density of ground cracking, rock fall, and slumping extended from Round Lake to the Highway 140 bridge over the southern end of Howard Bay (Locality 1, Figure 2) and north along Highway 140 where it follows the west shore of Howard Bay. This zone corresponds with a previously mapped north-striking fault whose escarpment forms the east slope of Porter Butte and the west side of Howard Bay. Cracks generally trended north to northwest. Most cracks were only 3–6 m (10–20 ft) in length, but a few were more than 100 m (330 ft) long. Cracks cutting asphalt pavement and bed rock south of Howard Bay are believed to be related to compaction of underlying fill and to landsliding, respectively. Vertical displacements as large as 50 cm (1.6 ft) were found, but only where sliding or slumping was believed to have occurred.

One crack could be traced beyond road fill and into regolith. That crack was one of five or six found along a 30-m (100-ft) stretch of logging road north of Round Lake. Cracks in this set had irregular trends for lengths of 30–60 cm (1–2 ft) and overall trends of N. 5° W., N. 10° W., and N. 15° E., and opened as much as 1 cm (0.4 in.). Slip vectors were east-west (N. 86° W., N. 82° E., and N. 76° W.), as determined by aligning paired features such as gravel clasts and voids or embayments and protrusions.

Gaping cracks wide enough to insert a hand to the wrist characterized the embankment of Highway 140 along and south of Howard Bay. These cracks were related to spreading and slumping of road fill during and since the shaking events. Cracks along the centers of two gravel roads occurred in areas with thick fill and were similarly thought to result from lateral movement. Cracks were also found associated with culvert crossings.

Several cracks in a truck-turnaround pad constructed on the edge of a cinder cone north of Round Lake had a small component of normal separation, but the downdropped side coincided with the approximate outer (downslope) flank of the cinder quarry, and the downdip separation probably resulted from gravity failure. These cracks, which trended between N. 5° E. and N. 10° W., had opened about 2.5 cm (1 in.). One measured slip direction had a plunge of 15° on trend S. 76° E.

*Figure 5. Rock-fall boulder from steep ridge bordering Oregon Highway 140 west of Howard Bay (Locality 1, Figure 2). Boulder fell from near-vertical slope partly visible in background and came to rest on highway shoulder.*

The U.S. Forest Service reported a northwest-trending crack 8 m (26 ft) long that had opened as much as 5 cm (2 in.) and was located below water level in the marsh east of Malone Spring (Figure 2). Cracks were reported in fill along Cascade Canal, where it traverses the east slope of Rye Spur southeast of Fourmile Lake (Locality 2, Figure 2).

**Landslides**

The Klamath Falls earthquakes caused landslides throughout an area of about 420 $km^2$ (162 $mi^2$) surrounding the epicenter. Most landslides were rock falls or rock slides from road cuts, quarries, and steep bluff faces; these landslides occurred as far as 29 km (18 mi) from the epicenter of the strongest shock at 10:45 p.m.

The most numerous earthquake-induced rock falls were found along the east- to southeast-facing flank of a ridge immediately south and west of Howard Bay, 17 km (11 mi) east-southeast of the 10:45 p.m. epicenter (Locality 1, Figure 2). This ridge, which is 250 m (820 ft) high, has slopes exceeding 45° in some places. Basalt lava flows crop out in the upper part, and the lower slopes are mantled by boulder-rich colluvium and talus. Several dozen boulders, some as large as 4 m (13 ft) across, broke loose and fell or rolled down the slope during the earthquake. A few boulders came to rest on the shoulder and roadway of Oregon Highway 140 (Locality 1, Figure 2; Figure 5). One of these boulders was struck by an 18-wheeled truck, which then veered off the highway and into more boulders at the base of the cliff. Many more boulders came to rest on the unpaved road that climbs the southeastern side of the ridge.

The largest observed rock slide originated on a steep road cut on the east side of U.S. Highway 97, at a point 3 km (1.8 mi) south of the town of Modoc Point and 23 km (14 mi) from the 10:45 p.m. epicenter (Locality 3, Figure 2; Figures 6 and 7). This rock slide, which contained an estimated 300 $m^3$ (10,600 $ft^3$) of material, broke loose from a 60° slope composed of heterogeneous volcanic rock that is locally weakly cemented, intensely fractured, or both. The rock slide moved downslope about 100 m (330 ft); most of the material was contained behind a roadside barrier consisting of concrete sections surmounted by a steel fence, but one large boulder, 3.5 m (11.5 ft) in maximum dimension, crashed through the barrier onto the highway. The boulder hit a southbound vehicle, killing the driver.

Other rock falls and rock slides from road cuts were observed adjacent to Oregon Highway 140 as far as 17 km (11 mi) east and 29 km (18 mi) west of the 10:45 p.m. epicenter. These landslides were small (typically involving only a few cubic meters of material) and occurred from cuts that evidently had a history of spotty instability. One additional rock slide caused minor damage to railroad tracks near Algoma (Figure 2), according to a report in the Klamath Falls Herald and News (September 21, 1993, p. 1).

The Oregon Highway 140 bridge across Howard Bay, 17 km (11 mi) east-southeast of the 10:45 p.m. epicenter (Locality 1, Figure 2), was damaged by slumping and settlement at the north abutment and settlement of the south abutment. At the south abutment, the approach fill settled approximately 10 cm (4 in.). Left-lateral displacements totaling approximately 17 cm (7 in.) occurred across joints in the bridge deck, probably due to slumping and settling that caused the bridge deck to rotate counterclockwise. South of the bridge, the highway is built on a fill causeway at the edge of the marsh. For a distance of several hundred meters, the fill along the west shoulder of this causeway slumped into the marsh, opening cracks 5–10 cm (2–4 in.) wide (Figure 8).

*Figure 6. Rock slide from Modoc Rim, 2.9 km (1.8 mi) south of the town of Modoc Point and adjacent to U.S. Highway 97 (Locality 3, Figure 2). Note breach in roadside barrier and impact marks in highway pavement caused by large boulder that hit southbound vehicle and came to rest on road. The boulder was pushed off the road before the photograph was taken and is visible just behind the right side of the breach.*

*Figure 7. Close-up of large boulder from the Modoc Rim rock slide (Figure 6) that breached barrier along U.S. Highway 97.*

Several slumps in fill also occurred along the gravel road below the ridge immediately west of the bridge (Figure 9). These slumps were characterized by crescent-shaped open cracks that were concave downslope in plan view. The largest cracks were more than 100 m (330 ft) long and 30 cm (12 in.) wide. Several such slumps occurred in the quarry and the quarry road on the southeast-facing slope of the ridge, and at least two slumps occurred lower on the road, adjacent to a canal.

The types and areal limits of landslides (Figure 10) caused by the Klamath Falls earthquakes are typical for earthquakes of this magnitude. The area throughout which landslides occurred (Figure 10a), the maximum epicentral distances for rock slides and rock falls (Figure 10b), and the maximum epicentral distances for rotational slumps (Figure 10c) are comparable to similar data from other historical earthquakes. In addition, rock falls, rock slides, and slumps of fill material are among the most common types of landslides in other historical earthquakes of comparable magnitude (Keefer, 1984).

*Figure 8. Linear cracks in the causeway fill south of Howard Bay bridge on Oregon Highway 140. These cracks were caused by slumping of fill in a westward direction, toward the right edge of the photograph.*

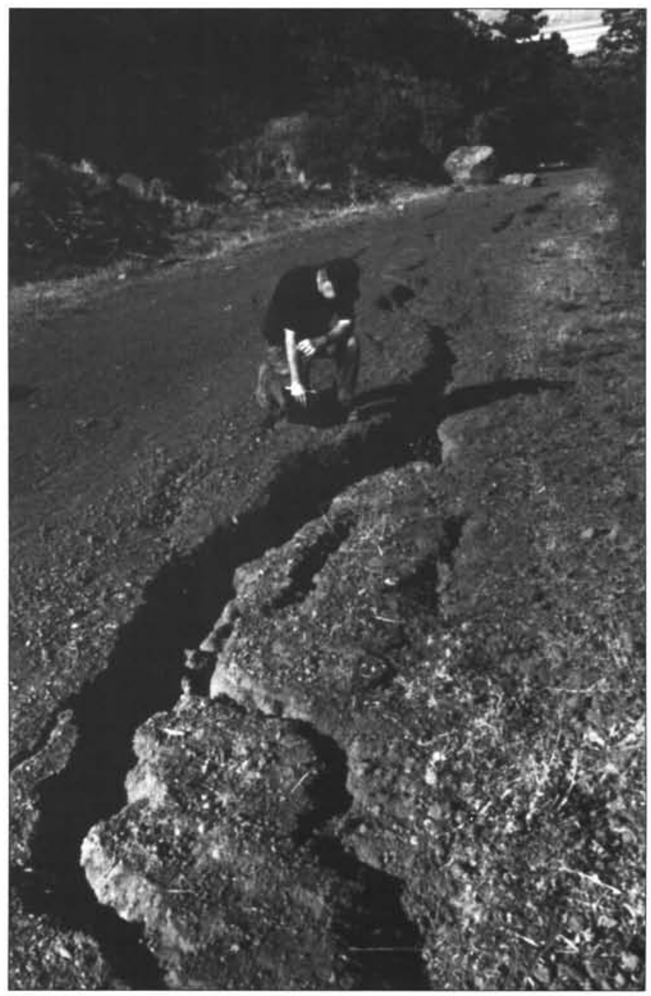

*Figure 9. Crescent-shaped cracks associated with rotational slump in fill. Slumps involved unpaved road in quarry at Locality 1 on Figure 2. Boulders on road from earthquake-induced rock falls are visible in background.*

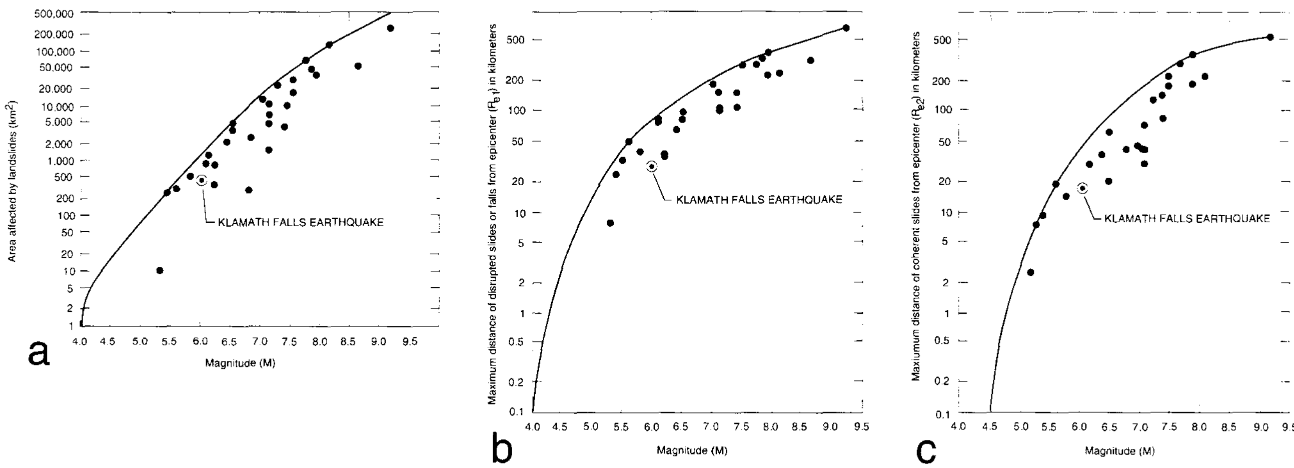


*Figure 10. Plots comparing landslides caused by Klamath Falls earthquakes with landslides caused by other historical earthquakes (solid dots). Data on historical earthquakes and solid line denoting upper limit are from Keefer (1984). (a) Area affected by landslides. (b) Maximum epicentral distance of rock falls and rock slides (disrupted slides and falls). (c) Maximum epicentral distance of slumps (coherent slides).*

## EFFECTS ON SURFACE AND GROUND WATER

No changes in surface water have been reported as of October 11. A rancher with a water gauge on Upper Klamath Lake (Locality 1, Figure 2) reported that the lake level on September 21 and September 24 (after the main shocks) was identical to that measured on September 20 (prior to the earthquakes).

Several residents who rely on ground-water systems near the epicenter reported wells with cloudy or dirty water—"the color of chocolate milk"—that cleared on continued pumping. Piping for several wells was damaged.

Water district employees for the City of Klamath Falls reported that well levels in the urban geothermal system rose 2 ft (60 cm) in the first 36 hours after the quakes and had risen another foot by October 6. This contrasts with a typical year in which water levels decline in late September and early October. In a geothermal system monitored by the Oregon Institute of Technology, water levels reportedly fell 1–7 ft (30–220 cm) before stabilizing on the third day after the earthquake.

One continuously monitored well near Grants Pass, 100 km (60 mi) west of the epicenter, recorded a 35-cm (14-in.) drop in static level following the earthquake and never recovered.

## RELATION OF EARTHQUAKES TO NEARBY FAULTS

Dramatic north- to northwest-trending fault-line scarps are the dominant topographic feature throughout the Klamath Falls area (Figure 2; Smith and others, 1982; Hawkins and others, 1989; Sherrod and Pickthorn, 1992). These scarps and the associated system of Basin and Range normal faults trend into the High Cascades volcanic arc in the epicentral area. Fault-plane solutions (Figure 4) suggest that the two main shocks occurred on a northwest- to north-northwest-striking, east-dipping normal fault or several faults. The surface projection of such a fault would lie east of the Lake of the Woods fault zone (Hawkins and others, 1989), assuming a 60° dip and a hypocentral depth of 12 km (8 mi). Aftershocks located by the portable seismic net define two north-trending bands of epicenters (Figure 2): The western band corresponds with the main shock epicenters as located by the regional seismic net. The eastern zone underlies the western shore of Upper Klamath Lake and is coincident with the north-trending zone characterized by the greatest amount of ground cracking and landsliding. Better definition of the fault or faults responsible for these earthquakes must await velocity modeling and thorough analysis of aftershocks recorded by portable seismographs.

## INTENSITY AND DAMAGE

The Klamath Falls earthquakes caused two deaths and damaged more than 1,000 buildings. One person died when a car was struck by a boulder on U.S. Highway 97 near Modoc Point (Locality 3, Figure 2). The second fatality was the result of a heart attack.

Damage assessments reported by the Oregon Emergency Management Division (OEM) and the Federal Emergency Management Agency (FEMA) showed that residential, commercial, nonprofit, and government buildings and facilities suffered an estimated total dollar loss of more than $7.5 million (Table 1). The Klamath County Courthouse (built in 1924) and Courthouse Addition suffered the greatest damage, with a combined dollar loss of $3.14 million. Many unreinforced masonry buildings in the city of Klamath Falls were severely damaged. FEMA lists two residences as destroyed. Well-built wood-framed houses that were bolted to their foundations and commercial buildings constructed to modern building codes generally suffered little or no damage. The few modern structures that sustained damage may indicate areas where local conditions, building geometry, or building conditions resulted in more severe damage. Damage to buildings was reported from Tulelake, California, to Modoc Point, north of Upper Klamath Lake (Figure 11, Mercalli zones VI and VII).

Table 2 shows a comparison with the Scotts Mills earthquake of March 25, 1993, demonstrating how a smaller earthquake can be more damaging if it is centered beneath a more populous area. See the May issue of *Oregon Geology* (Madin and others, 1993).

An intensity questionnaire published in several Oregon newspapers resulted in intensity reports from the public that have yet to be compiled. Readers with observations from personal experience or who sustained damage to their homes are urged to fill out and send in the form at the end of this article (page 135).

## HISTORICAL AND EXPECTED FUTURE EARTHQUAKES

During the last 50 years, at least 12 earthquakes have occurred within 33 km (20 mi) of Klamath Falls. Seven of these were larger than magnitude 3 and were large enough to be felt (Jacobson, 1986). Evidence from this historic record, combined with geologic evidence for large numbers of large earthquakes in the prehistoric past, suggests that one or more earthquakes capable of damage (magnitude 4–6) hit south-central Oregon every few decades. Earthquakes as large as magnitude 7 have probably occurred (Hawkins and others, 1989).

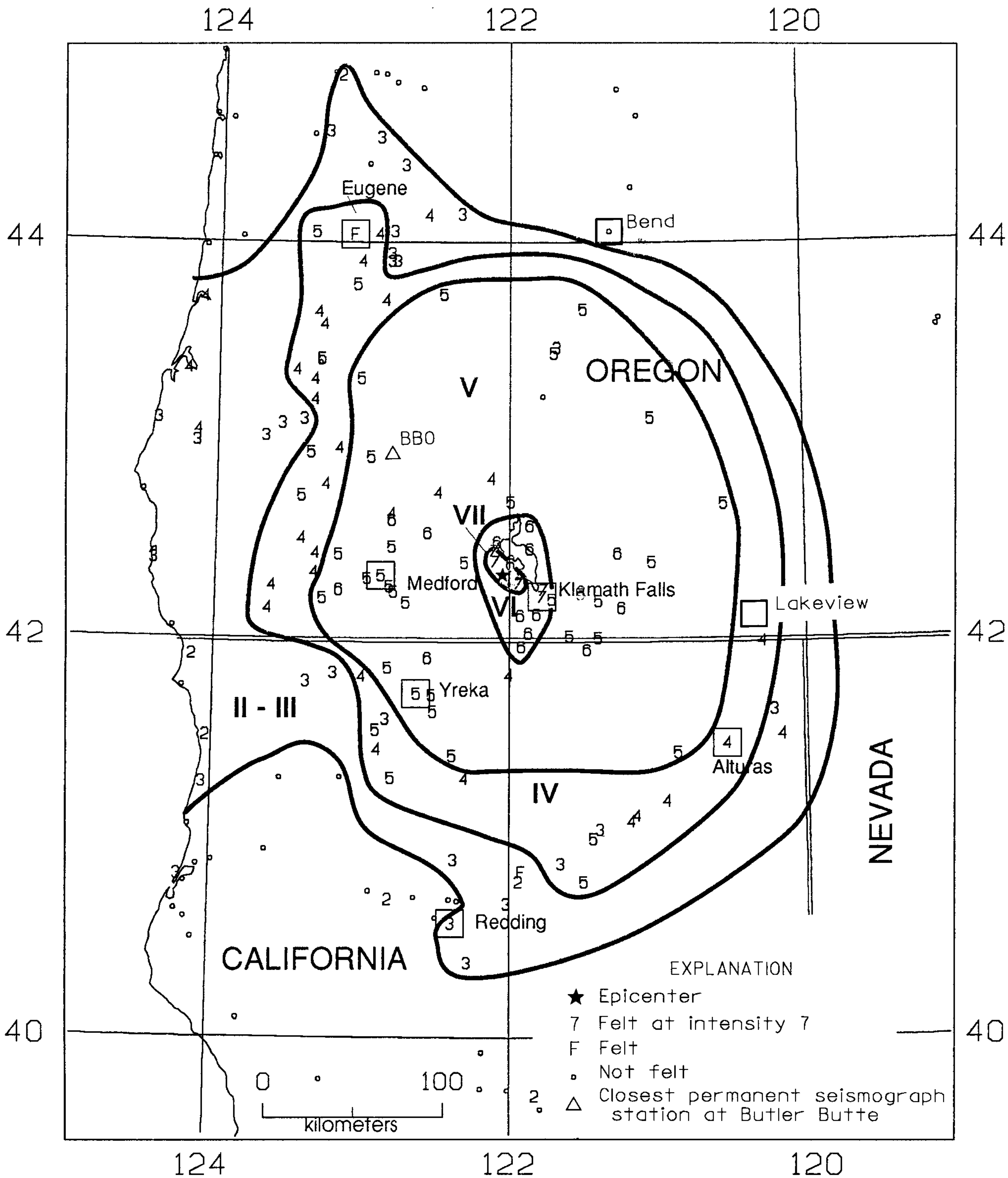


*Figure 11. Preliminary Modified Mercalli intensity map for the September 20, 1993, Klamath Falls earthquakes. Explanation of intensities (Roman numerals) in Table 3.*

Table 1. *Damage and cost estimates by FEMA*

**Klamath County Public Facilities**

| | |
|---|---|
| Klamath County Courthouse | $1,720,000 |
| Klamath County Courthouse, New Addition | $1,420,000 |
| Klamath County Library | $5,000 |
| Klamath County Schools | $26,000 |
| Klamath County | $727,000 |
| Klamath Falls City Schools | $113,000 |
| City of Klamath Falls | $151,000 |
| Klamath Tribes Medical Office | $3,500 |
| Klamath Tribes Chiloquin Hatchery | $44,000 |
| Klamath Tribes Algae Building | $3,000 |
| Merle West Medical Center | $5,000 |
| Oregon Department of Transportation | $15,000 |
| Estimated total dollar loss | $4,232,500 |

**Individual assistance damage estimates in Klamath County**

| | | |
|---|---|---|
| Number of residences | | |
| Destroyed | 2 | |
| With major damage | 20 | |
| With minor damage | 142 | |
| Affected habitable | 777 | |
| Total | 941 | |
| Estimated dollar loss | | $1,140,000 |
| Number of businesses | | |
| Destroyed | 0 | |
| With major damage | 25 | |
| With minor damage | 76 | |
| Total | 101 | |
| Estimated dollar loss | | $1,963,000 |
| Number of others—non-profit | | |
| Destroyed | 0 | |
| With major damage | 2 | |
| With minor damage | 7 | |
| Total | 9 | |
| Estimated dollar loss | | $258,000 |
| Total—residences and businesses | | |
| Number | 1,051 | |
| Estimated total dollar loss | | $3,361,000 |

Table 2. *Comparison between Klamath Falls earthquakes and Scotts Mills earthquake. Note that area in which the Scotts Mills earthquake was felt was limited by the Pacific Ocean and might have been 20 percent larger if the earthquake had occurred inland.*

| | Klamath Falls | Scotts Mills |
|---|---|---|
| Magnitude | 6.0 and 5.9 | 5.6 |
| Depth | 18 and 20 km | 18 km |
| Maximum intensity | VII | VII |
| Area felt (km2) | 131,000 | 134,000 |
| Fatalities | 2 | 0 |
| Damage (millions of dollars) | ~7.5 | ~12.6 |
| Buildings destroyed | 2 | 0 |
| Landslides | out to 29 km | no |
| Ground cracks | yes | no |

Table 3. *Excerpts[1] from Modified Mercalli intensity scale of Wood and Neumann (1931) as used in Figure 11*

| Intensity | Description |
|---|---|
| II–III | Observations range from "felt by a few persons at rest" to "felt quite noticeably." |
| IV | Felt indoors by many, outdoors by few. Dishes, windows rattle; walls creak; standing cars rock noticeably. |
| V | Felt by nearly everyone, many awakened. Some dishes and windows broken; cracked plaster in a few places; unstable objects overturned; trees, poles, and other tall objects disturbed. |
| VI | Felt by all, many people run outdoors; some moderately heavy furniture moved. |
| VII | Everybody runs outdoors; damage negligible in buildings of good design and construction, considerable in poorly built or badly designed structures; some chimneys broken; noticed by persons driving cars. |

[1] More complete versions of this scale have been published lately in, e.g., *Oregon Geology* (Sept. 1993, p. 118, and Jan. 1989, p. 17–18; *California Geology* (Sept. 1991, p. 203); and in the U.S. Geological Survey free pamphlet *The Severity of an Earthquake.*

The Klamath Falls earthquake sequence was a multiple event, with two main shocks that probably ruptured different parts of a fault at different times. Aftershocks since then have followed a commonly observed decline curve, decreasing dramatically in both number and magnitude.

This behavior contrasts with earthquake swarms, which are characterized by numerous temblors of similar magnitude and no recognizable main shock. Historic earthquake swarms in the region produced magnitude 4–5 earthquakes that continued for a month or more. For example, earthquake swarms struck 70 km (44 mi) south of Klamath Falls in the 1978 Stephens Pass, California, earthquakes (Bennett and others, 1979) and 160 km (100 mi) to the east in the 1968 Warner Valley earthquakes (Couch and Johnson, 1968).

However, since earthquakes are unpredictable, there is still a chance that significant aftershocks may strike the Klamath Falls area in the months ahead.

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## EARTHQUAKE QUESTIONNAIRE

The Oregon Department of Geology and Mineral Industries (DOGAMI) needs the help of the public to accurately determine the effects of the September 20, 1993, Klamath Falls earthquakes. If you live in southern or southwest Oregon, northern California, or northern Nevada, please take the time to read this questionnaire and answer the questions as fully as possible. We need information from as many residents of the earthquake area as possible, **even if you did not feel any effects**. This information may allow us to predict which areas might experience the greatest damage in future large earthquakes. Send to **Klamath Falls Earthquake Survey, DOGAMI, 800 NE Oregon St. #28, Portland, OR 97232.** Thank you for your help!

Where were you in the earthquake(s)? Please describe your location, either by a street address or nearest cross streets. Include the name of the town, or distance and direction from the nearest town if you were out in the country.

Were you in the open, in a car, in a building? If you were in a building, list which floor you were on and how many floors the building has.

What effects did you feel? Describe the sensation. Was it barely felt, strongly felt, hard to stand?

What effects did you observe to surrounding objects, buildings, or ground? (Rocking cars, dishes rattling on shelves, furniture or machinery shifting, rocks falling, road moving, changes in water levels in wells, cracking of the ground or roads, rapid ejection of water from ground, etc.).

□

# Reader survey results tallied

We of the Oregon Department of Geology and Mineral Industries (DOGAMI) thank the 183 readers who took the time to answer the questionnaire that appeared in the July 1993 issue of *Oregon Geology*. The responses, which represent approximately 11 percent of the distributed copies of any issue of *Oregon Geology*, were tallied by DOGAMI volunteers Martha Carlson, Emma Geitgey, Rosemary Kenney, Margaret Steere, and Phyllis Thorne. Jean Pendergrass, DOGAMI secretary, tabulated the numerous written comments.

Here are some of the things we learned about the readers who responded to the survey. Approximately 17 percent of them are women; the rest are men. The average age falls into the 46–64 age category. Sixty-one percent of the responders are Oregonians, with 25 percent of those living in the Portland area. Washington is home for 13 percent of the other responders, while California, Texas, Idaho, Colorado, Alaska, and Minnesota and then the other states, in that order, are the home states for almost all of the rest. Of the remainder, 3 percent come from Canada. The farthest response came from Germany.

Twelve percent of the responders are high school graduates; 19 percent attended college, and 39 percent are college graduates. Twenty percent have done some graduate work, and 50 percent have advanced degrees. The largest single category of occupation is professional geologist, followed by prospector, scientist, government employee, educator—plus a variety of other occupations including librarians, physicians, carpenters, tree farmers, secretaries, and train dispatchers. Half of the responders live in households with an annual income of $50,000 and over.

The responders are physically active in the out-of-doors in their leisure time: Camping, hiking, amateur geology, rockhounding, travel, and photography are some of the favorite activities. Reading is about 2½ times as popular as watching TV.

Most of the responders take *Oregon Geology* because they are interested in geology and want to keep up in current activities in geology. Favorite topics include geology of specific areas, volcanoes, earthquakes, plate tectonics, mineral/fossil/gemstone areas, geologic hazards, meteorites, mineralogy, and mining history. Field trip guides, announcements of new publications, and book reviews are liked by many. About 64 percent are satisfied with the magazine as it is now, and another 29 percent are somewhat satisfied. Only 2 percent are somewhat dissatisfied, and none are totally dissatisfied. Reasons for dissatisfaction with *Oregon Geology* include "too technical," "not timely enough," "printed too infrequently," and "technical terms not defined." Most of you like the subject matter of *Oregon Geology*, because suggestions for improvement included the addition of more of all kind of things—more general interest material, more paleontology, more amateur geology information, more gemstones and rockhounding, more pages, more field trip guides, more detailed locations of drilling locations, and more information on current geologic research in the state.

About 54 percent like to receive *Oregon Geology* every two months; 38 percent would like it every month, and 8 percent prefer receiving it every three months. Fifty-nine percent would be willing to pay more for a subscription to get the magazine every month, with 2 percent willing to raise the annual subscription to $9, 15 percent to $10, 23 percent to $12, 3 percent to $14, 25 percent to $15, 11 percent to $16, and 20 percent to $18. Sixteen percent would not be willing to pay more for monthly publication. Twenty-five percent answered the "depends" category, giving such comments as "content is most important, and I would pay more if additional papers are not just fluff," "if quality and volume are retained," and "depends on content" (several times).

Thirty-nine percent don't care if advertising is added to the magazine, and 36 percent think it is a good idea. The 25 percent who think it is a bad idea added such statements as "I like it as it is," "bad idea unless selective," bad idea unless there is no alternative," and "I don't like it, but if it helps keep cost down I'd put up with it."

The question of adding color had responders fairly evenly divided, with 37 percent willing to pay more for color, 39 percent unwilling, and 24 percent saying "depends," offering such comments as "instead, make color photos available to buy", or "if you want color, there would be a tendency to have a beauty standard instead of selecting accurate pictures." The raised annual subscription prices selected by those who would be willing to pay for color range through 3 percent for $9, 7 percent for $10, 3 percent for $11, 26 percent for $12, 3 percent for $14, 20 percent for $15, 6 percent for $16, and 32 percent for $18.

Twenty-six percent were interested in including other topics in *Oregon Geology*, 51 percent said "no," and 23 percent said "depends," adding comments such as "keep it related to earth sciences," "add education," "no, you'd be in competition with too many other recreation rags," "would dilute the publication with side issues," "include programs or aids for education," "don't make it a travel magazine," "maintain scientific credibility," and "there are plenty of magazines that deal with hiking but few that deal with Oregon geology." Many of the responders correctly pointed out that we had included some geologic topics in the list of other possible topics but went on to select paleontology, history, archaeology, geography, natural hazards, and the Oregon coast as some of the most preferred topics for articles.

Forty-six percent of the responders responded favorably to expanding the focus of the magazine to the entire Pacific Northwest, while 54 percent said "no," adding such comments as "OK when the geologic topics cross state boundaries," "it might water down *Oregon Geology*," "we already subscribe to *Washington Geology* and *California Geology*, "might be too much," "interesting idea because Idaho doesn't have a magazine and articles about Idaho might be printed here," and "OK, but keep main focus on Oregon."

Finally, the responders added many helpful comments and ideas at the end of the questionnaire. Clearly, many of you care a lot both about geology and about the magazine and have all kinds of ideas on how to improve *Oregon Geology*. Rest assured we are taking your suggestions to heart and will do all we can to implement them. Because of your willingness to communicate with us, we now know more about you and what you think and want from us. We will do the best with the resources we have. Any changes that we make will always be in your best interests. Thank you again from all of us at DOGAMI. □

# THESIS ABSTRACTS

*The Department maintains a collection of theses and dissertations on Oregon geology. From time to time, we print abstracts of new acquisitions that in our opinion are of general interest to our readers.*

**Hydraulic control of grain size distributions and differential transport rates of bedload gravels in Oak Creek, Oregon,** by Shyuer-Ming Shih (M.S., Oregon State University, 1989), 74 p.

Grain-size distributions of gravels transported as bedload in Oak Creek, Oregon, show systematic variations with changing flow discharges. At low discharges the gravel distributions are nearly symmetrical and Gaussian. As discharges increase, the distributions become more skewed and follow the ideal Rosin distribution. The patterns of variations are established by goodness-of-fit comparisons between the measured and theoretical distributions, and by Q-mode factor analysis. Two end members are obtained in factor analysis, respectively having almost perfect Gaussian and Rosin distributions, and the percentages of the two end members within individual samples vary systematically with discharge.

Transformation from the Gaussian to a Rosin distribution with increasing discharge may be explained by processes of selective entrainment of grains from a bed of mixed sizes. Samples of bed material in Oak Creek follow the Rosin distribution. At high discharges, the transported bedload approaches the grain sizes of that bed-material source and mimics its Rosin distribution. Random-selection processes must be more important to grain entrainment at lower discharges, so that the resulting Gaussian distributions of transported bedload reflect similar distributions of bed stresses exerted by the stream flow.

The results from Oak Creek demonstrate that competence of the flow is reflected in the entire distribution of transported gravel sizes. A sequence of layers of fluvial gravels, modern or ancient, might show systematic variations between coarse Rosin and finer-grained Gaussian distributions, and these could be used to infer frequencies of various discharges and establish a relationship to the source sediment.

A differential bedload transport function is formulated utilizing the dependence of two parameters in the Rosin distribution on the flow stress. The total transport rate, which is also a function of the flow stress, is apportioned within the Rosin grain-size distribution to yield the fractional transport rates. The derived bedload function has the advantage of yielding smooth, continuous frequency distributions of transport rates for the grain-size fractions, in contrast to the discrete transport functions which predict rates for specified sieve fractions. A group of differential transport frequency curves can be constructed that reflects a particular stream's bedload transport characteristics. Successful reproduction of the measured fractional transport rates and bedload grain-size distributions by this approach demonstrates its potential in flow-competence estimates, evaluations of differential transport rates of size factions, and in investigations of downstream changes in bed material grain-size distributions.

**Stratigraphy and sedimentology of the late Eocene Bateman Formation, southern Oregon Coast Range,** by David G. Weatherby (M.S., University of Oregon, 1991), 161 p.

During the Eocene epoch, a thick sequence of sedimentary and interbedded volcanic rocks was deposited in a fore-arc basin in the central southern Oregon Coast Range, southwest of Elkton, Oregon. Eocene sedimentary formations representing deep-sea-fan, shelf, marginal-marine, and nonmarine environments provide a record of the filling of the basin. The late Eocene Bateman Formation is the stratigraphically highest formation in the central southern Coast Range and represents final deposition in a prograding delta complex.

Sedimentary facies representing deltaic distributary channel, interdistributary swamp and marsh, delta-front, and prodelta environments are present in the Bateman Formation. Deposition of the Bateman Formation on a prograding delta is inferred from the presence of several small- and large-scale, upward-coarsening sequences in which prodelta sediments are overlain by delta-front and distributary-channel sediments. Small-scale upward-fining sequences composed of distributary swamp and marsh sediments represent meandering of distributary channels. Paleocurrent data indicate that delta progradation was to the north-northwest. Lateral facies relationships show that marine delta-front and prodelta sediments are generally more common in the direction of delta progradation, whereas nonmarine distributary-channel and interdistributary swamp and marsh sediments are less common in the direction of sediment transport.

Petrographic analysis of sandstone composition indicates that Bateman sandstones were derived dominantly from an andesitic volcanic arc with minor input from metamorphic, plutonic, and sedimentary sources. Paleocurrent data suggest that the source was located to the southeast, probably in the Western Cascades and the northern Klamath Mountains. □

# Strong ground shaking in the Portland, Oregon, metropolitan area: Evaluating the effects of local crustal and Cascadia subduction zone earthquakes and near-surface geology

*by Ivan G. Wong, Woodward-Clyde Federal Services, 500 12th Street, Suite 100, Oakland, CA 94607; Walter J. Silva, Pacific Engineering and Analysis, 311 Pomona Avenue, El Cerrito, CA 94530; and Ian P. Madin, Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street, Portland, OR 97232*

**ABSTRACT**

In its 150-year existence, the Portland metropolitan area has gone relatively unscathed by damaging earthquakes. However, an increasing amount of geologic and seismologic data indicate that crustal earthquakes in the Portland region larger than Richter magnitude ($M_L$) 6 and Cascadia subduction zone earthquakes of moment magnitude ($M_W$) 8 or greater will occur in the future. If either were the case, strong ground shaking generated by these events would have a major impact on the Portland area. In this study, we have estimated deterministically site-specific ground motions at four sites located in Portland using a state-of-the-art stochastic methodology. The events modeled were crustal earthquakes of $M_W$ 6 and $M_W$ 6.5 at source-to-site distances of 5, 10, and 15 km and a $M_W$ 8.5 Cascadia subduction earthquake at a distance of about 120 km. In all cases, ground motions will be significant and damaging. The severity of such ground shaking in the Portland metropolitan area will be controlled in large part by the nature of the unconsolidated sediments at each specific location.

**INTRODUCTION**

The Portland metropolitan area and surrounding vicinity have been the most seismically active region in Oregon in historical times. Based on the relatively brief 150-year historic record, six earthquakes of Richter magnitude ($M_L$) 5 or greater have occurred within the greater Portland area (Bott and Wong, 1993). The recent occurrence of the damaging $M_L$ 5.6 event of March 25, 1993, at Scotts Mills is testimony to the hazards posed by apparently randomly occurring crustal earthquakes. Recent geophysical studies suggest the presence of crustal faults beneath the Portland metropolitan area, which—albeit speculatively—could generate a potentially much more damaging crustal earthquake of $M_L$ 6 or larger. A recent evaluation of earthquake recurrence suggests that a crustal earthquake of $M_L$ 6 or larger should occur somewhere in the Portland region every 300–350 years and an event of $M_L$ 6½ or larger about every 800–900 years (Bott and Wong, 1993). The seismic hazards posed by these earthquakes occurring within the earth's

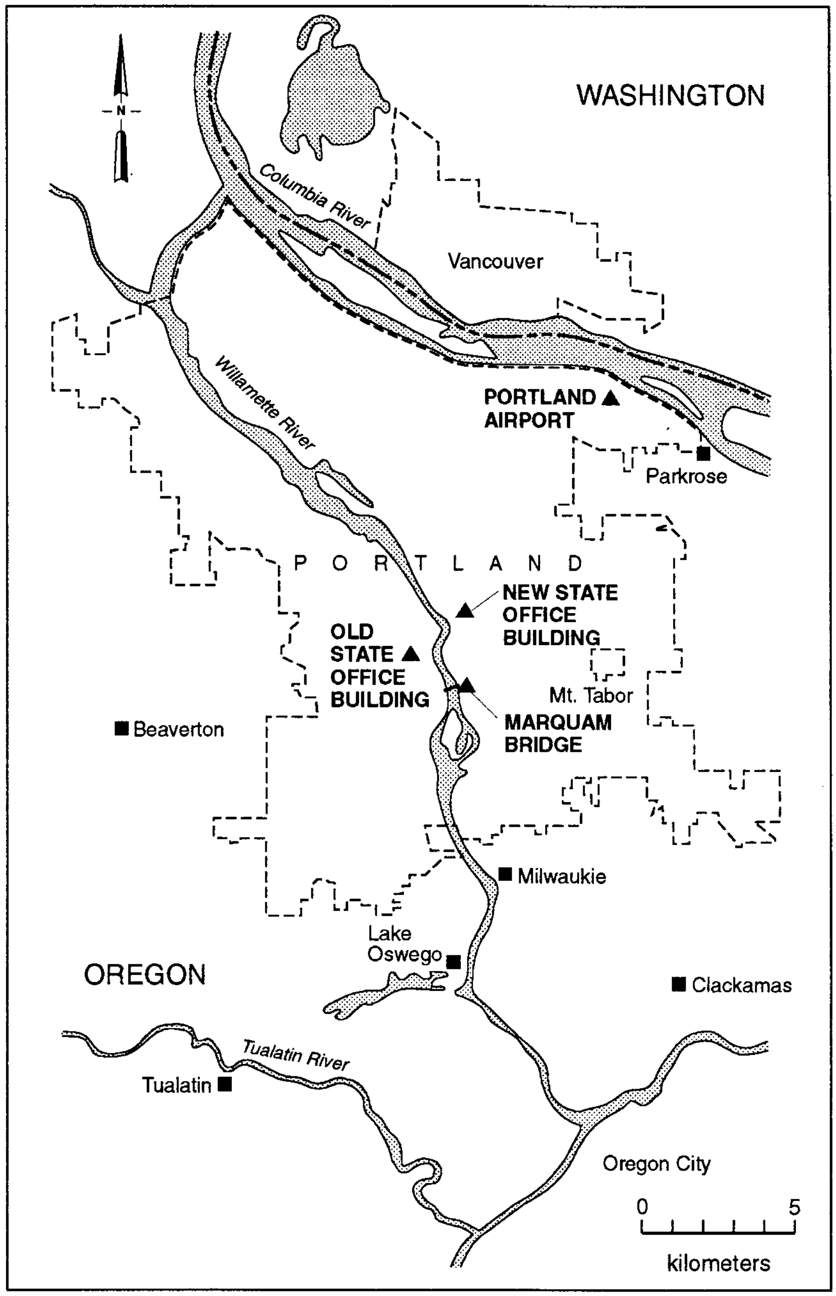


*Figure 1. Location of sites (triangles) evaluated in this study.*

crust are in addition to the recently recognized threat from a future great earthquake (moment magnitude $M_W \geq 8$) occurring along the interface between the Juan de Fuca and North American plates within the Cascadia subduction zone.

In this study, we have estimated the strong earthquake ground shaking that might be experienced at four sites in the Portland metropolitan area due to (1) moderate to large crustal earthquakes of $M_W$ 6 and 6.5 occurring somewhere beneath the Portland Basin and (2) a $M_W$ 8.5 Cascadia subduction zone earthquake. Our analysis is based on a state-of-the-art methodology that combines the Band-Limited-White-Noise (BLWN) ground-motion model and random vibration theory (RVT). An equivalent-linear site response technique is also employed to accommodate nonlinear soil behavior. This general approach has been previously used in a preliminary assessment of earthquake ground shaking in the Portland area (Wong and others, 1990).

Compared to our earlier study, we have (1) expanded our analyses to four sites and seven hypothetical earthquakes, (2) utilized recently acquired near-surface geologic and shear wave velocity data for the sites, and (3) refined our characterization and approach to modeling the Cascadia subduction zone event. Peak horizontal accelerations and five-percent damped acceleration response spectra have been computed for the following sites (Figure 1): (1) a soft soil site at the east end of the Marquam Bridge in southeast Portland, (2) a deep soft soil site at the Portland airport, (3) the moderately stiff soil site of the old State Office Building in downtown Portland, and (4) the relatively thin soil site of the new State Office Building in northeast Portland. The earthquakes modeled are two crustal earthquakes of $M_W$ 6 and 6.5 at source-to-site distances of 5, 10, and 15 km and the $M_W$ 8.5 Cascadia event at a distance of about 120 km.

It should be noted that our analysis is deterministic with no consideration for the frequency of occurrence of these earthquakes other than they are credible events with some finite probability of occurring. Thus the ground motions estimated in this study, specifically for the crustal earthquakes occurring in the Portland area, should not be used directly for seismic design but as potential scenarios for the greatest ground shaking that might be expected. It is also important that the uncertainties in any ground motion evaluation be fully appreciated given the uncertainties in earthquake source, path, and geologic site parameters that are the basic input into such analyses.

## METHODOLOGY

The BLWN-RVT methodology is a stochastic ground motion modeling technique that has been used successfully in recent years to estimate earthquake ground shaking. Because the methodology can incorporate aspects of the source, path, and site that are specifically appropriate for the earthquake region and location to be modeled, it is particularly valuable in areas where few, if any, strong motion records exist. Such is the case for the Portland area. In this study, the crustal earthquakes have been modeled based on a point source representation of the BLWN model. This approach is applicable, given the magnitudes of the events and source-to-site distances being considered. However, because source dimensions will be significant for a great Cascadia subduction zone earthquake relative to its source-to-site distance, the finite fault version of the BLWN-RVT methodology is employed to estimate the ground motions for this event. Details of the point source and finite fault approaches can be found in Silva and others (1992) and Silva and others (1990), respectively.

## INPUT PARAMETERS

The earthquake source, propagation path, and site parameters that are required for the site-specific ground motion estimates are described in the following paragraphs.

### Earthquake sources

Although the largest known crustal earthquake in the Portland region was the recent 1993 Scotts Mills earthquake, events as large as or larger than $M_L$ 6½ (or $M_W$ 6½) are thought to be possible. Thus, the two crustal earthquakes modeled in this study were $M_W$ 6 and $M_W$ 6.5. The distance defined in the stochastic point source approach is measured from the site of interest to the center of energy release or approximately the center of the potential rupture plane. Source-to-site distances of 5 to 15 km were chosen to evaluate the potential ground shaking that might result from an earthquake occurring on a crustal fault beneath Portland.

Although to date no seismogenic faults have been identified in the Portland area, the relatively high level of crustal seismicity suggests that such faults do exist. Their maximum earthquake generating potential is as yet unknown. Crustal earthquakes in western Oregon tend to occur at depths down to 20–25 km, deeper than do most western U.S. earthquakes. Consequently, the likelihood of a moderate to large earthquake at a source-to-site distance of 5 km is low in the Portland region, unless the event occurs on a fault whose rupture extends up to or close to the earth's surface.

In order to estimate ground motions using the BLWN-RVT point source approach, the stress drop of the modeled earthquake is required. Recently, Youngs and Silva (1992) observed that a stress drop of about 85 bars provides a good fit to recently developed empirical rock attenuation relationships for spectral acceleration based on strong motion data from California. Given the uncertainty of stress drops for Pacific Northwest crustal earthquakes, a value of 100 bars was selected as a reasonable value to use in the point source estimates.

Geologic and seismologic studies conducted over the last five years have led, in the earth science community, to a general acceptance of the view that the Cascadia subduction zone interface has produced large megathrust earthquakes ($M_W \geq 8$) in the prehistoric past and is likely to produce them in the future (e.g., Rogers and others, 1991). The $M_W$ 7.0 Cape Mendocino earthquake of 1992 in northwestern California probably

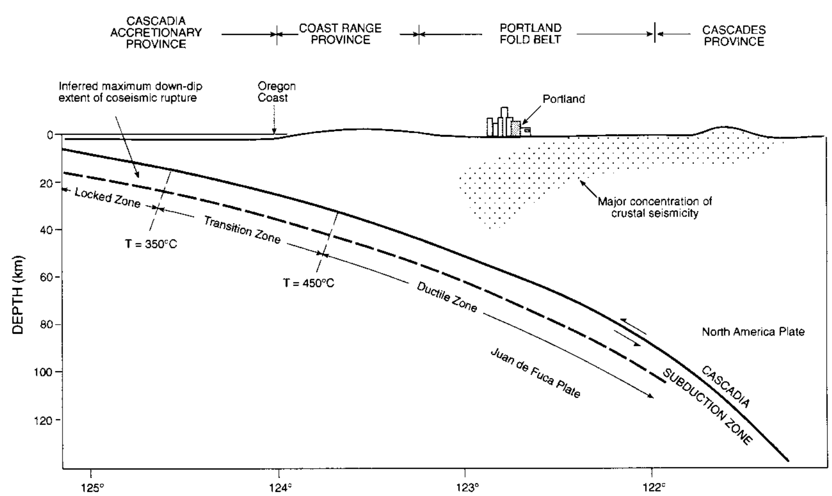


*Figure 2. Schematic cross-section through the Cascadia subduction zone at the latitude of Portland, Oregon, modified from Unruh and others (1993). Divisions of subduction zone from Hyndman and Wang (1993). We have assumed that coseismic rupture will extend approximately into the western third of the transition zone.*

occurred on the interface and hence demonstrates that the subduction zone, at least at its southern end, is seismogenic (Oppenheimer and others, 1993). The size of the maximum magnitude earthquake that might occur along the interface is, however, the subject of considerable current debate and research. The size of the earthquake is dependent on the length and width of the rupture zone (hence rupture area), which is in turn primarily dependent on the segmented nature and downdip extent of the subducted slab. Current estimates of these rupture parameters are uncertain, given our existing knowledge of the subduction zone. In this study, we have assumed a maximum magnitude of $M_W$ 8.5 as a reasonable value to use at this time.

On the basis of thermal modeling, Hyndman and Wang (1993) defined four down-dip divisions of the Cascadia subduction zone interface (Figure 2, showing zones 2–4): (1) a zone of stable sliding in the unconsolidated and/or clay-rich sediments at the seaward end of the detachment; (2) a locked zone of unstable sliding behavior that allows elastic strain to accumulate; (3) a transition zone in which slip would occur, in part, during earthquake displacement and, in part, during post-seismic slip; and (4) a zone of plastic behavior (ductile) associated with high temperatures. The width of the zone defined by Hyndman and Wang (1993) as locked is about 70 km wide off the coast of Oregon. Adopting their locked zone as the primary site of future rupture, we also conservatively assume that a third of the transition zone will be involved in coseismic rupture. These assumptions result in a rupture width of about 90 km off the coast of Oregon. As derived from an empirical relationship between rupture area and magnitude (Wells and Coppersmith, in preparation), the corresponding rupture length for a $M_W$ 8.5 earthquake would be approximately 300–350 km. Such a length is comparable to other values suggested by investigators who assume a segmented Cascadia subduction zone. Extending the rupture one-third into the transition zone also results in a source-to-site distance from the eastern extent of the rupture to the Portland area of about 120 km. This distance probably has an uncertainty of several tens of kilometers. The depth of the eastern edge of the potential 10° eastward-dipping rupture plane will be approximately 20 km (Figure 2).

In the absence of *a priori* information on the actual slip distribution of a future event, randomized slip distributions were used in the finite fault modeling for the Cascadia subduction zone earthquake. A total of 50 randomized slip models were used. Samples of these models are shown in Figure 3. In order to generate these slip models, the two-dimensional wave-number spectrum of the slip model for the $M_W$ 8 earthquake of 1985 at Michoacan, Mexico, was computed and its phase spectrum randomized.

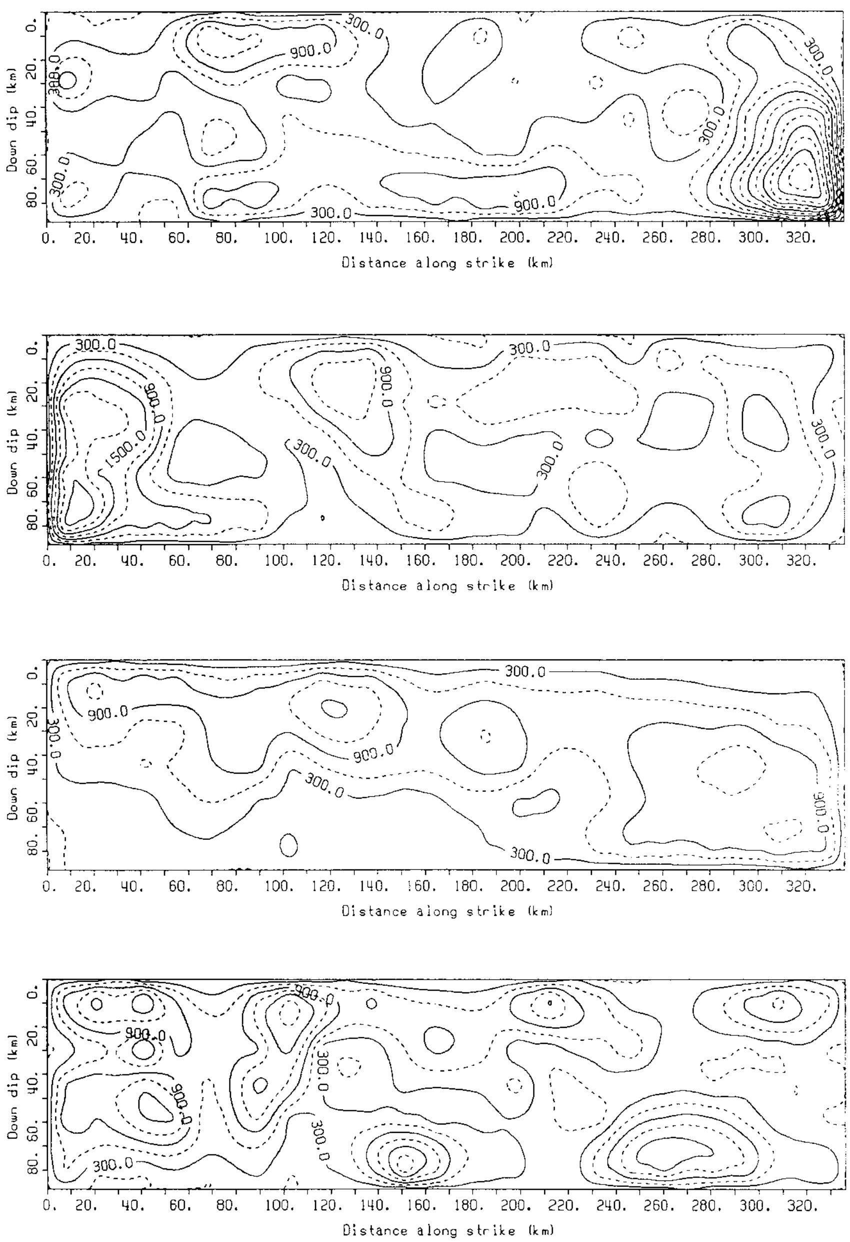


*Figure 3. Examples of the 50 randomized slip distribution models used in the estimation of ground motions for the $M_W$ 8.5 Cascadia subduction zone earthquake. Contours represent coseismic slip along the rupture planes in cm. Areas of large slip are called asperities.*

Again, in the absence of *a priori* knowledge, points of rupture initiation were randomized along a zone that extends along strike and is located in the lower half of the fault plane toward its eastern edge. Rupture is expected to proceed updip in a Cascadia megathrust earthquake.

## Path

To describe the frequency ($f$)-dependent seismic wave attenuation along the crustal path between source and site (described as $Q[f] = Q_0 f^{\eta}$) for the crustal events, a $Q_0$ of 200 and $\eta$ of 0.35 were adopted from Singh and Herrmann (1983), who analyzed the coda waves of recorded local and near-regional earthquakes. These values were determined from the seismograph station located in Corvallis. Given the short source-to-site distances for the crustal events, attenuation has very little effect on the computed ground motions. A shear wave velocity ($v_s$) of 3.8 km/s and density of 2.8 g/cm$^3$ were used to characterize the path between the source and the site.

For the Cascadia earthquake, a $Q_0$ of 273 and $\eta$ of 0.66 were used to characterize the attenuation of seismic waves along the path from the subduction zone to the site. This attenuation model was adopted from observations of the 1985 Michoacan earthquake (Humphrey and Anderson, 1992).

### Sites

All four sites analyzed in this study are located in the alluvium-filled Portland Basin. Near-surface stratigraphy based on borehole data and shear-wave velocities from downhole profiling was provided by DOGAMI (Mabey and Madin, 1992) for the Marquam Bridge and airport sites (Figure 4). The profile for the new State Office Building was slightly revised from the one previously used in Wong and others (1990). Subsurface data for the old State Office Building site are from Shannon and Wilson and Agbabian Associates (1980). The stratigraphy beneath the boreholes is based largely on a few deep exploration boreholes in the Portland Basin and a limited amount of seismic data (Wong and others, 1990). Due to this lack of site-specific data, considerable uncertainties are associated with deeper portions of the geologic profiles, although ground motions of engineering interest in the frequency range of 1 to 10 Hz are controlled largely by the shallow site geology, particularly the unconsolidated sediments.

Occurring within the Portland Basin is the Columbia River basalt (Figure 4), which serves as the top of rock at the four sites in this study despite the relatively high shear-wave velocities for the Troutdale gravel. The basalt is overlain by the Sandy River Mudstone at three of the four sites, by the Troutdale gravel, and then by varying thicknesses of soft, relatively low-velocity alluvial sands and silts. All layers above rock were considered in the equivalent-linear analysis. Three shear modulus reduction curves were used to characterize the dynamic behavior of the unconsolidated sediments at each site: Seed and Idriss (1970) for upper-range sand and mid-range gravel (Troutdale) and Sun and others (1988) for the Sandy River Mudstone. Seed and Idriss (1970) mid-range damping curves for sand and gravel were used for the sands and Troutdale gravels, respectively. A damping curve was developed and used in this study specifically for the mudstone. Modulus reduction and damping curves are a source of uncertainty, since they are based on laboratory measurements of non-site-specific samples.

### RESULTS

Earthquake ground shaking on soil sites is influenced by two opposing effects: site amplification and material damping. Amplification by unconsolidated sediments often results in the increase in amplitudes at certain frequencies due to (1) conservation of energy effects as the seismic waves travel from a faster, more rigid material to a slower, softer material; and (2) resonant effects due to constructive interference of multiple reflections. Damping in soils is the dissipation of energy due to a variety of loss mechanisms.

The five-percent damped acceleration response spectra computed in this study for the crustal earthquakes are shown in Figures 5 and 6. The estimated peak horizontal accelerations are summarized in Table 1. For comparison, we have also computed peak horizontal accelerations based on several state-of-the-practice empirical attenuation relationships for crustal earthquakes (Table 2). Inherent in the empirical approach to estimating ground motions is the inability to incorporate site-specific geologic data and hence, site response effects unique to each location.

For the Marquam Bridge site, peak horizontal accelerations range from 0.13 to 0.43 *g*, levels which can result in minor to

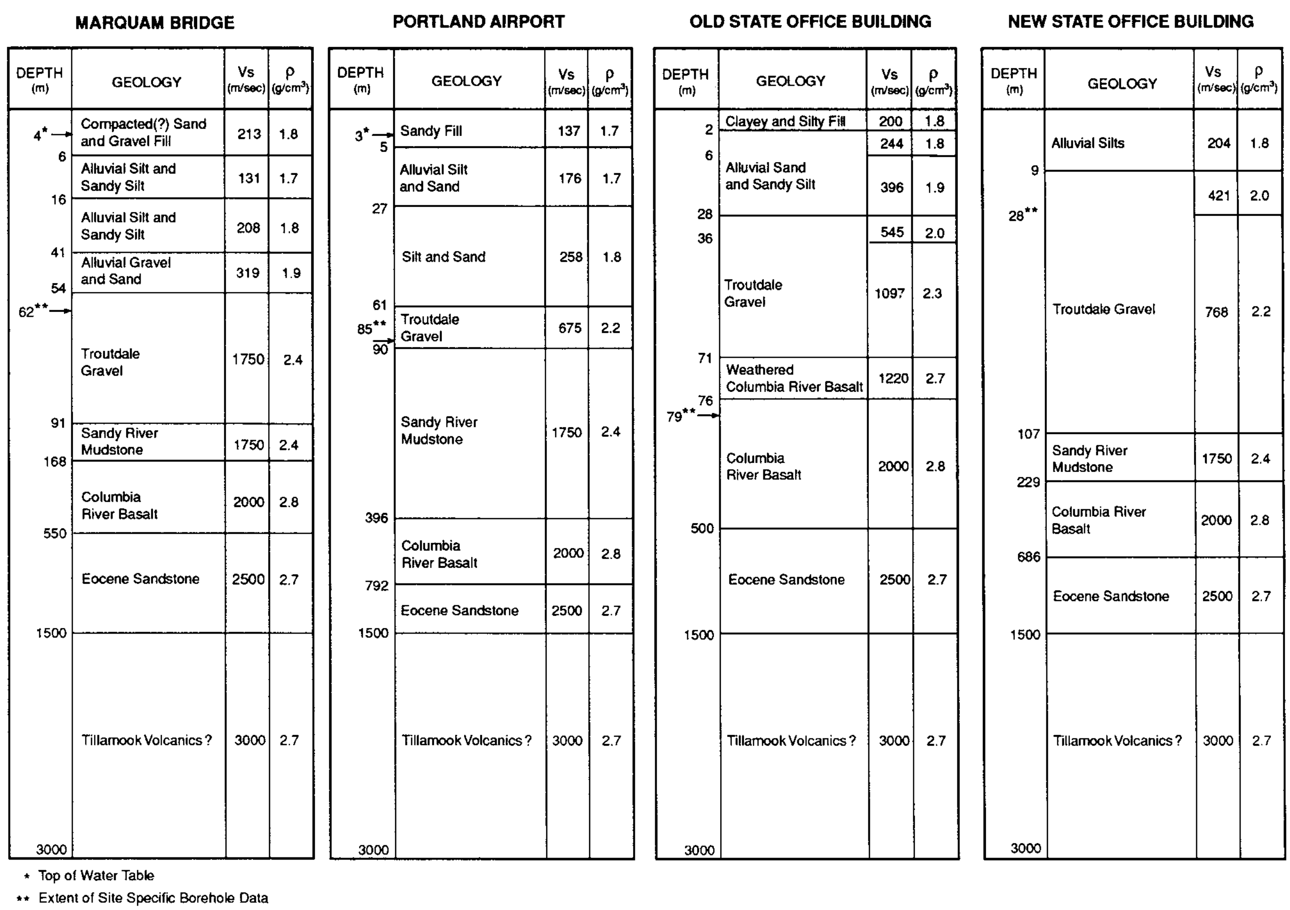


*Figure 4. Geologic profiles beneath the four sites analyzed in this study.*

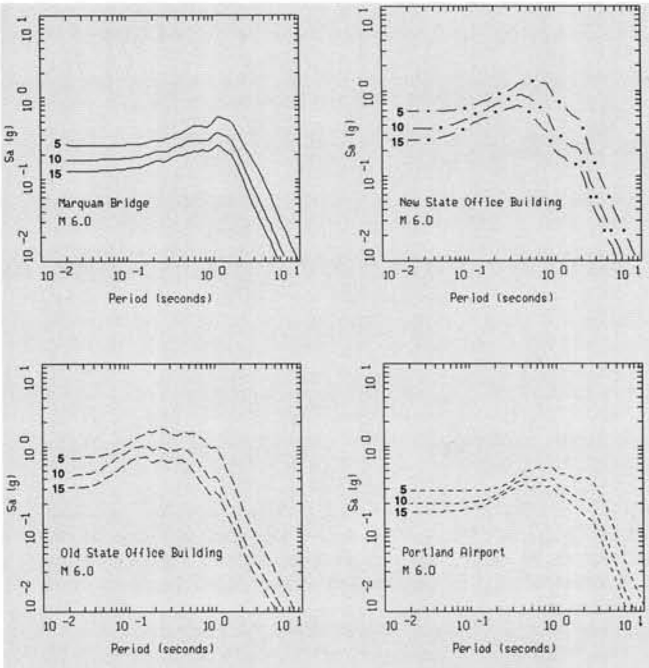


*Figure 5. Site-specific five-percent damped median acceleration response spectra for the $M_W$ 6 crustal earthquake at source-to-site distances of 5, 10, and 15 km for the four sites analyzed.*

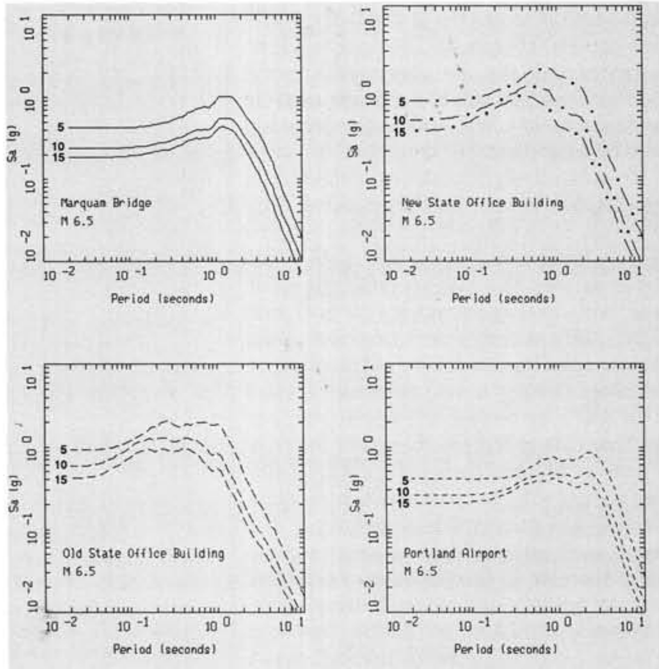


*Figure 6. Site-specific five-percent damped median acceleration response spectra for the $M_W$ 6.5 crustal earthquake at source-to-site distances of 5, 10, and 15 km for the four sites analyzed.*

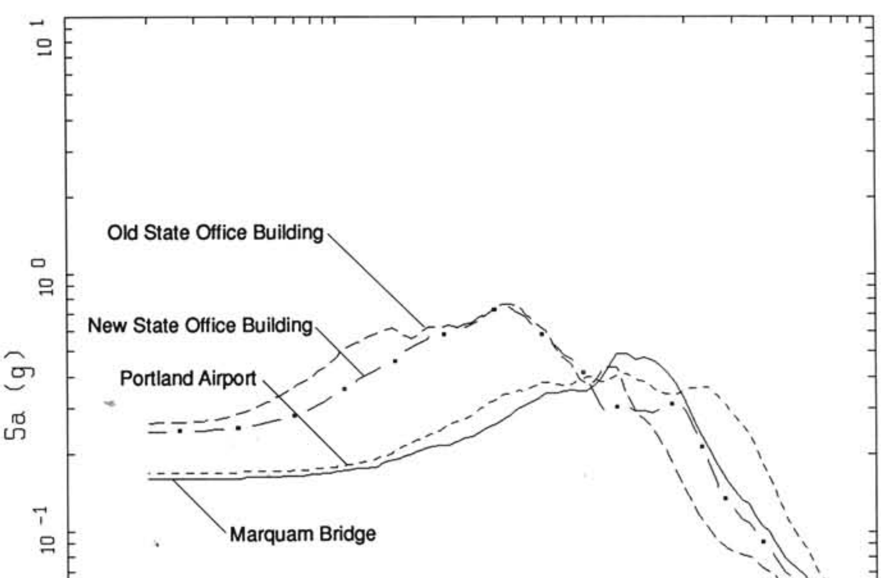


*Figure 7. Site-specific five-percent damped median acceleration response spectra for the $M_W$ 8.5 Cascadia subduction zone earthquake for the four sites analyzed, at a source-to-site distance of 120 km.*

significant structural damage (Table 1). (Ground acceleration is often expressed in terms of "*g*," or the gravitational acceleration at the earth's surface.) For comparison, ground shaking recorded 50 km away in the Portland area during the recent Scotts Mills earthquake was less than 0.05 *g* (U.S. Geological Survey, 1993).

The strong velocity contrast at the top of the Troutdale gravel beneath the Marquam Bridge site (Figure 4) probably accounts for some site amplification of the ground motions, although this effect appears to be offset by damping in the 54-m-thick low-velocity silts and sands. The low-velocity zone (131 m/s) between the depths of 6 and 16 m (Figure 4) may also act to trap some upgoing energy. In almost all cases, the site-specific stochastic peak horizontal accelerations for the crustal earthquakes are less than typical median empirical values (Tables 1 and 2), attesting to the damping effects of this relatively deep-soil site. The spectral shapes, in particular the resonant peak at a period of 1.5 s, are similar for both the $M_W$ 6 and the $M_W$ 6.5 earthquakes, reflecting the influence of the near-surface site geology (Figures 5 and 6).

The ground motions at the Portland airport reflect the site response of a deep-soil site, although the absence of a low-velocity zone may account for the slightly higher peak horizontal accelerations compared to the Marquam Bridge (Table 1; Figures 5 and 6). Significant short-period damping is probably occurring within the 90-m-thick unconsolidated to poorly consolidated sediments (including the low-velocity Troutdale gravels) (Figure 4). The peak accelerations for this site are comparable to the median empirical values estimated with the relationship of Idriss (1985) for deep-soil sites (Tables 1 and 2).

In contrast, significant site amplification appears to be influencing the ground motions at the old State Office Building site and to a slightly lesser extent at the new State Office Building site. The site-specific stochastic peak horizontal accelerations for both sites significantly exceed typical empirical values (Tables 1 and 2). Beneath the old State Office Building, a strong velocity contrast is located at the boundary between the weathered top of the Troutdale gravel and the rest of the layer (Figure 4). Material damping is not as significant at these sites, due to the thinner nature of the soils and unconsolidated sediments. If a crustal earthquake of $M_W$ 6 or greater were to occur at source-to-site distances of 5–15 km, such as beneath downtown Portland, very strong ground shaking would be experienced (Figures 5 and 6). Given the uncertainties in ground motion estimates, the peak accelerations for the old State Office Building site could exceed 0.6 *g* (Table 1).

Velocity contrasts exist beneath the new State Office Building at boundaries within the Troutdale gravel. The Sandy River Mudstone represents a low-velocity zone within the profile, which probably accounts for the lower peak accelerations and spectral accelerations at short periods, compared to the old State Office Building (Table 1 and Figure 4). The highest spectral accelerations at these two sites occur at periods of 0.1 to 1.0 s (1 to 10 Hz) (Figures 5 and 6), the bandwidth of significant engineering relevance.

Despite the source-to-site distance of 120-km, the $M_W$ 8.5 Cascadia earthquake could generate significant ground shaking in the Portland metropolitan area, particularly at the old and new State Office Building sites (Figure 7 and Table 1). These ground motions, however, must be viewed cautiously, given the large uncertainties surrounding the source-to-site distances to the eastern extent of rupture of a megathrust earthquake and, of course, the maximum magnitude of such an event. The shift in the broad spectral peaks to longer periods for the Portland airport and Marquam Bridge compared to the old and new State Office Buildings reflects the influence of the deep unconsolidated sediments at the former two sites (Figure 7).

An important effect not addressed in this study, especially for the Cascadia earthquake, is the duration of strong ground shaking. Given the extended rupture dimensions of a large megathrust earthquake, duration is a parameter that needs to be considered in seismic design and seismic safety evaluations, particularly for long-period structures, such as tall buildings and bridges, and in areas where soil liquefaction is a potential hazard.

Table 1. *Site-specific stochastic peak horizontal accelerations. MB = Marquam Bridge, NB = new State Office Building, OB = old State Office Building, PA = Portland airport*

| Earthquake | Magnitude ($M_W$) | Distance[1] (km) | Peak horizontal accelerations MB (*g*) | NB (*g*) | OB (*g*) | PA (*g*) |
|---|---|---|---|---|---|---|
| **Cascadia** | 8.5 | 120 | 0.16 | 0.24 | 0.26 | 0.17 |
| **Crustal** | 6 | 5 | 0.26 | 0.58 | 0.72 | 0.29 |
| | | 10 | 0.18 | 0.36 | 0.44 | 0.20 |
| | | 15 | 0.13 | 0.26 | 0.31 | 0.16 |
| | 6.5 | 5 | 0.43 | 0.78 | 0.92 | 0.41 |
| | | 10 | 0.24 | 0.47 | 0.57 | 0.26 |
| | | 15 | 0.19 | 0.35 | 0.41 | 0.21 |

[1] Source-to-site

Table 2. *Median empirical peak horizontal accelerations for crustal earthquakes*

| Magnitude ($M_W$) | Distance[1] (km) | Campbell (1990) (*g*) | Sadigh (1987)[2] (*g*) | Idriss (1985) Stiff[3] (*g*) | Deep[4] (*g*) |
|---|---|---|---|---|---|
| 6 | 5 | 0.37 | 0.29 | 0.36 | 0.31 |
| | 10 | 0.22 | 0.20 | 0.25 | 0.22 |
| | 15 | 0.15 | 0.14 | 0.18 | 0.17 |
| 6.5 | 5 | 0.43 | 0.37 | 0.43 | 0.36 |
| | 10 | 0.28 | 0.26 | 0.30 | 0.27 |
| | 15 | 0.20 | 0.20 | 0.23 | 0.20 |

1 Source-to-site

[2] Described in Joyner and Boore (1988)

[3] Stiff-soil sites are underlain by cohesionless soils or stiff clays less than 61 m deep

[4] Deep-soil sites are underlain by more than 76 m of cohesionless soil deposits

## SUMMARY

If a crustal earthquake of moderate or larger magnitude ($M_W$ 6) should occur beneath the Portland Basin, significant strong ground shaking is likely. As has been observed in numerous cases worldwide, the amplitudes and frequency content of such ground motions will be strongly influenced by the nature of the soils and unconsolidated sediments beneath a given location in the Portland metropolitan area. Thin-soil sites such as the old and new State Office Buildings can produce severe ground shaking in either a nearby crustal earthquake or a distant large event on the Cascadia subduction zone. Deep-soil sites such as at the Marquam Bridge and the Portland airport, though still capable of experiencing strong shaking, will dampen as well as shift short-period ground motions to longer periods. The range of ground motions observed in this study further emphasizes the need for assessing such hazards on a site-specific basis in the Portland metropolitan area.

## ACKNOWLEDGMENTS

This study was supported by the Oregon Department of Geology and Mineral Industries (DOGAMI) under Contract No. 6175002. Funding provided to DOGAMI was through the U.S. Geological Survey National Earthquake Hazards Reduction Program. Our thanks go to Jim Humphrey, Cathy Stark, Roy Hyndman, Sylvia Li, Doug Wright, Jeff Unruh, Fumiko Goss, and Sue Penn for their assistance in this study. This paper benefitted from critical reviews by Stephen Dickenson, Michael Hagerty, and Jackie Bott and from an engineering perspective from Dave Driscoll.

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# BLM protects "Cenozoic Park" fossils

*by John Zancanella; reprinted from* BLM News, *September 1993, page 4.*

With the popularity of the movie *Jurassic Park*, interest in fossils is greater than ever before. Few people realize, however, that the Bureau of Land Management is steward to many fossil treasures here in Oregon.

"Fossil remains of dinosaurs like those portrayed in the movie are generally found in the Great Plains and Rocky Mountains regions," explained paleontologist Dr. James Martin. "In Oregon, we have fossils from the Age of Mammals, the Cenozoic Era, which extends back nearly 50 million years."

Martin, from the South Dakota School of Mines and Technology, has been hired by BLM to develop a statewide plan for paleontology, the study of ancient life through the fossil record.

"After conducting research in Oregon for 20 years, I understand that educating people about this resource is as important as working to preserve it," Martin said. "Public responsibility is the key."

In central Oregon, the red, blue-green, and buff-colored sedimentary rocks of the Clarno, John Day, Mascall, and Rattlesnake Formations represent environments that changed from tropical and subtropical forests to a cooler and dryer savanna. The fossils found in these rocks include horses, elephants, rhinoceroses, rodents, cats, dogs, camels, and large piglike animals called oreodonts.

The John Day Formation, visible along the upper John Day River and the surrounding hills, was punctuated by volcanic ash falls that now allow scientists to accurately determine how the plants and animals have changed over time. This formation is significant because its seven- to ten-million-year sequence of fossil-bearing rock is one of the most complete and continuous in the world.

"In fact," Martin explained, "evolutionary changes of the horse were first determined from fossils recovered from the John Day River basin. Erosional and volcanic forces since that time have combined to sculpt and mold these ancient landscapes into the dramatic and wonderful scenes we see today."

In June, the resurgence of excitement about fossils and their importance to scientific study prompted BLM's Oregon/Washington State Director Dean Bibles to visit two Cenozoic fossil sites on BLM-managed lands in central Oregon.

Bibles and Martin toured Logan Butte in BLM's Prineville District and Fossil Lake in BLM's Lakeview District. Ted Fremd, paleontologist with the John Day Fossil Beds National Monument, was also on hand to attest to the importance of the Logan Butte site.

"I was impressed with the wide variety and sheer quantity of the fossil record at these sites," Bibles said. "At the same time, however, I'm disturbed to see so much evidence of unauthorized collection and destruction caused by careless visitors."

Current federal law prohibits the collection of any vertebrate fossils from federal lands without a permit, whereas most invertebrate and plant fossils can be collected by the general public.

"It is essential that we carefully collect and document specimens on public lands, but the process doesn't stop there," explained Martin. "We must preserve fossils for those to come and be able to retrieve them for future study."

Bibles showed enthusiastic support for Dr. Martin's efforts and stated that more education of both BLM staff and the public is needed to protect fossil resources on public lands.

"Fossils are a nonrenewable resource, and vertebrate fossils are the rarest," Bibles said. "We're committed to doing whatever is necessary to ensure that BLM's 'Cenozoic Park' may be studied and enjoyed by future generations." □

## DOGAMI PUBLICATIONS

Released September 22, 1993:

**Geologic map of the Vale 30 x 60 minute quadrangle, Malheur County, Oregon, and Owyhee County, Idaho,** by Mark L. Ferns, James G. Evans, and Michael L. Cummings. It is published as map GMS–77. Price is $10. — This has been released together with **Geologic map of the Mahogany Mountain 30 x 60 minute quadrangle, Malheur County, Oregon, and Owyhee County, Idaho,** by Mark L. Ferns, Howard C. Brooks, James G. Evans, and Michael L. Cummings. It is DOGAMI map GMS–78. Price is $10.

A 3,000-$mi^2$ area of northern and central Malheur County in extreme eastern Oregon is covered by these two geologic maps, the north half by GMS–77 and the south half by GMS–78. Over a period of more than seven years, geologists have mapped, one by one, the 64 7½-minute quadrangles that make up the complete west half (a little more than the Oregon portion) of the Boise 1°x2° quadrangle. The new maps represent a compilation of this work.

Together, they inform the public about the region's geology, which provides the framework for newly discovered gold deposits such as Newmont's Grassy Mountain. They also present information on other geologic resources, among them nonmetallic minerals, geothermal energy, and natural gas, and give a brief assessment of geologic hazards such as landslides and ground-water pollution.

The original mapping work was done at the more detailed scale of 1:24,000, and a portion of it has been published already. The new compilation maps, GMS–77 and GMS–78, are done at the scale of 1:100,000, each including a full-color map sheet approximately 31 by 45 in. in size and a 12-page text with rock descriptions and discussions of the geologic evolution and geologic resources and hazards of the region.

The maps cover parts of two geomorphic provinces, the Owyhee Uplands and the western Snake River Plain. Both provinces are extensional basins, large scars on the earth's surface from two periods of rifting along the Oregon-Idaho border.

The older basin, the Oregon-Idaho Graben, is now partially filled with a variety of volcanic and sedimentary rocks. It extends north-south and began to form shortly after eruption of the voluminous flood basalts of the Columbia River Basalt Group some 15 to 17 million years ago. Large rhyolite calderas and eruptive centers, similar in size to those of modern-day Yellowstone, formed early during the development of the Oregon-Idaho Graben. Gold mineralization was associated with smaller scale calc-alkaline volcanism along the axis of the graben.

The younger basin now forms the northwest-trending western Snake River Plain. It began cutting across the north end of the Oregon-Idaho Graben about 7 million years ago. For a period of about 5 million years, this part of the western Snake River Plain was filled by ancient Lake Idaho (comparable in size to some of the modern-day Great Lakes). The lake was emptied by the Snake River through Hells Canyon about 1.5 million years ago.

Released August 12, 1993:

**Pilot erosion rate data study of the central Oregon coast, Lincoln County. Final report to the Federal Emergency Management Agency**, by G. R. Priest. I. Saul, and J. Diebenow. The 232-page report includes 30 colored photographs and has been released as Open-File Report O–93–10 for library access only. Photocopies may be obtained at cost.

The pilot study was undertaken to support the Federal Flood Insurance Program. The goal of this program is to explore ways of measuring erosion rates so that bluff and shoreline positions can be predicted accurately up to 60 years in the future and the erosion rates used to set flood insurance rates.

The study area extends along most of the coastline of Lincoln County, between Cascade Head and Seal Rock. The area was chosen as representative of the many coastal environments of Oregon because it includes bluffed beaches, hard-rock headlands, sand spits, and river-mouth beaches. On the basis of geology and geomorphology, the entire length was divided into 32 segments and subsegments, and erosion rates were studied for each of them.

This report is available for inspection in the library of the Portland office of the Oregon Department of Geology and Mineral Industries (see address on page 126 of this issue). Copy services may be obtained from Kinko's at 1605 NE 7th Avenue, Portland, OR 97232, phone 503–284–2129.

Released January 8, 1993:

**Neotectonic map of the Oregon continental margin and adjacent abyssal plain,** by C. Goldfinger, L.D., Kulm, R.S. Yeats, C. Mitchell, R. Weldon II, C. Peterson, M. Darienzo, W. Grant, and G.R. Priest. Released as Open-File Report O–92–4. Price is $30.

The neotectonic map shows the structure of the continental margin along the Oregon coast and other details that help determine the earthquake hazard potential of the state. Data were contributed by Oregon State University, U.S. Geological Survey, National Oceanic and Atmospheric Administration, and Chevron and Shell Oil Companies. Compilation and publication were supported by the National Earthquake Hazards Reduction Program.

The main map (Plate 1) is a color electrostatic plotted sheet measuring 36 by 45 in. It shows faults and folds along the Oregon continental margin at the Cascadia subduction zone and presents representative sections through salt marshes. A one-color map (Plate 2) shows the track lines for offshore geophysical data. The release also includes a 17-page text with discussions and explanations.

The neotectonic map illustrates how the continental margin has been and is being deformed by underthrusting of the oceanic plate beneath the continental plate. It shows dozens of newly discovered, potentially active submarine faults, some of which may penetrate all the way to the Oregon coast.

The map also shows uplift rates along the coast. This uplift is probably caused by strain that builds up between great subduction-zone earthquakes. The uplift rates, when compared to the rates of global sea-level rise, indicate the parts of the coast that are most vulnerable to gradual coastal flooding and erosion.

Released July 26, 1993:

**Schematic fence diagram of the southern Tyee basin, Oregon Coast Range, showing stratigraphic relationships of exploration wells to surface measured sections**, by I.-C. Ryu, A.R. Niem, and W.A. Niem, has been published as Oil and Gas Investigation 18. The black-and-white fence diagram is printed on a 36 by 60 in. sheet and is accompanied by a 48-page geologic interpretation. Price is S9.

As part of the final phase of a five-year program to assess the oil, gas, and coal potential of the southern Tyee basin, the fence diagram was constructed from 24 composite measured geologic sections and the stratigraphy of 11 oil and gas exploration wells.

The southern Tyee basin includes and area of approximately 4,800 $mi^2$ located mainly in Coos, northern Curry, and western Douglas Counties, west of a line marked by Interstate Highway 5 between Cottage Grove and Grants Pass. The southern part of the basin appears to have the greatest oil and gas potential. The mapping work and the resulting fence diagram have produced significant modifications of the stratigraphic nomenclature of the southern Coast Range.

With the exception of Open-File Report O–93–10, the new reports are now available for purchase over the counter, by mail, FAX, or phone from the Nature of Oregon Information Center, Suite 177, State Office Building, 800 NE Oregon Street #5, Portland, Oregon 97232–2109, phone (503) 731–4444, FAX (503) 731–4066; and the DOGAMI field offices: 1831 First Street, Baker City, OR 97814, phone (503) 523–3133, FAX (503) 523–9088; and 5375 Monument Drive, Grants Pass, OR 97526, phone (503) 476–2496, FAX (503) 474–3158. Orders may be charged to Visa or Mastercard. Orders under $50 require prepayment except for credit-card orders. □

## In memoriam: Norman S. Wagner

"Wag," as he was known to his friends, was born on May 24, 1909, in Wilkes Barre, Pennsylvania. He died October 20, 1993, in St. Elizabeth Hospital in Baker City, Oregon. He will be buried next to his wife Estelle in Oak Hill Memorial Park in San Jose, California.

Wag received bachelor's and master's degrees in geology from Cornell University. In 1936, he was chief assayer for the Idaho Maryland Gold Mine near Donner Pass in California.

In 1942 he started working for the Oregon Department of Geology and Mineral Industries as a resident geologist in charge of the Baker office, one of the department's two field offices. He served in this position until his retirement at the end of 1973. Wag published extensively in his field and received numerous recognitions. He was responsible for extensive pioneer rock location throughout eastern Oregon. He was also interested in the reclamation of dredge tailings in eastern Oregon.

Wag belonged to many professional organizations, including the Society for Mining, Metallurgy, and Exploration, Inc., the American Institute of Mining Engineers, the Northwest Mining Association, and the Idaho Association of Professional Geologists, and he was a charter member of the American Institute of Professional Geologists. Wag was named by the Governor to the Oregon Geographic Names Board.

Wag will be deeply missed by his family and the many friends whose lives were touched and enriched by this truly charming and unique man. □

## Russians to play major role at NWMA meeting

For decades, world leaders and people in the mining industry have speculated about the purported endless supply of minerals which lay hidden in the secretive former Soviet Union.

Some of the mystery surrounding Russian mineral resources will be lifted this December in Spokane, Washington, at the 99th annual meeting of the Northwest Mining Association (NWMA).

A half-dozen experts from throughout Russia will share their knowledge of Russian geology and related mineral sciences at the NWMA short course "Global Business Opportunities: Examining the Differences" on November 28–30, 1993, and the NWMA convention "International Mining: Pros and Cons" on November 30 to December 3, 1993.

The Russian experts include Dr. Anatoly A. Siderov and Dr. Leonid M. Parfenov, Russian Academy of Sciences, who will discuss opportunities and problems for joint mining ventures in the Russian Northeast and Northern Siberia at a three-day short course in the Sheraton-Spokane Hotel. The course will also cover business opportunities in Latin America and the Pacific Rim/Asia.

Parfenov, who is chief for the Laboratory on Regional Geology and Tectonics at Yakutsk in Northern Siberia, will also open the NWMA convention as the welcoming luncheon speaker on December 1. This address will be "The Life of a Russian Geologist in Siberia." Before his appointment in Siberia about 10 years ago, he was chief of a similar laboratory at the Institute of Tectonics and Geophysics at Khabarovsk in the central Russia Far East.

Other Russian scientists and scholars will discuss geology and minerals of their country on December 2 and 3.

The convention, one of Spokane's largest, typically draws more than 3,000 attendees from across the globe. Technical sessions are held in the Spokane Convention Center and the Opera House as well as in the Sheraton-Spokane Hotel. A three-day trade show with more than 300 exhibitors is held at the Ag Trade Center Dec. 1–3.

A second short course, Applied Biogeochemical Prospecting in Forested Terrain, will be held Nov. 29–30 at the Sheraton-Spokane. Course instructors are specialists in geology, geochemistry, chemistry, botany, and forestry.

The NWMA membership is made up of individuals and companies of all sizes, representing the small prospector as well as the large corporation.

For information or registration forms for the NWMA annual meeting, call 509/624–1158 or write NWMA, 10 N. Post, Suite 414, Spokane, WA 99201–0772. *—NWMA news release*

## IGA announces Geothermal Congress 1995

The International Geothermal Association (IGA) will hold its 1995 World Geothermal Congress May 18–31, 1995, in Florence, Italy. The theme is "Worldwide Utilization of Geothermal Energy." The congress is convened by IGA, co-convened by the Geothermal Resources Council, and sponsored by ENEL, the Italian Electric Power Company.

The Congress will include plenary sessions with invited presentations from various countries that have significant geothermal development, technical sessions, field trips, short courses, exhibits, and a full guest program.

The primary purpose of the 1995 World Geothermal Congress is to provide a forum for international exchange of scientific and technological information on geothermal development during the period 1990–1995. The Congress will generally follow the successful format of the 1975 United Nations International Symposium on Geothermal Energy.

For a circular with further information, interested persons should contact George Fry, Executive Director, International Geothermal Association, LBL 50C, Rms. 106–108, One Cyclotron Road, Berkeley, CA 94720, USA; phone (510) 486-4584, FAX (510) 486-4889. *—IGA news release*

## Did you know—?

Russian geologists have made a unique discovery in the northernmost reaches of the Ural Mountains: Searching for mineral resources, they happened upon a cave in which the walls were covered with gigantic crystals of smoky quartz. The biggest specimen had a diameter of 2.2 m (more than 7 ft) and weighs about 1,700 kg (3,750 lb). The crystals are estimated to be 220–260 million years old.

The uniqueness of the find lies in the smoky-transparent color of the megacrystals. Quartz crystals of similar size have been discovered before, in Arkansas, Brazil, or Norway, for instance. But all of these were milky. Quartz crystals form by crystallization of silicon-saturated solutions, under high pressure and at temperatures up to 250°C (approx. 500°F). Clear crystals form when the temperature remains consistently high for a long time; if it fluctuates, microscopic droplets are included, and these disperse light and make the crystal milky. The smoky-brown coloration is the result of inclusion of other elements in the crystal matrix of silica ($SiO_2$) and is intensified by natural irradiation. A large portion of the smoky quartz that is offered for sale is really artificially irradiated clear quartz.

The newly found megacrystals will most likely end up in museums and private collections. Before they can be sold, however, considerable difficulties in mining them will have to be overcome. The necessary heavy equipment must be flown in and can be used only when temperatures are down to -50°C (-58°F). Only at these temperatures will the deep snow cover on the ground near the cave be frozen hard enough to carry the load of the machines.

*—From a note by Arlette Kouwenhoven in* Die Zeit, *overseas edition, no. 42 (October 22, 1993), p. 18*

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*Numbers refer to volume and beginning page of entry. Most subject entries include cross-references to author entries (in parentheses).*

# AVAILABLE PUBLICATIONS
# OREGON DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES

## GEOLOGICAL MAP SERIES

| | Price | ✔ |
|---|---|---|
| **GMS-5** Powers 15′ quadrangle, Coos and Curry Counties. 1971 | 4.00 | |
| **GMS-6** Part of Snake River canyon. 1974 | 8.00 | |
| **GMS-8** Complete Bouguer gravity anomaly map, central Cascades. 1978 | 4.00 | |
| **GMS-9** Total-field aeromagnetic anomaly map, central Cascades. 1978 | 4.00 | |
| **GMS-10** Low- to intermediate-temperature thermal springs and wells. 1978 | 4.00 | |
| **GMS-12** Oregon part, Mineral 15′ quadrangle, Baker County. 1978 | 4.00 | |
| **GMS-13** Huntington/Olds Ferry 15′ quads., Baker/Malheur Counties. 1979 | 4.00 | |
| **GMS-14** Index to published geologic mapping in Oregon, 1898-1979. 1981 | 8.00 | |
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