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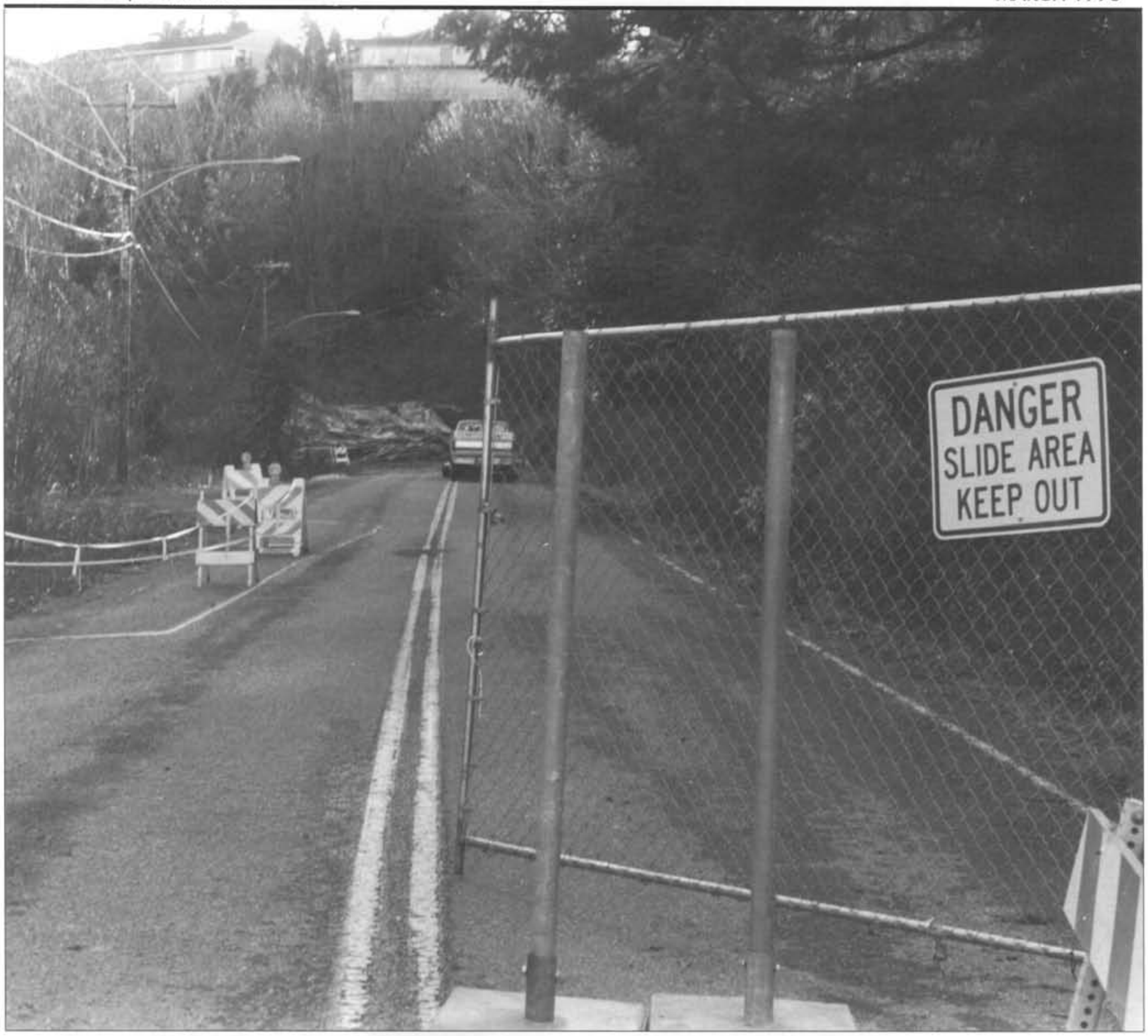

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Oregon Geology is designed to reach a wide spectrum of readers interested in the geology and mineral industry of Oregon. Manuscript contributions are invited on both technical and general-interest subjects relating to Oregon geology. Two copies of the manuscript should be submitted. If manuscript was prepared on common word-processing equipment, a file copy on diskette should be submitted in place of one paper copy (from Macintosh systems, high-density diskette only). Graphics should be camera ready; photographs should be black-and-white glossies. All figures should be clearly marked; figure captions should be together at the end of the text.

Style is generally that of U.S. Geological Survey publications. (See USGS *Suggestions to Authors*, 7th ed., 1991, or recent issues of *Oregon Geology*.) Bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Include names of reviewers in the acknowledgments.

Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, letters, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office (address above).

Cover photo

"Theme scene" from Portland's SW Council Crest Drive after the disastrous rains in February 1996: The rains caused not only the rivers to rise but also the hills to fall, leaving many Oregonians squeezed somewhere between them. Pages 42–43 of this issue show a preliminary look at some slides that occurred in Portland. Photo Scott F. Burns.

Governor proclaims April 1996 Earthquake and Tsunami Preparedness Month

Office of the Governor, State of Oregon
Proclamation

Whereas: Oregon has recently suffered considerable damage from two small earthquakes; and

Whereas: Scientific evidence indicates that Oregon is at risk for much larger earthquakes in the future; and

Whereas: A major earthquake associated with the Cascadia Subduction Zone could, also, generate a destructive tsunami; and

Whereas: The loss of life and property can be greatly reduced if appropriate earthquake preparedness measures are taken BEFORE such an earthquake or tsunami occurs; and

Whereas: Oregon enacted a law in 1995 that requires schools to instruct and drill students on emergency procedures such as those related to earthquakes and tsunamis; and

Whereas: Emergency management agencies, the Department of Geology and Mineral Industries, and the American Red Cross will highlight these preparedness strategies and provide earthquake safety information to citizens during the month of April,

Now,

Therefore, I, John A. Kitzhaber, Governor of the State of Oregon, hereby proclaim April 1996

EARTHQUAKE AND TSUNAMI PREPAREDNESS MONTH

in Oregon and encourage all citizens to increase their awareness of and preparedness for earthquake and tsunami hazards.

In witness whereof, I hereunto set my hand and cause the Great Seal of Oregon to be affixed. Done at the Capitol in the City of Salem in the State of Oregon, on this day, January 22, 1966.

STATE OF OREGON 1859

John A. Kitzhaber, Governor

Phil Keisling, Secretary of State

Seismically induced water-level oscillations in a fractured-rock aquifer well near Grants Pass, Oregon

by Douglas Woodcock, Oregon Water Resources Department, Salem, Oregon 97310, and Evelyn Roeloffs, U.S. Geological Survey, Vancouver, Washington 98660

INTRODUCTION

Groundwater data have been collected from water wells in the Grants Pass area for the last several years to assess groundwater conditions and aquifer behavior. Thirteen unused water wells have been monitored with analog water-level recorders to observe short- and long-term responses to precipitation, pumpage, barometric effects, and well interference. One of these monitored wells stands apart from the others for its response to the strain produced by Earth tides but also, more interestingly, for its extreme sensitivity to earthquakes that have occurred locally and at great distances from the well. A digital data logger has expanded the data-recording capabilities at the well and has captured detailed seismic wave trains. These "hydroseismograms" provide an interesting look at how a water well developed in a fractured-rock aquifer responds to earthquakes.

There are practical reasons to study the response of water wells to earthquakes. For example, to ensure the safety of underground waste repositories, it is essential to understand how distant earthquakes could affect subsurface stress or fluid pressure. Distant fluid-pressure changes may also explain why large earthquakes, like the 1992 earthquake at Landers, California, sometimes trigger additional earthquakes as far as several hundred kilometers away.

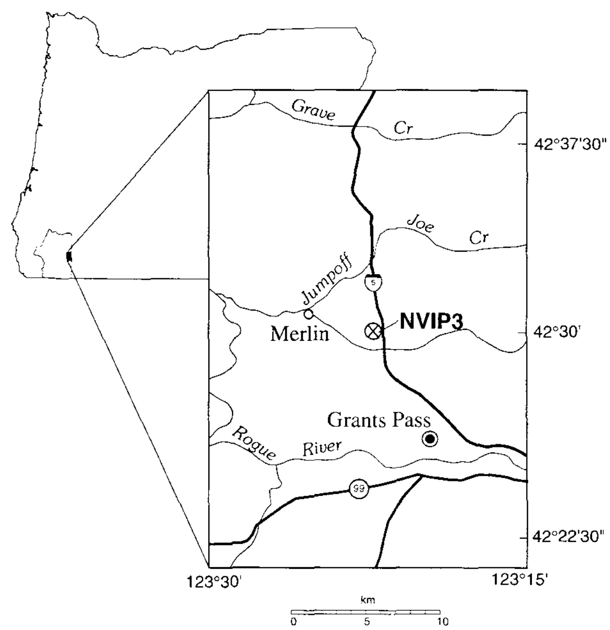

Figure 1. Geographic location of NVIP3 in Josephine County.

THE SETTING

The well of interest is the North Valley Industrial Park #3 well (NVIP3), located about 6 km (3.75 mi) northwest of the city of Grants Pass in Josephine County (Figure 1). It is a 15-cm (6-in.)-diameter well and is 91.4 m (300 ft) deep. The driller's log reports that cement grout was placed to a depth of 36.6 m (120 ft) and casing to 50.9 m (167 ft). The well is open to the formation from 50.9 to 91.4 m (167–300 ft). It was drilled to supply the industrial park with groundwater, but only domestic quantities of water were encountered, so the well has gone unused. The well is developed in fractured granitic rock of the Grants Pass pluton, a 260 km^2 body of granodiorite, quartz diorite, and related intrusives. A down-hole video shows, in the bottom 23 m (75 ft) of the borehole, a fractured, complex intrusive contact between the pluton and a dark metamorphic rock. It is unknown whether the well has fully penetrated the pluton or has only encountered a large block of incorporated country rock.

THE ANALOG DATA YEARS

The Josephine County Water Resources Department recognized the value of using NVIP3 as a long-term observation well and, shortly after completion of the well in 1984, installed a continuous analog water-level recorder. This type of recorder consists of a recording drum attached to a float and counterweight mechanism. As the water level rises and falls in the well, the change in water level is traced on the recording drum. This recorder was maintained until the end of 1993, when it was replaced with a digital unit.

Comparison of the water-level record at NVIP3 to those records collected from shallower wells in the Grants Pass pluton suggests that the deeper, fractured aquifer is confined. That is, the water at depth cannot flow freely to the water table, because the water-bearing zones are bounded by rock of lower permeability. Thus, the aquifer at depth is under a pressure greater than atmospheric pressure and is sensitive to forces that produce small volumetric changes in the rock body.

Figure 2 is an analog chart from NVIP3 showing the diurnal and semi-diurnal water-level response to the strain induced by Earth tides. As with coastal tides, water-level amplitudes reach their maximum and minimum at two-week intervals—when the gravitational attraction of the moon and sun are in alignment (at full and new moon) and when those forces are perpendicular with respect to the

Earth (called "lunar quadrature"). However, in contrast to coastal tides, the water level in a tide-sensitive well declines when the tide-generating force is overhead. This is because the lithostatic pressure on the aquifer is reduced when the gravitational force pulls on the Earth's crust.

Over the period of record, the analog charts also show 155 rapid water-level fluctuations, which are superimposed on the smooth, relatively slow changes due to Earth tides, barometric pressure changes, and groundwater recharge.

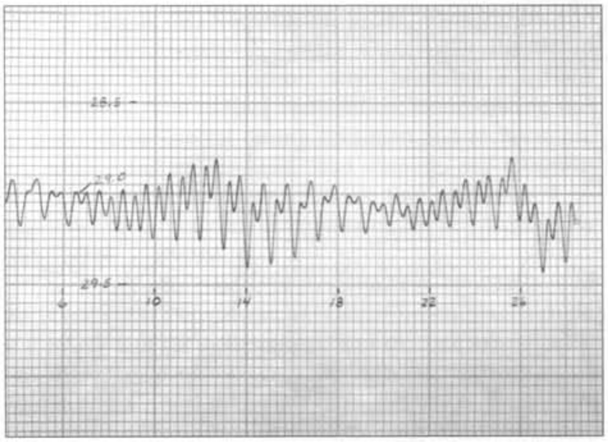

Figure 2. Strong diurnal and semi-diurnal Earth-tide signal dominates the water level in this analog recording for the month of November 1989. The numbers on the left side of the photograph indicate water level in feet below land surface, while the numbers across the bottom indicate days of the month.

Figure 3. Analog recording of the September 19, 1985, earthquake at Michoacan, Mexico (Ms 7.9) and aftershock (Ms 7.5) superimposed on earth tide signal. The numbers on the left side of the photograph indicate water level in feet below land surface, and the numbers across the bottom reflect days of the month. The main shock caused 32 cm (1.05 ft) of peak-to-peak fluctuation, the aftershock 7 cm (0.23 ft).

These rapid fluctuations correlate with earthquakes. For example, well responses to the 1985 Michoacan (Mexico) earthquakes, with surface-wave magnitudes (M_S) of 7.9 and 7.5, are shown in Figure 3. The peak-to-peak response was 32 cm (1.05 ft) from the main shock and 7 cm (0.23 ft) from the aftershock. Both epicenters were approximately 30 arc degrees (~3,330 km) distant from the well.

We correlated rapid water-level oscillations on the analog charts to earthquakes by matching the event time on the recorder chart with large earthquakes, which are logged in the catalog *Preliminary Determination of Epicenters* (PDE) maintained by the U.S. Geological Survey National Earthquake Information Center. The majority of the water-level charts were recorded at a time scale of 8 h / 2.5 mm, yielding a time resolution of about two hours. Thus the earthquake database was searched for any large earthquakes that occurred within ± 2 h of the recorded oscillation. Occasionally, the database lists more than one large earthquake within this time window, which makes correlation difficult. Furthermore, battery and pen failures and freezing clocks caused either gaps in the record or discrepancies in clock time. Still, of the 155 rapid fluctuations in the analog record, 119 occurred within two hours of an earthquake with a magnitude 6.0 or greater somewhere in the world. An additional 13 of the water-level fluctuations correspond to earthquakes in or offshore Oregon or California with magnitudes 4.0 or greater.

CONVERSION TO DIGITAL DATA ACQUISITION

Detailed responses to earthquakes could not be resolved from the analog records because of their compressed time scale. For this reason, a UNIDATA digital shaft encoder, data logger, and barometric transducer were installed in November 1993 (Figure 4). Like an analog recorder, the shaft encoder utilizes a float-and-counterweight mechanism to track water-level change in the well. The difference

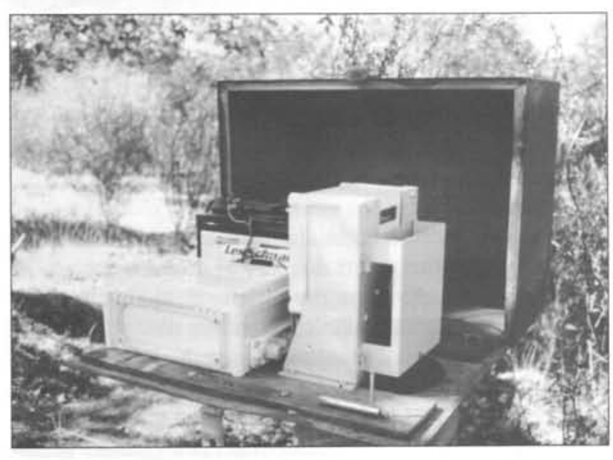

Figure 4. Configuration of UNIDATA instrumentation at NVIP3. Shaft encoder (on right) digitally encodes water-level data for storage in data logger (in weatherproof housing on left).

is that the data are digitally encoded and stored in the data logger for later retrieval. The data logger is configured to record water level and barometric readings every 15 minutes but goes to a high-speed sampling interval—one sample per second—anytime the water-level movement equals or exceeds 0.18 cm (0.006 ft) in a one-second interval. This split sampling scheme provides data for a long-term record and at the same time allows a finer resolution for short-term phenomena.

Since the change to digital instrumentation, 80 additional rapid fluctuations have been recorded. Figure 5 shows the digital record for a portion of January 1994. It includes the response to the Northridge, California, event (M_S 6.8) as well as three other earthquakes. The peak-to-peak response to the Northridge main shock was 22.3 cm (0.73 ft). Figure 6 expands the time scale for this response and compares it to the vertical component of a broadband seismogram recorded at Yreka, California. The comparison shows that the well and recorder are emulating a seismograph, recording the passage of the early arriving *P* and *S* waves and the later arriving surface waves.

Because of the greater detail provided in the record, the digital equipment allows a more accurate determination of the timing of events. Time resolution, now on the order of seconds as opposed to hours, has greatly improved the confidence of correlating earthquakes to fluctuations in the water-level record.

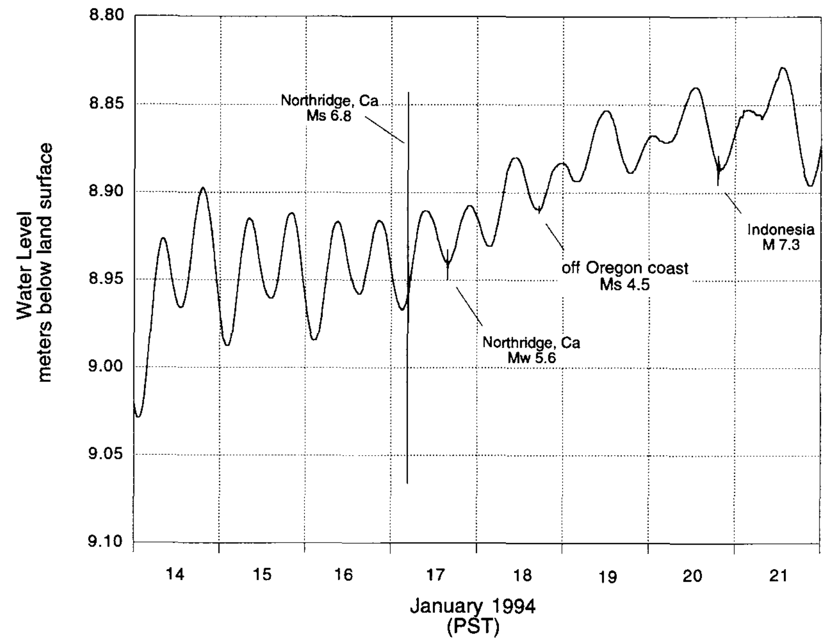

Figure 5. Digital recording of water-level change for 8 days in January, 1994. Local and distant earthquakes are identified in the record.

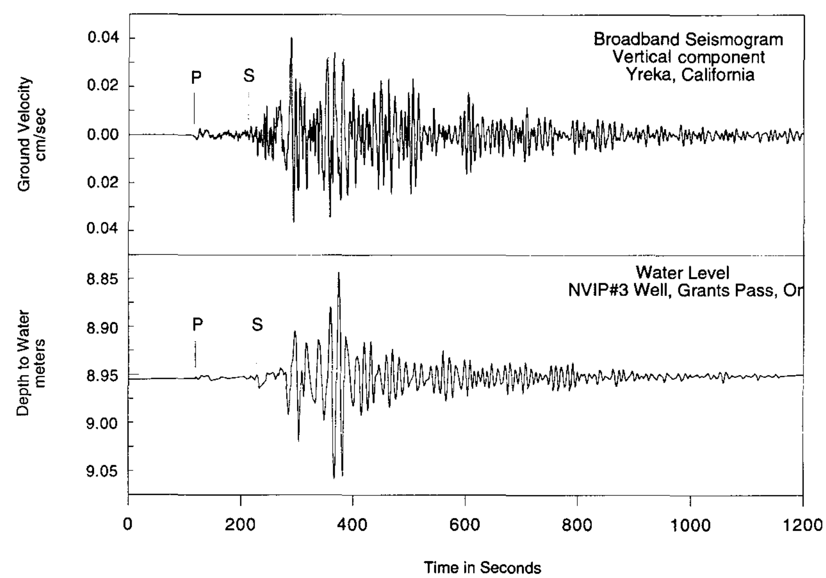

Figure 6. Northridge main shock, January 17, 1994. Comparison of the water-level response observed at NVIP3 and the vertical component broadband seismogram collected at Yreka, California.

OSCILLATORY WELL RESPONSE

As can be seen in the response to the Northridge earthquake, the water level at NVIP3 fluctuates in response to the passage of various seismic waves. This dynamic response is produced by two simultaneous mechanisms: (1) rapid pressure changes in the aquifer as the waves compress and dilate the rock body, and (2) amplification by the momentum of the water column moving in the well.

Early work by Leggette and Taylor (1935) suggested that water wells that employ float recorders, such as NVIP3, are capable of recording only those aquifer pressure changes produced by long-period seismic waves (e.g., Rayleigh waves), because considerable time is necessary for water to flow into and out of the borehole in response to those changes. Eaton and Takasaki (1959) stated that of the different waves produced by an earthquake, it is only waves that produce volume changes in the rock that induce water-level fluctuations in a well. Both *P* waves and the later-arriving Rayleigh waves have this property, but Rayleigh waves would be expected to generate the larger oscillations because of their longer periods. Waves that induce a shearing motion as they propagate through a rock body, such as *S* waves and Love waves, do not dilate the rock as they pass and, theoretically, should not induce oscillations. Rexin and others (1962), however, identified many seismic phases, including Love waves and *S* waves, in expanded time-scale recordings from a well in Milwaukee, Wisconsin.

NVIP3 clearly responds not only to *P* waves and Rayleigh waves but also to the shearing motion of *S* waves. The relative amplitudes of the *S* wave and *P* wave responses cannot be determined at present because the one-second sampling rate is not fast enough to accurately record *P* waves, which have frequencies of several cycles per second. Consequently, the small fluctuations in response to *P* waves are not accurate representations of the pressure changes occurring in the aquifer. That the well responds at all to these higher frequency waves suggests that the hydraulic conductivity in the aquifer surrounding the well must be sufficiently high to allow rapid movement of water in and out of the well in response to the small but rapid pressure changes induced by *P* waves.

The well's response to nondilatational *S* waves is curious. One possible explanation is that hydraulic conductivity within the aquifer is dominated by a single permeable fracture or set of fractures having a preferred orientation. If a fracture is oriented normal to the shearing motion of an *S* wave, then elastic deformation of the fracture aperture—without volumetric change of the rock body—would produce pressure changes in the aquifer, thus inducing water movement in the well-aquifer system.

Cooper and others (1965) derived a mathematical equation for the amplification of water-level oscillations in a well relative to pressure fluctuations in the aquifer caused by seismic waves. The most interesting feature of Cooper's analysis is that, for wells in aquifers with sufficiently high hydraulic conductivity, there is a resonant frequency at which the water-level fluctuation in the well can be amplified orders of magnitude above the pressure fluctuation in the aquifer. The frequency at which resonance occurs is determined by the dimensions of the water column and the aquifer. Hydraulic conductivity is the key parameter governing the amplification. Liu and others (1989) modified Cooper's analysis to improve its agreement with observations for the case of a very thick aquifer. For the well and water column dimensions of NVIP3, Liu's equation suggests that seismic waves with periods of 10–20 s will produce a resonant water-level response. This is supported by the hydroseismograms recorded at NVIP3, which are dominated by oscillations at these periods.

RESPONSES TO LOCAL AND DISTANT EVENTS

The majority of earthquakes inducing a response at NVIP3 occurred along plate margins within the active Pacific rim, but small fluctuations (<1.0 cm) were correlated to large events in China, Sudan, Turkey, and India. Figure 7 shows the worldwide distribution of all earthquakes with magnitudes 6.0 or larger that have occurred since data have been collected at NVIP3. The largest fluctuations recorded at the well have been produced by earthquakes occurring along the western margin of North America, Alaska to Mexico. Local events (earthquakes with epicenters occurring in northern California, southern Oregon, or the near offshore) are responsible for many of these larger oscillations. Table 1 displays the 20 largest responses observed at this well.

Of 27 events in the PDE catalog with surface-wave magnitudes of 7.4 or greater, all but five showed a response in the well, including all such events that have taken place since 1989. All but one earthquake within 20 arc degrees of the well and with a magnitude of M_S 6.0 or greater produced a response. The most distant event to cause a water-level fluctuation (0.91 cm) was a M_S 7.1 event in the Sudan on May 20, 1990. Magnitude and distance being equal, a shallow event is more likely to produce a well response than a deep event. The deepest earthquake to cause a water-level fluctuation (0.18 cm) was a m_b 6.5 event in North Korea on July 21, 1994, at a depth of 471 km. (Here, m_b denotes a magnitude derived from body waves. Earthquakes this deep do not generate strong enough surface waves to calculate a meaningful M_S.) It is unknown whether water-level fluctuations were induced in response to the magnitude 8.2 earthquake 600 km beneath Bolivia on June 8, 1994—the largest earthquake ever documented at that depth—because the water-level recorder was inactive at the time of the event.

An earthquake's surface-wave magnitude and its distance (Δ) in arc degrees from the well can be used to estimate the amplitude (A) of 20-s Rayleigh waves at the well site using the formula

$$\log A = M_S - 1.66 \log (\Delta/20),$$

where Δ is measured in degrees, and A is in millimicrons of ground motion (see, for example, Evernden, 1971). The size of the water-level fluctuation tends to increase with the estimated Rayleigh wave amplitude, as shown in Figure 8. All earthquakes in the PDE catalog that produced Rayleigh waves with estimated peak-to-peak ground motion in excess of 5 mm (0.2 in.) caused water-level fluctuations to occur in the NVIP3 well.

Using long-period seismic waves, Shearer (1994) generated a global image of the Earth's response to seismic energy. Ground motion for a point on the Earth's surface was plotted as a function of time and distance from the earthquake. Among other things, this provides a methodology for identifying wave arrivals many hours after earthquake origin times. This model was used to identify Rayleigh wave arrival times from a great earthquake that occurred off the Kuril Islands, north of Japan. The M_S 8.2 event occurred on October 4, 1994, and produced an 18.9-cm (0.62-ft) response at NVIP3. The well continued to oscillate for over three hours. Early time data show a small but clear *P* wave response and a sharp response to *S* wave arrivals (Figure 9). Subsequent increases in oscillatory amplitude in the well correspond closely to the modeled arrival times of the Rayleigh wave components R1, R2, and R3 for the well

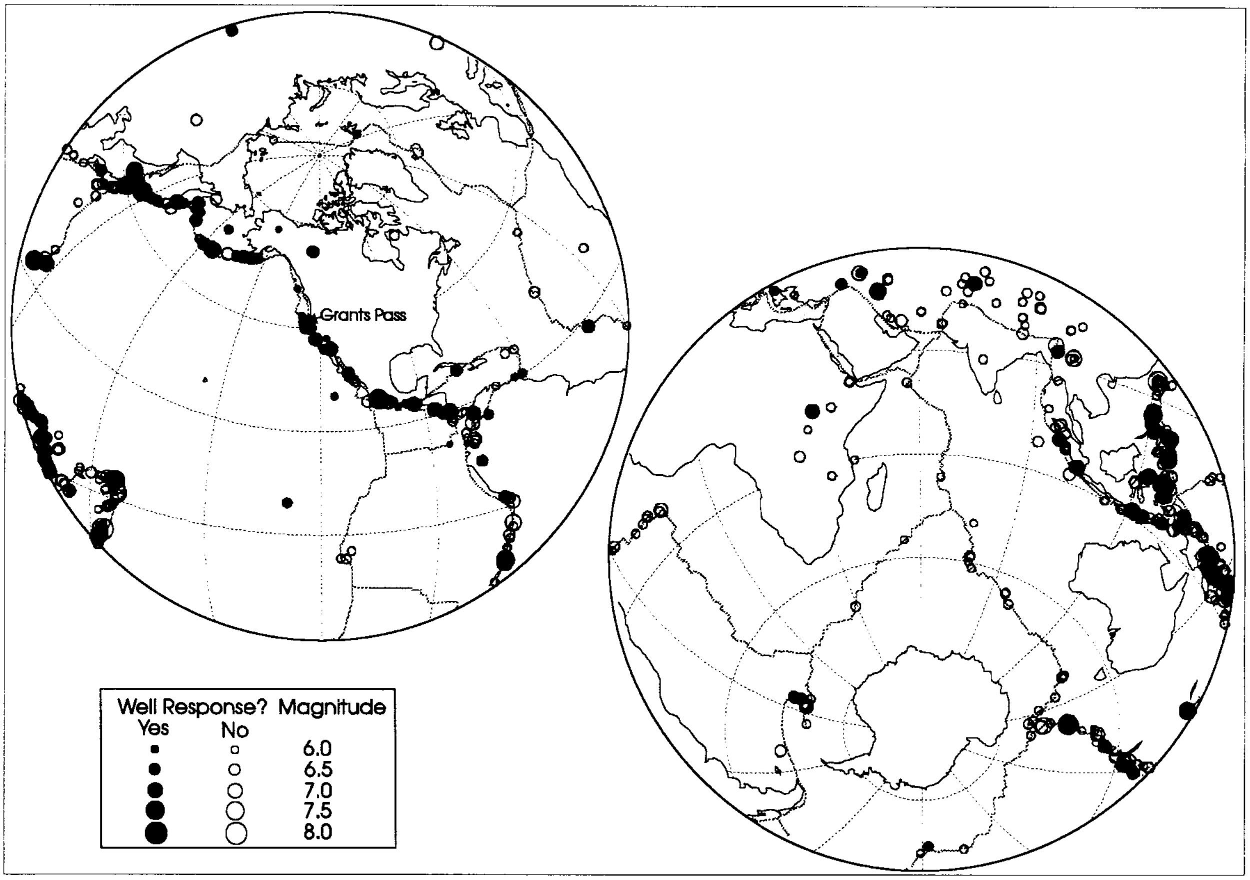

Figure 7. Two views of the Earth displaying earthquakes that occurred over the period of water-level record for NVIP3.

Table 1. Earthquakes generating the 20 largest peak-to-peak responses at NVIP3. Included are any observed coseismic water-level changes.

Location	Event date (GMT)	Magnitude	Depth (km)	Distance (arc degrees)	Well fluctuation (cm)	Well fluctuation (ft)	Coseismic change (cm)	Data format
Cape Mendocino	4/25/92 1806	M_S 7.1	15	2.3	114.3	3.75	21.0 drop	Analog
Landers, CA	6/28/92 1157	M_S 7.6	1	9.9	78.0	2.56	3.1 drop	Analog
Off north CA coast	8/17/91 2217	M_L 6.8	13	1.7	71.6	2.35	15.2 drop	Analog
Offshore Petrolia, CA	9/1/94 1515	M_W 7.2	10	2.7	62.2	2.04	15.2 drop	Digital
Yakutat, AK	11/30/87 1923	M_S 7.7	10	20.2	45.7	1.50	18.3 drop	Analog
Off Oregon coast	7/13/91 0250	M_L 6.7	11	1.7	41.8	1.37	7.0 drop	Analog
Gulf of Alaska	3/6/88 2235	M_S 7.5	10	19.1	36.6	1.20	(Pen skip)	Analog
Loma Prieta	10/18/89 0004	M_L 7.0	18	5.6	36.6	1.20	10.4 drop	Analog
Michoacan	9/19/85 1317	M_S 7.9	27	30.1	32.0	1.05	—	Analog
Klamath Falls	9/21/93 0545	M_D 6.0	12	1.0	29.6	0.97	27.4 drop over 2 shocks	Analog
Cape Mendocino	4/26/92 1118	M_S 6.6	22	2.3	24.4	0.80	—	Analog
Northridge, CA	1/17/94 1230	M_S 6.8	5	9.1	22.3	0.73	—	Digital
Klamath Falls	9/21/93 0329	M_D 5.9	12	1.0	19.8	0.65	27.4 drop over 2 shocks	Analog
Kuril Trench	10/4/94 1322	M_S 8.2	33	61.8	18.9	0.62	—	Digital
Cape Mendocino	4/26/92 0741	M_S 6.6	20	2.3	18.6	0.61	—	Analog
Off north CA coast	2/18/95 0403	M_S 6.6	10	2.6	17.8	0.58	—	Digital
Aleutians	5/7/86 2247	M_S 7.9	33	35.4	15.2	0.50	—	Analog
Off north CA coast	8/17/91 1929	M_L 6.0	12	2.0	15.2	0.50	—	Analog
Guam	8/8/93 0834	M_S 8.2	60	82.6	15.2	0.50	—	Analog
Guatemala	9/10/93 1912	M_S 7.2	34	38.3	15.2	0.50	—	Analog

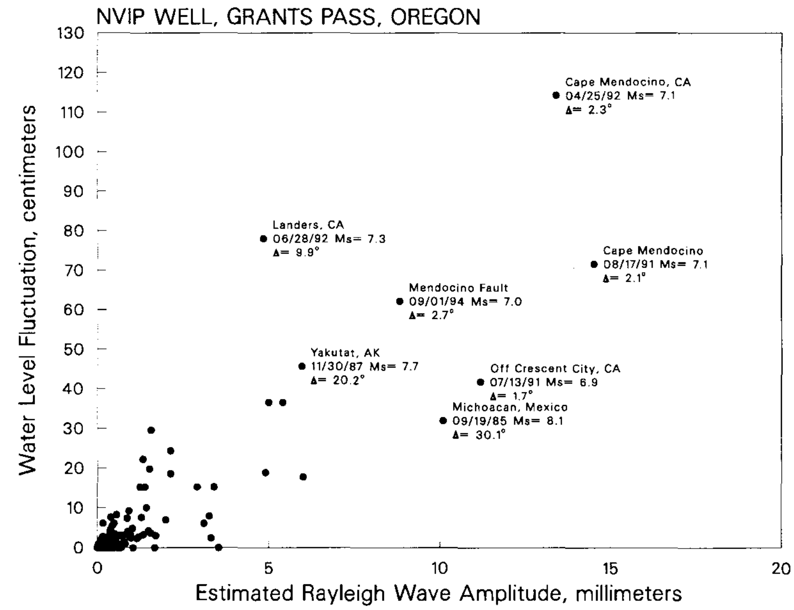

Figure 8. A comparison plot of the observed water-level response recorded at NVIP3 and the calculated Rayleigh wave amplitude at the well site.

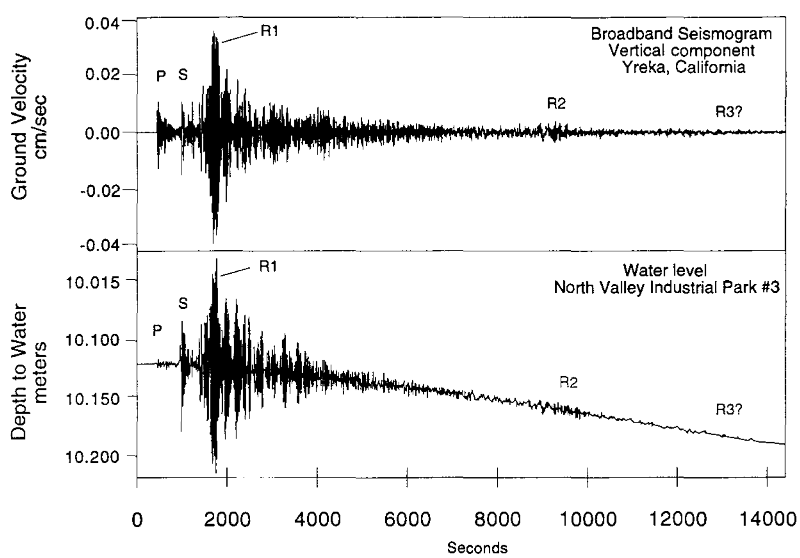

Figure 9. Earthquake east of Kuril Islands on October 4, 1994. Comparison of the water-level response observed at NVIP3 to the vertical-component seismogram collected at Yreka, California. Note strong S *wave response. The water-level data are unfiltered, and the decline is in response to Earth-tide strain.*

location, which is 62 arc degrees from the event origin (P.M. Shearer, personal communication, 1994). The significance of these Rayleigh components is in their travel paths. R1 travels 62 degrees along the shortest great-circle path to the well and should produce the largest water-level oscillations. R2 should produce a smaller set of oscillations—due to the decrease of wave amplitude with distance—as it takes the opposite path along the great circle, traveling a distance of 298 degrees. R3, which represents R1 making its second pass by the well, will have traveled 422 degrees around the Earth. R1 and R2 are clearly evident in the well record and in the seismogram of Figure 9. R3, however, is not as distinct; in the well record, an isolated cluster of low-amplitude (0.18-cm) oscillations occurs at the calculated time and may very well represent the arrival of R3. If R3 was recorded in the vertical seismogram it is not readily apparent.

COSEISMIC WATER-LEVEL CHANGES

An interesting and unexplained phenomenon associated with the larger oscillations in the NVIP3 well is a coseismic drop in water level. The observed water-level declines after large events range from 3.0 to 27.4 cm (0.1–0.9 ft). Figure 10 shows the response to the Mendocino fault earthquake of September 1, 1994, off the coast of northern California and near the town of Petrolia, and the subsequent 15.2-cm (0.5-ft) drop in water level. The degree of water-level decline attributable to the earthquake is evident when water-level oscillations, barometric pressure, and Earth-tide strain are filtered from the record (Figure 11). The coseismic drop begins shortly after the earthquake and continues for approximately 20 hours. It is unknown at this time whether the water-level drop represents permanent or semi-permanent aquifer deformation or some movement or discharge of groundwater from the system or both. Coseismic changes in the NVIP3 well are always water-level drops, decaying over a period of hours. The return to preseismic levels may take weeks. That this phenomenon occurs after very large fluctuations suggests that it is related to the passage of surface waves; however, the water-level losses are not proportional to the amplitude of the oscillation. Also, the large distance to the epicenter for some events (e.g., Yakutat, Alaska, 1987, M_S 7.7) suggests that the mechanism is due to something other than a change in the stress field around the active fault.

Rojstaczer and others (1995) examined reported hydrologic changes in fractured-rock aquifers near the 1989 Loma Prieta, California, earthquake. Increases in stream flow and coseismic drops of water levels in wells were

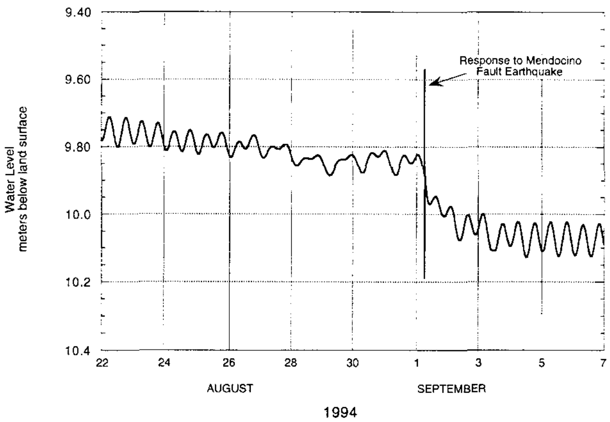

Figure 10. Compressed time-scale recording of the water-level response to the September 1, 1994, Mendocino fault earthquake off the California coast near the town of Petrolia. Note 15.2-cm drop in water level following the event.

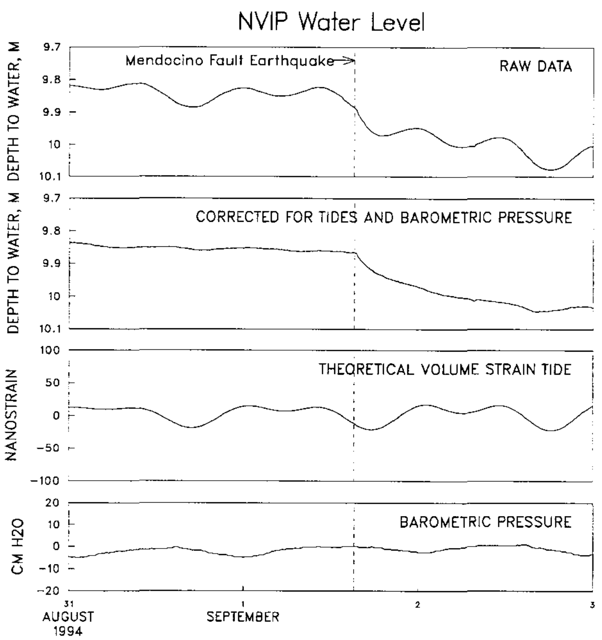

Figure 11. Residual water-level data after removing the oscillatory response, barometric pressure, and Earth tides. Note water-level decline following water-level response to the Mendocino fault earthquake.

found to be consistent with permeability enhancements in the aquifer. The increased permeability allows an increase in groundwater discharge to streams, which can lower the water level in the aquifer, if recharge to the aquifer is not equally enhanced. Surface-water data are not available for the area around the NVIP3 well, so it is unknown whether increases in stream flow accompany the coseismic drops.

SUMMARY

NVIP3 is unusual among wells monitored in the Grants Pass area in that it is highly sensitive to earthquakes generated locally and at great distances from the well. It responds to both dilational and nondilational seismic waves, but the largest amplitude oscillations occur in response to the dilational Rayleigh waves. NVIP3 resonates at wave periods of 10–20 s, producing peak-to-peak water-level fluctuations as large as 114.3 cm (3.75 ft). Over the period of record, all earthquakes that generated more than 5 mm (0.2 in.) of ground motion at the well site produced a well response. In addition to this oscillatory response, persistent water-level drops occur after those earthquakes that induce the larger fluctuations in the well.

The value of NVIP3 and other wells that are developed in strain-sensitive aquifers is their utility for teaching us how earthquakes affect aquifer systems at a distance. It is well documented that water wells respond to the passage of seismic waves, even at teleseismic distances. But there is still much to learn about the movement of groundwater or the aquifer deformation that can result from those waves.

ACKNOWLEDGMENTS

The authors would like to thank Geoff Carrigg of Unidata America for his assistance in configuring the digital recording equipment for high-speed water-level sampling and Norman Daft of the Josephine County Water Resources Department for his diligent collection of data at NVIP3 and other recorder sites in the Grants Pass area. We also thank Jennifer Hughes for her assistance with correlating the earthquake and water-level databases and Andrew Fountain and Karl Wozniak for technical reviews.

REFERENCES CITED

Cooper, H.H., Jr., Bredehoeft, J.D., Papadopulos, I.S., Istavros, S., and Bennett, R.R., 1965, The response of well-aquifer systems to seismic waves: Journal of Geophysical Research, v. 70, no. B16, p. 3915–3926.

Eaton, J.P., and Takasaki, K.J., 1959, Seismological interpretation of earthquake-induced water-level fluctuations in wells: Seismological Society of America Bulletin, v. 49, no. 3, p. 227–245.

Evernden, J.F., 1971, Variation of Rayleigh-wave amplitude with distance: Seismological Society of America Bulletin, v. 61, p. 231–240.

Leggette, R.M., and Taylor, G.H., 1935, Earthquakes instrumentally recorded in artesian wells: Seismological Society of America Bulletin, v. 25, no. 2, p. 169–175.

Liu, L.B., Roeloffs, E.A., and Zheng, X.-Y., 1989, Seismically induced water-level oscillations in the Wali well, Beijing, China: Journal of Geophysical Research, v. 94, no. B7, p. 9453–9462.

Rexin, E.E., Oliver, J., and Prentiss, D., 1962, Seismically induced fluctuations of the water level in the Nunn-Bush well in Milwaukee: Seismological Society of America Bulletin, v. 52, no. 1, p. 17–25.

Rojstaczer, S., Wolf, S., and Michel, R., 1995, Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes: Nature, v. 373, p. 237–239.

Shearer, P.M., 1994, Imaging Earth's seismic response at long periods: EOS, v. 75, no. 39, p. 449–452. ☐

Shaking things up down on the farm

by Bruce Pokarney, Oregon Department of Agriculture, 635 Capitol St. NE, Salem, Oregon 97310, phone 986-4559.

When the big one comes, it won't just be the city folks who will be affected. Their country cousins—including those who represent agriculture in Oregon—will be shaking and rattling, too. Earthquake experts say rural Oregon needs to prepare itself just as much as urban Oregon.

"Earthquakes can occur anytime, anywhere," says Matthew Mabey, an earthquake specialist with the Oregon Department of Geology and Mineral Industries, who himself grew up on a farm. "In fact, the odds are that the epicenter of an earthquake will be in a rural area simply because most of the land mass in Oregon is rural."

It was nearly three years ago that an earthquake measuring 5.6 on the Richter scale shook much of the Willamette Valley. The "Spring Break Quake" was centered in a rural area near Scotts Mills. Extensive damage was reported after a pair of earthquakes in Klamath Falls in 1993. Although a major earthquake measuring perhaps as high as 8.5 is predicted for Oregon some time in the next 200 years, no one can precisely predict where it will be located. Even if it strikes the Portland area, as some expect, its shock waves surely will roll through Oregon farms and ranches.

"Earthquakes, like other natural disasters, could certainly have an impact on our agricultural operations," says Phil Ward, Assistant Director of the Oregon Department of Agriculture.

Everything from production to marketing could be affected, not to mention the daily way of life all residents face, whether they live in the city or the country.

"The collective impact of an earthquake may be less in rural areas where there are fewer people and fewer buildings," says Mabey. "But rural residents still need to think about preparing for an earthquake and its aftermath."

The indirect effects of a major earthquake on agriculture may be greater than those impacts that are felt immediately. The loss of electrical power would cripple many operations. But the loss of the infrastructure could be more damaging.

"Growers need to get the goods to market," says Mabey. "Transportation of those goods could be interrupted. Ports could be affected. The costs of getting the goods to a processor or the end market could be higher."

A look at Kobe, Japan, shows what can happen to commerce. Port facilities were still crippled months after the 1995 earthquake. Agricultural trade suffered, too, of course.

One Oregonian who has thought long and hard about earthquakes and their impact on rural residents is Ralph Richie of Lane County. A transplanted Californian who has experienced a number of big quakes, Richie has written a book entitled *Emergency Procedures for Country Living*, which features an entire section on earthquakes. (The book —nearly 200 pages, $24.95— can be obtained from the author whose address is 90586 Nadeau Road, Mohawk Valley, Springfield, OR 97478, phone 541-741-0794. *—editor*).

His booklet outlines the potential danger spots unique to the farm. It starts out with the rural dwelling itself.

"Wood frame houses move with vibration, so they're more likely to withstand the shock of an earthquake than other structures," says Richie. "Whether a house is tied to a foundation is critical. An outer wall has to move only four inches, and it's off the foundation. Any house off its foundation is headed toward collapse."

Old stone farmhouses are less likely to withstand the shaking. Manufactured homes—common in rural areas—are many times founded on blocks or jacks. Those, too, could be in trouble during a quake and should be secured as well as possible.

Rural homes often rely on propane or butane for heating. The tanks need broad footings to remain standing upright. If they topple, pipes can break, and gas can escape, threatening fire danger. Water pipes can break, and electricity and telephone service can be cut off. Anything on the farm that can be tipped over probably will be.

Then there are those things on a farm or ranch that are not manmade.

"During an earthquake, herd animals will stampede," says Richie. "One of the casualties of earthquakes is fencing. That brings up the point of whether or not all of your animals are identified well enough so they can be brought back home."

Richie advises everyone, city or country, to put together emergency packs that include at least two weeks' worth of water just for human consumption. Farmers with animals will need more. He also urges rural folks to form neighborhood disaster groups, even if homes are separated by miles.

"You can't expect help from city crews," says Richie. "I would expect 911 to be overloaded immediately in the event of a major earthquake. Out here, forget it."

Richie says neighbors can assemble a skills inventory, equipment inventory (especially important is a list of items that don't need electricity), and a feed schedule for each others' animals in case the rightful owners can't make it back to the farm.

Most experts agree that rural folks are generally better suited than their city cousins to handle a major earthquake.

"Living out in the country already is an indication of independence," says Richie. "The rural resident tends to have the ability to face a problem and handle it independently without having to dial 911. I'd rather be out here in the country than in the city where all that help is supposed to be available."

Still, farmers and ranchers in Oregon can't afford to have their heads in the clouds when the ground under their feet starts shaking. Preparing for earthquakes and the damage they can cause is essential when you live in an earthquake zone. □

Earthquake intensity maps for the March 25 1993, Scotts Mills, Oregon, earthquake

by Gerald L. Black, Oregon Department of Geology and Mineral Industries, Portland, Oregon 97232

ABSTRACT

The magnitude 5.6 Scotts Mills, Oregon, earthquake was the largest recorded event in northwest Oregon. Following the earthquake the Oregon Department of Geology and Mineral Industries received nearly 5,000 intensity responses from a variety of sources. The responses were coded according to the Modified Mercalli scale of Wood and Neumann (1931), the data were entered into spreadsheets, and the intensities plotted with MapInfo®, a desktop mapping system. The resulting digital plots were hand-contoured to produce a 1:500,000-scale isointensity map of the felt area and a 1:100,000-scale isointensity map of the Portland-Vancouver (Oregon-Washington) metropolitan area. The felt area map is similar to a previous intensity map by Dewey and others (1994), but it also shows, in several communities, increased shaking that probably resulted from amplification by poorly consolidated sediments. The isointensity map of the metropolitan area shows variations that can be correlated to local geology. Also, where the data density is adequate in the Portland quadrangle, areas of increased shaking correlate fairly well with intensities predicted for bedrock shaking with a peak acceleration of 0.03 *g* (equivalent to a moderate magnitude earthquake at the distance of Scotts Mills).

INTRODUCTION

The Richter magnitude (M_L) 5.7 Scotts Mills earthquake occurred on March 25, 1993, at 5:34 a.m., Pacific Standard Time. It is the largest recorded event in northwest Oregon. The earthquake was felt over an area extending from Roseburg, Oregon, on the south to Seattle, Washington, on the north and from the Oregon coast on the west to Prineville, Oregon, on the east. In the epicentral area, significant damage was done to a large number of unreinforced masonry (URM) buildings. The preliminary damage estimate was $28.4 million (Madin and others, 1993). The final damage figure is certainly higher, though there is no official mechanism for tracking damage.

The epicenter, as located by the Pacific Northwest Seismograph Network (PNSN), was at lat 45.033°N., long 122.586°W. (sec. 19, T. 6 S., R. 2 E.) (Thomas and others, 1996), approximately 3 mi (4.8 km) due east of Scotts Mills, a small community in Marion County near Silverton and Mount Angel (Figure 1). The focal depth was 15.1 km (Thomas and others, 1996).

Initial speculation for the source of the earthquake centered on the Mount Angel fault, a structure first mapped by Hampton (1972) near Mount Angel (Figure 1). Werner and others (1992), working with commercial seismic-reflection data and water well logs, extended the fault to the northwest to Woodburn. They also suggested that the fault might be active, basing this on a series of six small earthquakes that occurred near Woodburn in 1990. Focal mechanisms for these earthquakes indicate that the Mount Angel fault is a right-lateral strike-slip fault with some reverse motion on a steeply north-dipping plane (Werner and others, 1992). The Mount Angel fault is part of the northwest-trending Gales Creek-Mount Angel structural lineament which extends for approximately 150 km across the Willamette Valley (Beeson and others, 1985).

The focal mechanism for the Scotts Mills earthquake was determined by Dewey and others (1994), Nabelek and Xia (1995), and Thomas and others (1996). The preferred fault plane strikes N. 44° W. to N. 56° W. and dips 58° to 63° NE. Movement on this fault plane is approximately equal parts right-lateral and reverse slip, consistent with the findings of Werner and others (1992).

The exact relationship of the main-shock focal mechanism and the Mount Angel fault is uncertain. The strike of the main-shock focal mechanism is identical to the strike of the southern end of the Mount Angel fault. However, a projection of the focal mechanism fault plane intersects the surface southwest of the mapped Mount Angel fault (Dewey and others, 1994; Nabelek and Xia, 1995). One possible explanation is that the dip of the main-shock focal mechanism

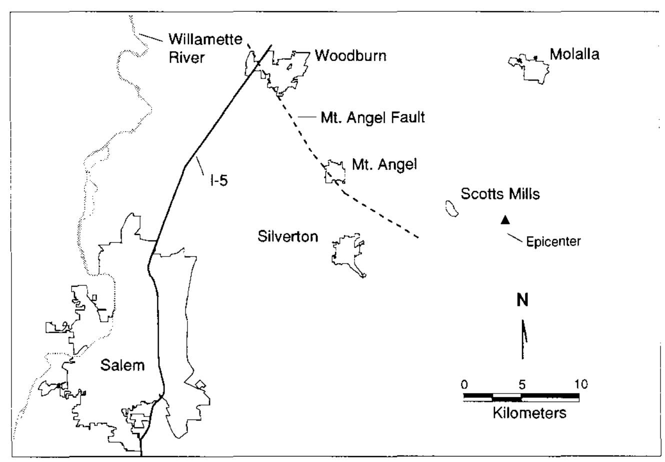

Figure 1. Index map showing the epicentral area of the Scotts Mills earthquake. Large triangle is the epicenter. Dashed line is the trace of the Mount Angel fault (location taken from Werner and others, 1991).

steepens as it nears the surface, so that it intersects the surface at the extended trace of the Mount Angel fault (Nabelek and Xia, 1995). A second possibility is that the Scotts Mills earthquake occurred on one of several parallel en echelon faults (Dewey and others, 1994; Nabelek and Xia, 1995).

PURPOSE OF THIS REPORT

Ideally an earthquake's magnitude is a number that represents the total energy released by that earthquake. Therefore, in theory, an earthquake should have only a single magnitude. In fact, however, several different magnitude scales exist, estimating the released energy on the basis of different parts of the seismic wave spectrum. These different scales give slightly different magnitudes for any given earthquake. For information on various magnitude scales, see Allen (1993) or Bolt (1993).

The intensity is a number that describes the effects of an earthquake on people, manmade structures, and the Earth's surface. The intensity scale most commonly used in the United States is the Modified Mercalli scale of 1931 (Wood and Neumann, 1931). An abridged form of this scale is reproduced in Table 1. The contours on an isoseismal map separate areas of equal seismic intensity.

In 1994, the Oregon Department of Geology and Mineral Industries (DOGAMI) received a grant from the U.S. Geological Survey (USGS) to produce two isoseismal maps for the Scotts Mills earthquake: a 1:500,000 map of the felt area, and a 1:100,000 map of the Portland metropolitan area. The results of that study are described in this paper.

Several previous studies have examined the effects of the Scotts Mills earthquake. Both Madin and others (1993) and Wong and others (1993) described some of the damage associated with the earthquake. Dewey and others (1994) produced small-scale isoseismal maps for the earthquake and described the damage in communities near the epicenter.

The additional isoseismal maps were produced for two reasons: First, the work by Dewey and others (1994) was based on 460 mail questionnaires sent to post offices, police stations, and fire stations in the vicinity of the epicenter. DOGAMI obtained approximately 5,000 additional data points. This greater data density enabled us to correlate areas showing greater than expected shaking with geologic conditions. Second, in 1993 DOGAMI published a set of earthquake hazard maps for the Portland quadrangle (Mabey and others, 1993). Included in this study was a relative ground motion amplification map of the Portland quadrangle (Mabey and Madin, 1993). This map shows areas in the Portland quadrangle where shaking might be worse than expected due to local geologic conditions. The Scotts Mills earthquake gives us an opportunity to see if there is any correlation between predicted amplification and reported intensity resulting from a real earthquake.

METHODS

Immediately after the earthquake, DOGAMI placed a questionnaire in newspapers in the felt area (and in *Oregon Geology*) that asked responders to describe their location during the earthquake, what they felt, and what effects to surrounding objects they observed. DOGAMI received more than 3,500 responses to the questionnaire. An additional 510 responses were collected by Anthony Qamar of the University of Washington, and 700 damage reports were collected by the Oregon Emergency Management Division. Of the nearly 5,000 reports available, 4,774 contained usable information and were entered into Microsoft Excel® spreadsheets. The most common reasons for data to be unusable were a lack of adequate location information—and sound sleepers (i.e., the responder slept through the earthquake). Geology students of Michael Cummings of Portland State University sorted the responses by zip code and assigned preliminary intensities.

Each of the responses was assigned an intensity according to the Modified Mercalli scale of 1931 (Table 1). The assignment of intensities of IV and above was modified by practices described in Stover and Coffman (1993). These

Table 1. *Modified Mercalli intensity scale of 1931 (abridged)*

I	Not felt except by a very few under especially favorable circumstances.
II	Felt by only a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many are frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage **negligible** in buildings of good design and construction; **slight** to moderate in well-built ordinary structures; **considerable** in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	Damage **slight** in specially designed structures; **considerable** in ordinary substantial buildings, with partial collapse; **great** in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	Damage **considerable** in specially designed structures; well-designed frame structures thrown out of plumb; **great** in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

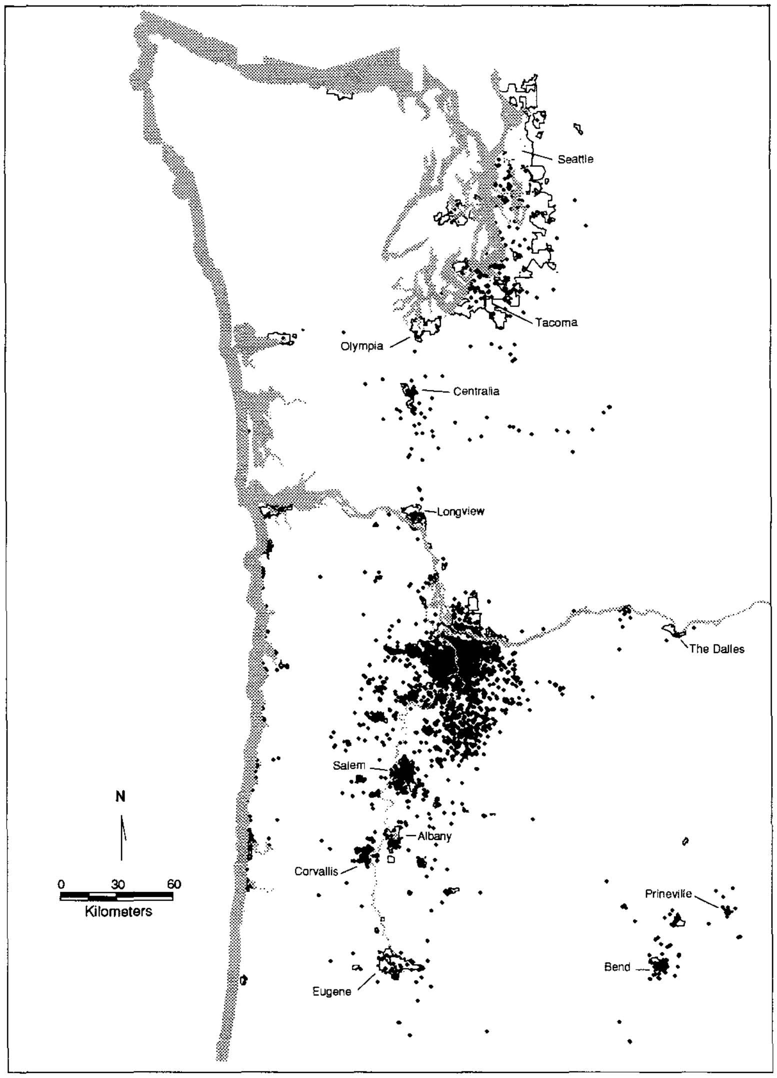

Figure 2. Map of the felt area for the Scotts Mills earthquake showing the distribution of data points used in producing the isoseismal map of Figure 3.

modifications are made because "subjective effects on people described in the MM intensity scale are not reliable considerations for assigning values above the intensity IV level" (Stover and Coffman, 1993). The modifications described below are taken directly from these authors:

IV–Felt by many to all. Trees and bushes were shaken slightly. Buildings shook moderately to strongly. Walls creaked loudly. Observer described the shaking as "strong."

V–'Felt,' 'frightened,' and 'awakened' effects are not used at this or higher intensity levels. Hanging pictures fell. Spilled liquid effects were not used to assign any intensity. Trees and bushes were shaken moderately to strongly. People had difficulty standing or walking. Felt moderately by people in moving vehicles.

VI–At this level, there must be reports of physical damage to manmade structures as described in the MM intensity scale. The only exception is that intensity VI is still assigned if many small objects fell from shelves and (or) many glassware items or dishes were broken.

VII–Only damage to buildings or other manmade structures (as described in the MM intensity scale) is considered.

After intensities were assigned and the data were entered into spreadsheets, MapInfo®, a desktop mapping system designed for personal computers, was used to create plots of the distribution of intensities. Of the 4,774 data points contained in the spreadsheets, all but 205 were successfully located by MapInfo®. More than half of the unlocatable points were in the Portland metropolitan area, where data are abundant The plots were hand-contoured to produce the isoseismal maps discussed below.

RESULTS

Figure 2 shows the distribution of the nearly 4,800 data points used to produce the isoseismal map of Figure 3. Immediately obvious is that most responses were from the Portland metropolitan area, with additional clusters of responses from urban areas, both large and small, in the northern Willamette Valley. What is significant is the lack of data in the Coast Range between the Willamette Valley and the coast.

When an earthquake occurs, the nature of the shaking at any point within the felt area is dependent on several factors, including the size of the earthquake, the distance to the epicenter, the nature of the earthquake source, and variations in local geologic conditions. It is this last factor that can be examined (in a subjective way) with intensity maps. In general, ground shaking is amplified by loose (unconsolidated) sedimentary deposits. Therefore, damage tends to be greater at sites underlain by this type of material than at adjacent sites underlain by bedrock.

Felt area isoseismal map

The isoseismal map of Figure 3 is similar to the map of Dewey and others (1994) with one major exception. Dewey and others (1994) extended the intensity V isoseismal line to the coast, enclosing an area from just south of Tillamook on the north to Newport on the south. In Figure 3, the intensity V isoseismal is closed east of the Coast Range because (1) the small number of data points in the Coast Range are all intensity III, and (2) so are most of the data points along the coast between Newport and Tillamook. Remaining higher intensities (mostly IV and a few V) are associated with the major bays and estuaries. These are interpreted as resulting from amplification in young, unconsolidated estuarine sediments and/or Pleistocene terrace deposits.

Both the intensity IV and V isoseismals of Figure 3 have

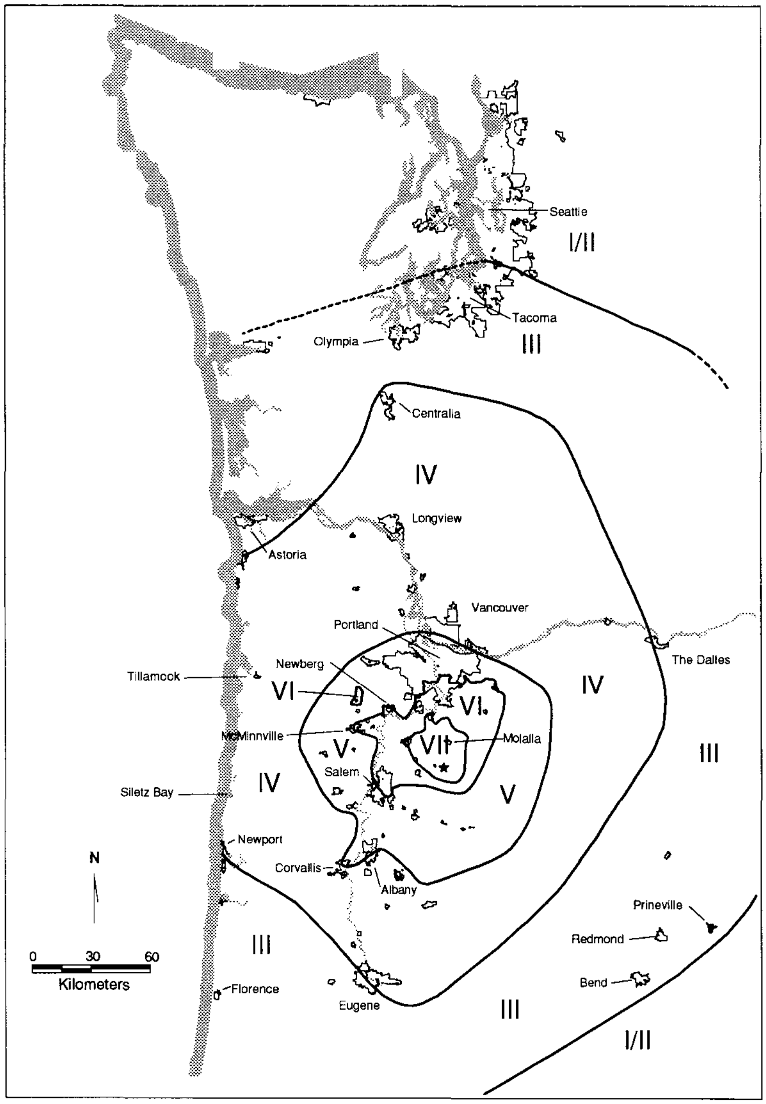

Figure 3. Isoseismal map of the felt area for the Scotts Mills earthquake. Star marks location of epicenter. Contours are isoseismal lines separating areas of equal seismic intensity (dashed where poorly constrained by data). Roman numerals are intensities.

are localized along young, unconsolidated alluvium deposited by these streams (as mapped by Schlicker and Deacon, 1967).

In Eugene, at the southern end of the Willamette Valley, most of the responses were intensity III and IV. There was, however, a block of I and II responses from the south end of town, probably reflecting location on a bedrock high.

Farther east, the community of Prineville lies within the intensity III zone, but there were two IV and one V response from the core downtown area. The remainder of the responses were intensity III. Prineville sits at the junction of the Crooked River and Ochoco Creek, and unconsolidated sediments probably caused some ground amplification there. The Bend-Redmond area also lies within the intensity III zone, but more than 70 percent of the responses were I and II. This lower level of shaking, even though slightly closer to the epicenter, reflects the area's location on bedrock basalt flows of the High Lava Plains.

Portland metropolitan area

Figure 4 shows the distribution of data points used to produce the isoseismal map of Figure 5. Notable data gaps are in the Forest Park and industrial areas of northwest Portland, along the east bank of the Willamette River north of the downtown core area, and in north Portland adjacent to the Columbia River. These areas are either unoccupied (Delta Park and the Port of Portland) or zoned for industrial use (i.e., largely unoccupied at 5:34 a.m.).

On Figure 5 are shown seismic intensity zones IV, IV/V, V, and VI. The IV/V zone contains mostly IV responses with about 18 percent III and 10 percent V responses. The adjacent intensity V zone contains only a few III responses and at least 30 percent intensity V responses.

southwest-trending "tails" that follow the course of the Willamette River. These "tails" probably result from increased shaking on poorly consolidated flood plain sediments of the Willamette River.

Newberg and McMinnville suffered damage during the earthquake (intensity VI) that probably resulted from local amplification by unconsolidated flood-plain sediments. Newberg is adjacent to the Willamette River and McMinnville adjacent to the Yamhill River. The small community of Yamhill, due north of McMinnville (see Figure 3), had many intensity VI responses (15 of intensity VI and one VII). Yamhill is located at the junction of Yamhill Creek and the North Yamhill River, and the high-intensity responses

The shape of the intensity VI isoseismal can be explained partially by the fact that the area is closest to the epicenter. It extends slightly farther northward than might be expected, and this probably results from increased shaking on poorly consolidated outburst-flood deposits that underlie much of east Portland and the area around Lake Oswego (Madin, 1990). The shape of the intensity V isoseismal is largely controlled by geology. Increased shaking is evident in the Tualatin Valley, downtown Portland, and northeast Portland, all areas underlain by poorly consolidated outburst-flood deposits, and lesser shaking (intensity IV/V) in the Portland Hills, which are underlain by bedrock basalt. De-

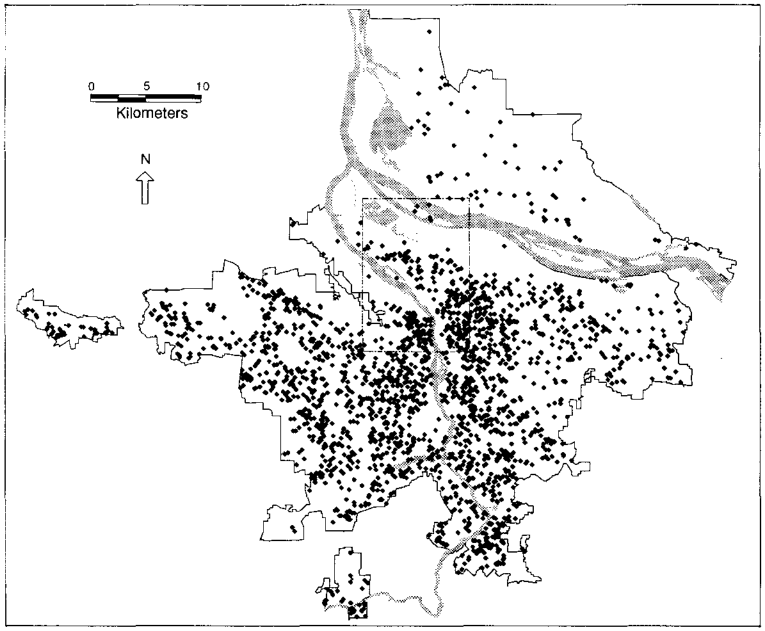

Figure 4. Map of the Portland metropolitan area showing the distribution of data points used in producing the isoseismal map of Figure 5. The boundary shown south of the Columbia River is the urban growth boundary. North of the Columbia River, it outlines the urbanized parts of southern Clark County, Washington. Box outlines the Portland 7½-minute quadrangle.

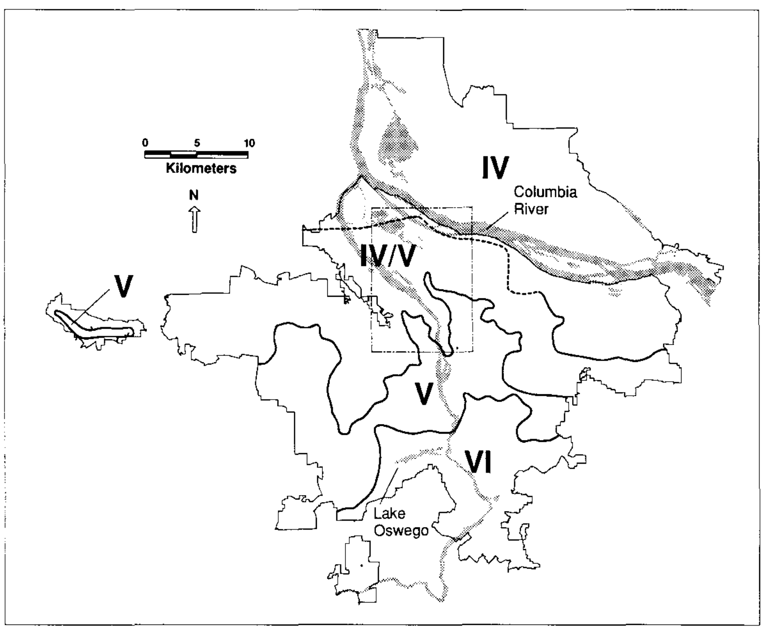

Figure 5. Isoseismal map of the Portland metropolitan area. The boundary shown south of the Columbia River is the urban growth boundary. North of the Columbia River, it outlines the urbanized parts of southern Clark County, Washington. Contours are isoseismal lines (dashed where poorly constrained). Roman numerals are intensities. Box outlines Portland 7½-minute quadrangle.

creased shaking to the north represents increasing distance from the epicenter.

Figure 6 is a map of the Portland 7½-minute quadrangle showing predicted intensities that resulted from bedrock shaking with a peak acceleration of 0.03 *g* (i.e., a moderate magnitude earthquake at the distance of Scotts Mills). The map was prepared by Matthew Mabey of DOGAMI and was constructed in a manner similar to the ground motion amplification map of Mabey and Madin (1993). A three-dimensional model of the geology and its material properties is used with the computer program SHAKE (Schnable and others, 1972). SHAKE performs ground motion analysis, which results in expected average peak accelerations throughout the quadrangle. A detailed description of the above methodology can be found in Mabey and Madin (1993). The average peak accelerations are correlated to intensity on the basis of information from Bolt (1993). The correlation of intensity versus average peak acceleration is reproduced in Table 2. For a variety of reasons, the intensities predicted in Figure 6 are higher than those actually experienced. The correlation between average peak acceleration and intensity (Table 2) is a very crude approximation. Also, the peak acceleration of 0.03 *g* used as the input to SHAKE was a little higher than actual bedrock shaking resulting from the Scotts Mills earthquake (Matthew Mabey, personal communication, 1996). Finally, the assumed bedrock shaking used to create Figure 6 was applied uniformly across the quadrangle. There was no accounting for variations in acceleration due to attenuation at differing distances from the earthquake source, so it is to be expected that the northern portion of the quadrangle would be "overpredicted" by a bit more than the southern portion of the quadrangle. What is most important is not the absolute value of the predicted intensities, but rather the patterns shown in Figure 6.

For a direct comparison of actual intensities with the predicted patterns, the relevant portions of the isoseismal contours of Figure 5 are overlaid on Figure 6. The Roman numerals on Figure 6 represent the intensity zones from Figure 5. Predicted intensities are denoted by the shading pattern. (It should be noted that the predicted intensity map was not examined until the intensities of Figure 5 had been plotted and contoured. No adjustments were made to either map after their initial preparation.)

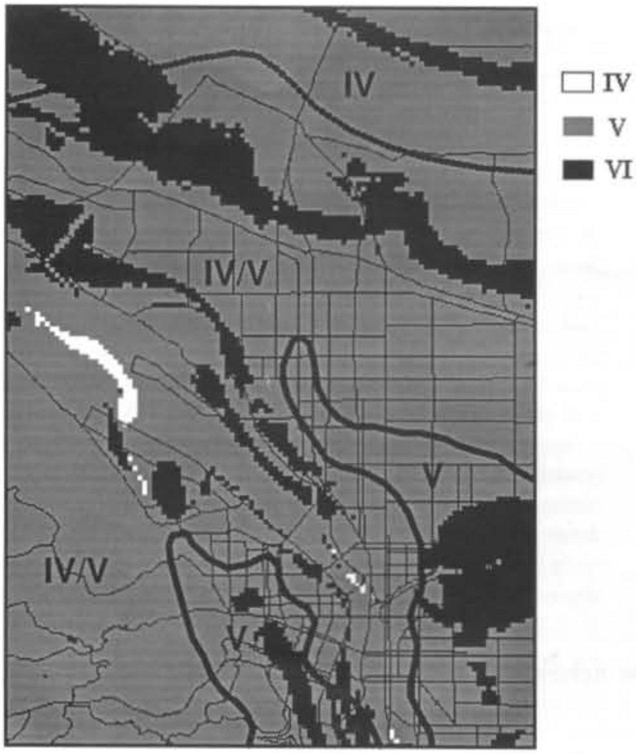

Figure 6. Predicted intensities in the Portland 7½-minute quadrangle as they would result from a magnitude 5.6 earthquake near Scotts Mills, Oregon. Contours are relevant isoseismal lines taken from Figure 5.

There are significant correlations between Figure 5 and Figure 6. West of the Willamette River, Figure 6 predicts increased shaking in the downtown core area, which is underlain by a combination of fill, alluvium, and unconsolidated, fine-grained outburst-flood deposits (Beeson and others, 1991). A north-northwest-trending tongue of intensity V responses confirms increased shaking in this area. Higher intensities are also predicted north of this intensity V tongue (adjacent to the Willamette River and in the northwest Portland industrial area), but they cannot be confirmed because of a lack of data (see Figure 4).

Higher intensities are also predicted to the east of the Willamette River, in areas of northeast Portland underlain by unconsolidated, fine-grained outburst-flood deposits (Beeson and others, 1991). Again, there is a north-northwest-trending tongue of intensity V responses that confirms increased shaking. Higher intensities predicted along the east bank of the Willamette River in fill and alluvium cannot be tested due to lack of data (see Figure 4).

In north Portland and across the Columbia River in Vancouver, Washington, Figure 6 predicts two west-northwest-trending bands of higher intensity. Neither band is evident on the isoseismal map. Data from Washington are sparse and show no obvious trend. This may be due to increased distance to the epicenter. Because the input bedrock acceleration used to create Figure 6 did not take into account

Table 2. Correlation of intensity and average peak acceleration. From Bolt (1993), Appendix D

Intensity value	Average peak acceleration in g (g = gravity = 980 cm/sec^2)
I–III	<0.015
IV	0.015–0.02
V	0.03–0.04
VI	0.06–0.07
VII	0.10–0.15
VIII	0.25–0.30
IX	0.50–0.55
X–XII	>0.60

distance to the epicenter, the northern part of the quadrangle tends to be "overpredicted" relative to the south part. Also, it is to be remembered that the correlation between intensity and average peak acceleration is crude, so that slight variations in acceleration may not show up as intensity variations.

South of the Columbia River, Figure 4 shows a distinct lack of data where higher intensities are predicted. There is, however, a hint that higher intensities may occur there. This area lies within the intensity IV/V zone (Figure 5). Where data for this zone are abundant, they consist of intensities III, IV, and a few V. Along the northern edge of this band of abundant data, however, there are no intensity III reports, only IV and one V. This is not enough to draw separate contours, just a hint that the level of shaking might be higher in the data gap to the north.

CONCLUSIONS

The Scotts Mills earthquake confirms that a significant earthquake hazard exists in western Oregon. It further demonstrates that when an earthquake occurs, one can expect significant damage. The early damage estimates for the Scotts Mills earthquake were $28.4 million (Madin and others, 1993). An earthquake of this size or larger centered under the Portland metropolitan area would do significantly more damage.

Seismic intensity maps, despite their limited precision and resolution, are a useful means of delimiting those areas where greater than expected shaking might occur. An example is the correlation between increased intensity and the presence of underlying alluvium in Figure 4. Intensity maps, however, depend on actual earthquakes.

The degree of correlation between intensities experienced during the Scotts Mills earthquake and intensities predicted by methods utilized in Mabey and Madin (1993) suggest that ground motion amplification maps are a useful means of predicting where excessive shaking will occur. This information can then be utilized to take mitigation steps before the earthquake actually occurs. An even better degree of hazard identification could be achieved with the aggressive placement of strong-motion instruments throughout the Portland metropolitan area, so that, when another earthquake like Scotts Mills occurs, accelerations throughout the city can be directly measured.

Since the Scotts Mills earthquake, DOGAMI has prepared earthquake hazard maps for an additional four quadrangles in the Portland metropolitan area (Mabey and others, 1995a,b,c,d) and for the Oregon coast at Siletz Bay (Wang and Priest, 1995). The Washington Division of Geology and Earth Resources has produced relative earthquake hazard maps for the Vancouver, Washington, urban area (Mabey and others, 1994). DOGAMI has additional studies in progress in Salem, Eugene, and the Portland metropolitan area.

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REFERENCES CITED

Allen, J.E., 1993, When is a Richter not a Richter?: Oregon Geology, v. 55, no. 3, p. 57–58.

Beeson, M.H., Fecht, K.R., Reidel, S.P., and Tolan, T.C., 1985, Regional correlations within the Frenchman Springs Member of the Columbia River Basalt Group: New insights in to the middle Miocene tectonics of northwestern Oregon: Oregon Geology, v. 47, no. 8, p. 87–96.

Beeson, M.H., Tolan, T.L., and Madin, I.P., 1991, Geologic map of the Portland quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–75, 1:24,000.

Bolt, B.A., 1993, Earthquakes: New York, W.H. Freeman and Co., 331 p.

Dewey, J.W., Reagor, B. G., Johnson, D., Choy, G.L., and Baldwin, F., 1994, The Scotts Mills, Oregon, earthquake of March 25, 1993: Intensities, strong-motion data, and teleseismic data: U.S. Geological Survey Open-File Report 94–163, 26 p.

Hampton, E.R., 1972, Geology and ground water of the Molalla-Salem slope area, northern Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 1997, 83 p.

Mabey, M.A., and Madin, I.P., 1993, Relative ground motion amplification map of the Portland quadrangle, Oregon, *in* Mabey, M.A., Madin, I.P., Youd, T.L., and Jones, D.F., 1993, Earthquake hazard maps of the Portland quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–79.

Mabey, M.A., Madin, I.P., and Meier, D.B., 1995a, Relative earthquake hazard map of the Beaverton quadrangle, Washington County, Oregon: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–90.

———1995b, Relative earthquake hazard map of the Gladstone quadrangle, Clackamas and Multnomah Counties, Oregon: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–92.

———1995c, Relative earthquake hazard map of the Lake Oswego quadrangle, Clackamas, Multnomah, and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–91.

Mabey, M.A., Madin, I.P., Meier, D.B., and Palmer, S.P., 1995d, Relative earthquake hazard map of the Mount Tabor quadrangle, Multnomah County, Oregon, and Clark County, Washington: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–89.

Mabey, M.A., Madin, I.P., and Palmer, S.P., 1994, Relative earthquake hazard map for the Vancouver, Washington, urban region: Washingon Division of Geology and Earth Resources Geologic Map GM–42.

Mabey, M.A., Madin, I.P., Youd, T.L., and Jones, D.F., 1993, Earthquake hazard maps of the Portland quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–79.

Madin, I.P., 1990, Earthquake-hazard geology maps of the Portland metropolitan area, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O–90–2, 21 p., 8 maps, 1:24,000.

Madin, I.P., Priest, G.R., Mabey, M.A., Malone, S., Yelin, T.S., and Meier, D., 1993, March 25, 1993, Scotts Mills earthquake—western Oregon's wake-up call: Oregon Geology, v. 55, no. 3, p. 51–57.

Nabelek, J., and Xia, G., 1995, Moment-tensor analysis using regional data: Application to the 25 March, 1993, Scotts Mills, Oregon, earthquake: Geophysical Research Letters, v. 22, no. 1, p. 13–16.

Schlicker, H.G., and Deacon, R.J., 1967, Engineering geology of the Tualatin Valley region, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 60, 103 p.

Schnable, P.B., Lysmer, J., and Seed, H.B., 1972, SHAKE—A computer program for earthquake analysis of horizontally layered sites: Berkeley, Calif., University of California, Earthquake Engineering Research Center Report EERC 72–12, 88 p.

Stover, C.W., and Coffman, J.L., 1993, Seismicity of the United States, 1568–1989 (rev.): U.S. Geological Survey Professional Paper 1527, 418 p.

Thomas, G.C., Crosson, R.S., Carver, D.L., and Yelin, T.S., 1996, The 25 March 1993 Scotts Mills, Oregon, earthquake and aftershock sequence: Spatial distribution, focal mechanisms, and the Mount Angel fault: Seismological Society of America Bulletin, scheduled for publication in August 1996 issue.

Wang, Y., and Priest, G.P., Relative earthquake hazard maps of the Siletz Bay area, coastal Lincoln County, Oregon: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–93, 4 maps.

Werner, K., Nabelek, J., Yeats, R., and Malone, S., 1992, The Mount Angel fault: Implications of seismic-reflection data and the Woodburn, Oregon, earthquake sequence of August 1990: Oregon Geology, v. 54, no. 5, p. 112–118.

Wong, I., Hemphill-Haley, M., and Salah-Mars, S., 1993, The Scotts Mills, Oregon, earthquake on March 25, 1993: Earthquakes and Volcanoes, v. 24, no. 2, p. 86–92.

Wood, H.O., and Neumann, F., 1931, Modified Mercalli intensity scale of 1931: Seismological Society of America Bulletin, v. 21, no. 4, p. 112–117. □

Landslides in the West Hills of Portland: A preliminary look

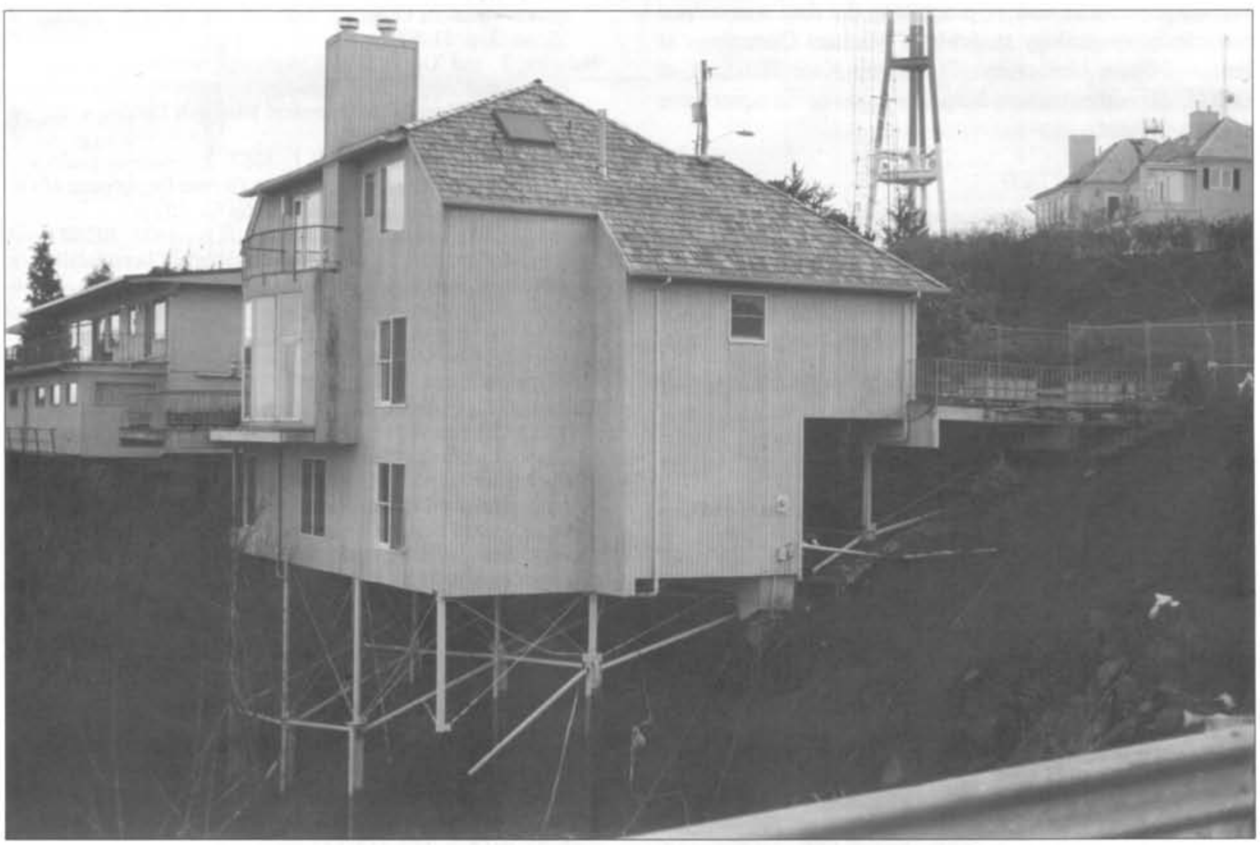
Photographs by Scott F. Burns, Geology Department, Portland State University

The heavy rains during February of 1996 caused not only disastrous flooding but also numerous landslides.

At the time of this writing, the City of Portland estimates 168 slides, of which over 90 percent occurred in the West Hills—and more slides are threatening. As of February 21, the estimate of damage just to public facilities was $32.5 million. By the end of February, 12 slide-affected homes had received red tags, which means that, for safety reasons, they cannot be entered at all. For another 25 homes yellow tags were issued, meaning that they cannot be continuously occupied because of serious problems that must be fixed.

All of the West Hills slides appear to have occurred in the Portland Hills Silt, a loess that mantles the Portland Hills and was deposited there by winds during dry interglacial periods. The Portland Hills Silt is a weak soil when wet. Heavy rainfall of over six inches in three days on soils that were already saturated, the oversteepened slopes of the West Hills, clogged or defective drainage systems, streets without curbs and gutters, and misdirected runoff water led to many of the disastrous slides. □

Asphalt berm placed on edge of SW Council Crest Drive to keep water from running over edge of road and flowing onto landslide below the road.



Slide next to house on 4300 block on SW Council Crest drive.

Slide on 2700 block of SW Fairmont. Plastic covers the slope to keep rainwater away from it.

Slide on 2600 block of SW Fairmont.

ABSTRACTS OF PAPERS

The following abstract is of a paper given at an international conference in May 1995 at the University of Washington. The conference, titled "Tsunami deposits—geologic warnings of future inundation," was sponsored by the Quaternary Research Center, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. Among the 80 registered participants were scientists from Canada, Germany, Japan, Norway, the Philippines, the United Kingdom, and the United States.

Properties and depositional characteristics of tsunamis in south coastal Oregon from a paired coastal-lake and marsh study, by Harvey M. Kelsey, Department of Geology, Humboldt State University, Arcata, California; Alan R. Nelson, U.S. Geological Survey, Denver, Colorado; and Eileen Hemphill-Haley, U.S. Geological Survey at Department of Geological Sciences, University of Oregon, Eugene, Oregon.

Through a paired study of two adjacent sites, we are studying the depositional properties of tsunami deposits of presumably the same age but deposited in two markedly different depositional environments. Both sites are on the south coast of Oregon, separated by 28 km of coastline. One site is Bradley Lake, a freshwater lake 0.5 km inland from the coast at an elevation of 5.5 m. The other site is Sixes River marsh, which borders the estuary of the Sixes River.

These two depositional environments both record the same set of great-earthquake-generated tsunami deposits for a period of time extending from the present back to ca. 5,000 years B.P. Individual tsunami events tentatively can be correlated between the Bradley Lake stratigraphy and the stratigraphy in the Sixes River marsh. The tsunami deposits are layers of sand capped by woody detritus. In the lake, eight to nine sand horizons are interlayered with lake sediments. The sands form continuous layers in the lake. In the oceanward portion of the lake, sand horizons attain thicknesses as great as 70 cm. Sand thicknesses decrease landward. For those sand intervals investigated in detail, the sands are overlain by lake mud that is rich in marine or brackish-water diatoms. Therefore, the sand was transported by a pulse of water that entered the lake from the ocean.

The data from the lake setting and the marsh setting together provide a good synoptic view of a tsunami. In the lake setting, a tsunami leaves widespread and well-preserved deposits that thin in a landward direction. In some cores and for some of the tsunami deposits, the tsunami has eroded the lake sediment substrate, preserving rip-up clasts of the substrate in the tsunami deposit. Because the tsunami deposit itself is not eroded, details of the deposit, such as the number and thickness of individual pulses, are preserved. The elevation and position of the lake provide estimates as to tsunami inundation extent and run-up magnitude, but the lake setting provides no information about land-level changes, as inferred from diatom stratigraphic data. In the marsh, tsunami deposits can also be related to incidences of liquefaction,

In conclusion, neither the lake setting nor the marsh setting in south coastal Oregon provides a complete data set to reconstruct a paleotsunami and any accompanying land-level change. However, the two data sets together can potentially give information on land-level change immediately preceding the tsunami, as well as data on inundation extent and run-up magnitude. □

In memoriam: Wally McClung

Wally McClung, volunteer for DOGAMI at the Nature of the Northwest Information Center, died January 25, 1996. Wally was known to all of us for his kindness, generosity, and knowledge and love of outdoor Oregon. He is survived by his wife Eleanor, two sons, and a daughter.

Wally was a past president of the Geological Society of the Oregon Country and a volunteer guide at the Japanese Gardens. His interest in geology led him to DOGAMI, where he provided his own help as well as that of other volunteers he found for us. He periodically brightened our lives by bringing exquisite flower arrangements, the product of another of his hobbies. One of the greatest joys of his life was fishing, and his knowledge of that and geology made him an invaluable help in the Information Center.

We miss him in many ways—his warm friendly smile, his encouragement, and his love of the out-of-doors. This summer, as people talk of fishing, geology, the Japanese Gardens—the things Wally made so vivid to us all—we will remember him and the way he enriched our lives by sharing his time and talents with us. □

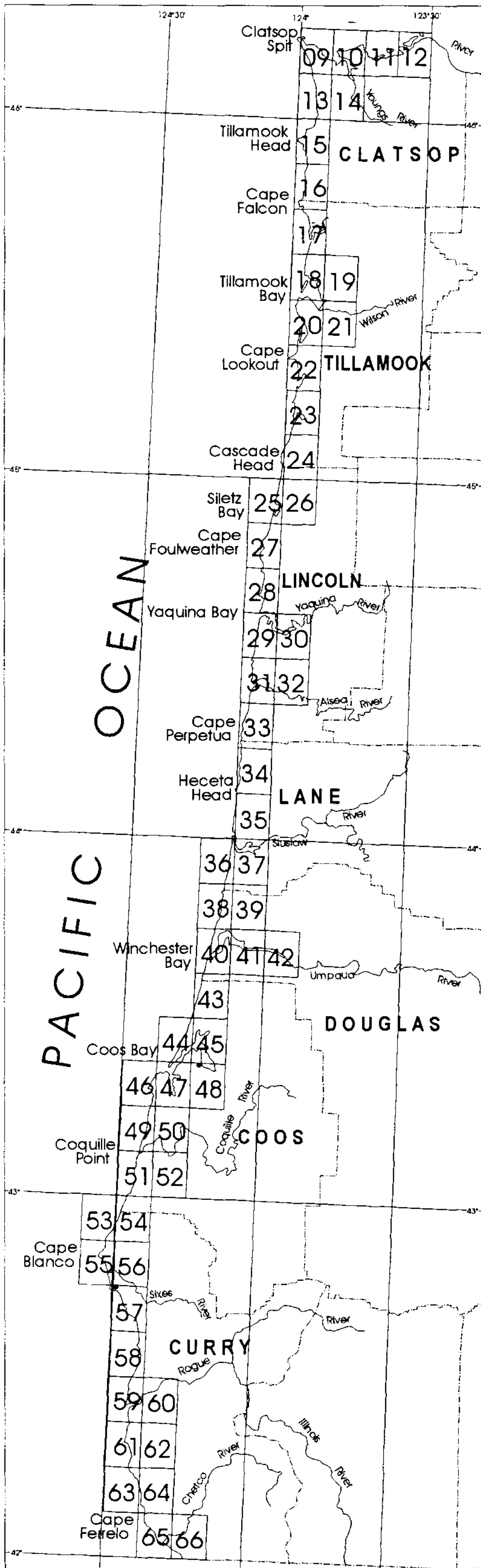
Tsunami hazard maps released

At its January 22, 1996, meeting in Grants Pass, the Governing Board of the Oregon Department of Geology and Mineral Industries (DOGAMI) adopted final rules and maps to implement Senate Bill 379, passed by the 1995 Oregon Legislature, which restricts construction of certain types of essential facilities and special-occupancy structures within the tsunami inundation zone.

The tsunami inundation zone is shown on 58 *Tsunami Hazard Maps*, Open-File Reports O–95–09 through O–95–66. Each map has a line that shows how far inland and uphill a tsunami caused by a magnitude 8.8 undersea earthquake is expected to go. Each of the blueline diazo maps is on a 7½-minute topographic map base, at a scale of 1:24,000. Cost of each map is $3. A complete set of all 58 maps costs $160. See order information on page 48.

An explanatory 100-page text is published separately as Open-File Report O–95–67, and can be purchased for $9.

The index map on the next page correlates the names of the quadrangles with the number of the respective open-file report. Coastal features and county borders on the index map allow for quicker orientation. □



Index map to Senate Bill 379 tsunami inundation zone maps

09 Use the last two digits of Open-File Report number to locate individual tsunami inundation maps

Open-File Report	USGS quadrangle map
O-95-09	Warrenton
O-95-10	Astoria
O-95-11	Cathlamet Bay
O-95-12	Knappa
O-95-13	Gearhart
O-95-14	Olney
O-95-15	Tillamook Head
O-95-16	Arch Cape
O-95-17	Nehalem
O-95-18	Garibaldi
O-95-19	Kilchis River
O-95-20	Netarts
O-95-21	Tillamook
O-95-22	Sand Lake
O-95-23	Nestucca Bay
O-95-24	Neskowin
O-95-25	Lincoln City
O-95-26	Devils Lake
O-95-27	Depoe Bay
O-95-28	Newport North
O-95-29	Newport South
O-95-30	Toledo South
O-95-31	Waldport
O-95-32	Tidewater
O-95-33	Yachats
O-95-34	Heceta Head
O-95-35	Mercer Lake
O-95-36	Goose Pasture
O-95-37	Florence
O-95-38	Tahkenitch Creek
O-95-39	Fivemile Creek
O-95-40	Winchester Bay
O-95-41	Reedsport
O-95-42	Deer Head Point
O-95-43	Lakeside
O-95-44	Empire
O-95-45	North Bend
O-95-46	Cape Arago
O-95-47	Charleston
O-95-48	Coos Bay
O-95-49	Bullards
O-95-50	Riverton
O-95-51	Bandon
O-95-52	Bill Peak
O-95-53	Floras Lake
O-95-54	Langlois
O-95-55	Cape Blanco
O-95-56	Sixes
O-95-57	Port Orford
O-95-58	Ophir
O-95-59	Gold Beach
O-95-60	Signal Buttes
O-95-61	Cape Sebastian
O-95-62	Sundown Mountain
O-95-63	Mack Point
O-95-64	Carpenterville
O-95-65	Brookings
O-95-66	Mount Emily

DOGAMI PUBLICATIONS

Released February 12, 1996:

Best Management Practices for Reclaiming Surface Mines in Washington and Oregon, by David K. Norman, Peter J. Wampler, E. Frank Schnitzer, and Jaretta M. Roloff. DOGAMI Open-File Report O–96–2, var. pag., $8.

This is a manual for landowners, land-use planners, and mine operators that describes reclamation and mining practices for Oregon and Washington.

The approximately 120-page, extensively illustrated manual provides information about planning a surface mine from start-up to final reclamation, incorporating water and erosion control during operation and reclamation, soil salvage and replacement, land shaping, and revegetation. The authors urge miners to use this manual as a resource in developing an environmentally and financially sound mine.

The report was produced cooperatively by members of the Washington Department of Natural Resources, Division of Geology and Earth Resources, and the DOGAMI Mined Land Reclamation Program. It has been released also by the Washington agency as Open-File Report 96–2. The project was supported in part by the U.S. Environmental Protection Agency and conducted under the Tri-State Agreement for Mining between Idaho, Oregon, and Washington.

Coauthor Peter Wampler of the DOGAMI Mined Land Reclamation Program explains that "The term 'best management practices' (BMPs) has generally been used to describe mechanical means of minimizing or eliminating water-quality problems. The BMPs presented here, however, apply as well to reclamation, planning, and specific methodologies to promote an integrated approach to mining." He adds that the manual presents "the most effective and economical reclamation and mining practices known to the issuing Washington and Oregon agencies."

Released March 7, 1996:

Geology and Mineral Resources Map of the Three Creek Butte Quadrangle, Deschutes County, Oregon, by Edward M. Taylor and Mark L. Ferns. Geological Map Series GMS–87, 1 map, 8 p. text, $6.

The Three Creek Butte quadrangle covers part of the eastern margin of the High Cascades geologic province between the cities of Bend and Sisters. The quadrangle map is at a scale of 1:24,000 and is produced in two colors: the brown topographic base is overlain by geologic information in black.

The map identifies rock units, faults, and the outlines of Pleistocene glaciers.The accompanying text describes three stages of geologic history for the quadrangle: Tertiary tectonic and volcanic activity between 7 and 5.5 million years ago, Pliocene-Pleistocene subsidence from about 5.4 million years ago, and Pleistocene volcanism and glaciation beginning about 600,000 years ago.

The text also discusses mineral, geothermal, and groundwater resources and includes geochemical analyses for major and trace elements of 34 samples collected in the quadrangle. Aggregate and building stone are the main mineral resources in the quadrangle. While the geology suggests geothermal energy potential, limited exploration so far has not identified a resource.

The report is one product of a cooperative mapping effort by geologists from Oregon State University, the Oregon Department of Geology and Mineral Industries, and the U.S. Geological Survey. One goal of the project is to provide a detailed geologic framework for Oregon Water Resources Department/U.S. Geological Survey groundwater studies in the Deschutes River basin.

These DOGAMI publications are now available over the counter, by mail, FAX, or phone from the Nature of the Northwest Information Center and the DOGAMI field offices in Baker City and Grants Pass. Addresses are on page 26 of this issue. Orders may be charged to Visa or Mastercard. Orders under $50 require prepayment except for credit-card orders. □

DOGAMI cooperates in earthquake hazard study

Gerald L. Black, geologist with the Oregon Department of Geology and Mineral Industries, was one of the three scientists who jointly studied certain effects of the 1964 earthquake in Alaska. He was joined by Timothy J. Walsh of the Washington Division of Geology and Earth Resources and Rodney A. Combellick of the Alaska Division of Geological and Geophysical Surveys.

The purpose of the study was to examine some of the geologic effects of earthquake-induced liquefaction during the 1964 Alaska earthquake as an analogue for recognizing and interpreting evidence of prehistoric earthquakes in the Pacific Northwest and the Cascadia Subduction Zone.

The 1964 Alaska earthquake—magnitude 9.2, property damage estimated at $311 million—caused much of its damage to railroads and highways by ground failure induced by liquefaction. What the scientists were able to observe in Alaska will help others to recognize such effects in the field and to understand better where to look for them as evidence of prehistoric earthquakes.

The resulting 80-page report has been published by the Washington Division of Geology and Earth Resources as Report of Investigations 32, under the title ***Liquefaction Features from a Subduction Zone Earthquake: Preserved Examples from the 1964 Alaska Earthquake***.

It is available for purchase from the Washington Division of Geology and Earth Resources in Olympia, P.O. Box 47007, Olympia, WA 98504-7007, and also from the Nature of the Northwest Information Center in Portland (see order information on the back page of this issue). The purchase price is $5. □

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