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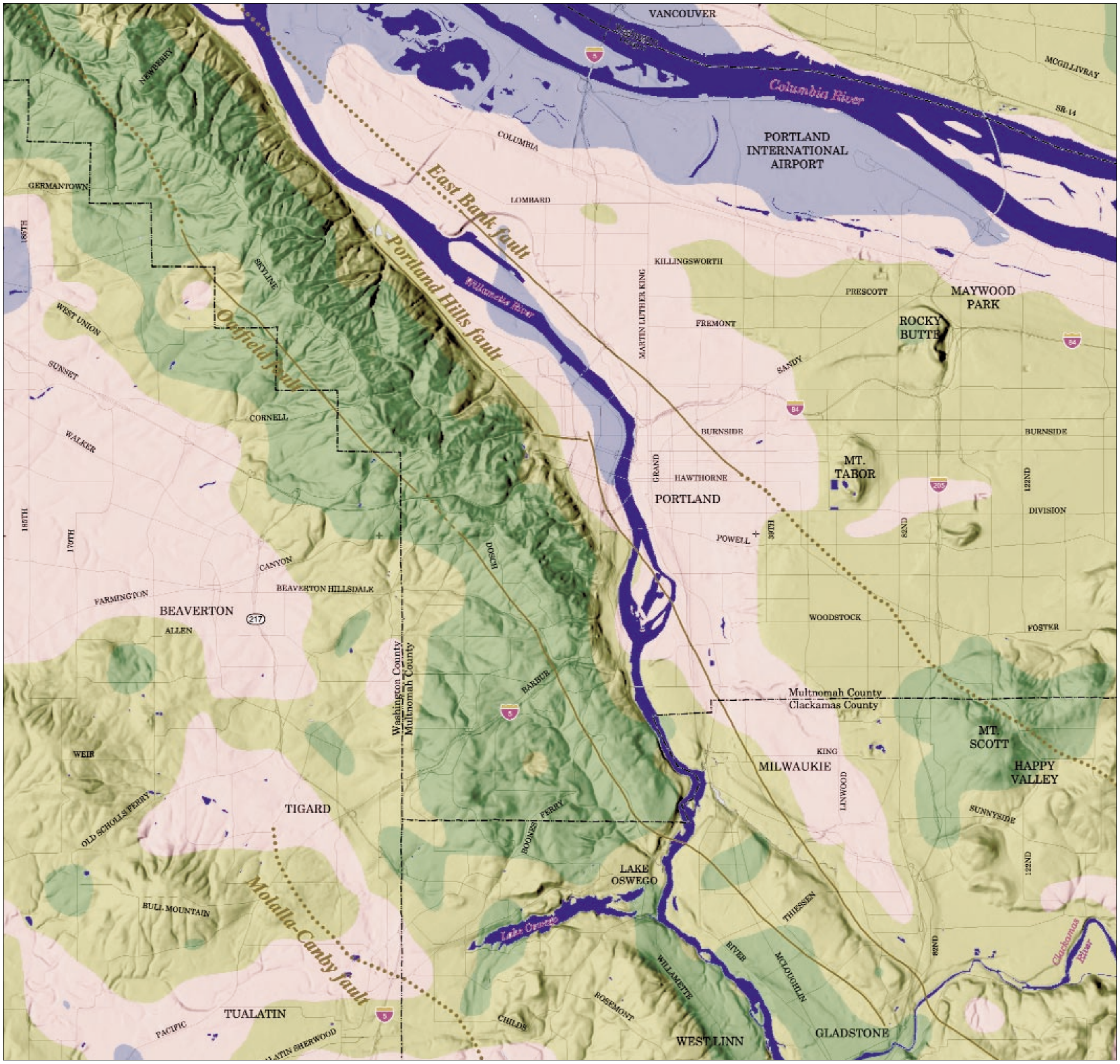

IN THIS ISSUE:

✧The Portland Hills fault✧

✧Seismic rehabilitation at the Oregon State Library in Salem✧

✧Results of a new method of Fourier grain-shape analysis✧

The Portland Hills fault: An earthquake generator or just another old fault?

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Editor's Note

During the final stages of preparing this article for publication, evidence was discovered that throws new light on the question in the title, without invalidating the essence of the paper. In a sidebar on pages 47–49, Ian P. Madin gives a preliminary assessment of the new-found evidence for activity on the Portland Hills fault in times more recent than had been known before. A more extensive description and discussion will be published by Madin in *Oregon Geology* at a later date.

ABSTRACT

Several lines of indirect evidence and preliminary interpretations of recently collected seismic reflection data have led to the conclusion that the Portland Hills fault at the eastern base of the Portland Hills appears to be capable of generating large-magnitude earthquakes. Although no historical earthquake can be associated with the Portland Hills fault, small-magnitude seismicity in the past 20 years in the vicinity of the Portland Hills fault zone, which includes the Oatfield and East Bank faults, suggests that one or all of these structures may be seismogenic. The Portland Hills fault may be 40–60 km long, probably dips to the southwest beneath the Portland Hills, and may slip in a reverse-oblique sense. Limited observations suggest that, on average, the intervals between large earthquakes are a few thousand to more than 10,000 years. Given its location in the midst of the Portland metropolitan area, rupture of the Portland Hills fault resulting in a large earthquake could be devastating. Future studies are required to characterize the earthquake potential of the fault in a more definitive manner and to provide an improved basis for predicting the hazards that would result from such a large earthquake.

INTRODUCTION

Since the mid-1960s, it has been suggested that a fault is located at the eastern base of the northwest-trending, westward-sloping Portland Hills and within the Portland metropolitan area which has a population of 1.4 million (Figure 1). Little consideration was given to the possibility that the "Portland Hills" fault was active[1] (or seismogenic, i.e., capable of generating earthquakes). This was consistent with the prevailing view held until the past decade that Oregon was not particularly seismically active. However, as speculation turned to recognition in the Pacific Northwest that the Cascadia subduction zone megathrust was seismogenic, attention began to shift also to evaluating the earthquake potential of inland crustal faults, particularly those located in or near urban areas. For example, significant efforts have been focused on the Seattle fault since the suggestion that it ruptured in a large earthquake (>M_W [moment magnitude] 7) 1,100 years ago (Bucknam and others, 1992). If urban crustal faults such as the Seattle and the Portland Hills faults are seismogenic, they could generate large, disastrous earthquakes similar to the M_W 6.9 earthquake in Kobe, Japan, in 1995.

In the following paper, we review what is known about the geology of the Portland Hills fault, particularly its characteristics, which might help quantify its earthquake potential. Recent studies, which have focused on this quantification, are discussed. Last year, Wong and others (2000a; 2000b) released scenario earthquake ground shaking hazard maps for the Portland metropolitan area. They assumed a M_W 6.8 earthquake rupturing 30 km of the Portland Hills fault at the base of the Portland Hills (Figure 2). The potential ground shaking from such an event would greatly exceed the ground motions from a M_W 9 Cascadia subduction zone megathrust event in the Portland area. This paper elaborates on the

[1] We consider a fault in the Pacific Northwest to be "active" if it has moved (been displaced) at least once during late Quaternary time (the past 780,000 years).

Figure 1. Oblique air photo of the Portland Hills toward the northwest and inferred location of the Portland Hills fault. The fault is mapped near the eastern base of the escarpment north of West Burnside Street. To the south, the inferred fault steps toward the east, where it traverses the downtown area and crosses the Willamette River (Figure 2). Fault location based on Madin (1990). Air photo courtesy of Northern Light Studio.

basis for selecting a M_W 6.8 scenario, although the evidence at that time was not compelling that the Portland Hills fault was seismogenic.

HISTORICAL SEISMICITY

The Portland area has exhibited a low to moderate level of historical seismicity (Figure 2), compared to other areas in the Pacific Northwest. The area is not as seismically active as the Puget Sound region to the north but may be the most active area in Oregon for events of M_W ≥3.0 based on the historical record (Wong and Bott, 1995). Detailed discussions of the historical seismicity can be found in Bott and Wong (1993) and of instrumentally recorded seismicity since 1982 in Yelin and Patton (1991) and Blakely and others (1995). Based on the historical earthquake record, seven felt earthquakes (Richter magnitude [M_L] >3.5) have occurred in the vicinity of Portland since 1850 (Bott and Wong, 1993).

The first significant earthquake to strike the Portland area occurred on October 12, 1877. It was felt in towns around Portland, but its maximum intensity was in the city (Modified Mercalli [MM] VII). This event of approximate magnitude M_L 5¼ damaged chimneys and was felt over an area of 41,000 km^2. On February 3, 1892, a "severe" earthquake of estimated M_L 5 caused brick buildings to sway and windows to rattle in Portland, terrifying its occupants. A M_L 4½ event on December 29, 1941, shook an area of about 9,000 km^2, including the towns of Portland, Hillsboro, Sherwood, and Yamhill in northwest Oregon and Vancouver and Woodland in southwest Washington. Effects included shattered windows, cracked plaster, and overturned objects. Another M_L 4½ earthquake occurred somewhere between Portland and Vancouver on December 15, 1953. Effects were similar to those encountered in 1941. An earthquake on November 6, 1961 (M_L 5) shook a large area (23,000 km^2) of northwest Oregon and southwest Washington. Damage included a fallen chimney, cracked plaster, broken interior lights, jammed doorframes, and groceries thrown from shelves. The instrumental location of this event is uncertain, although an aftershock felt mostly in Portland suggests the main shock also occurred there. On January 27,

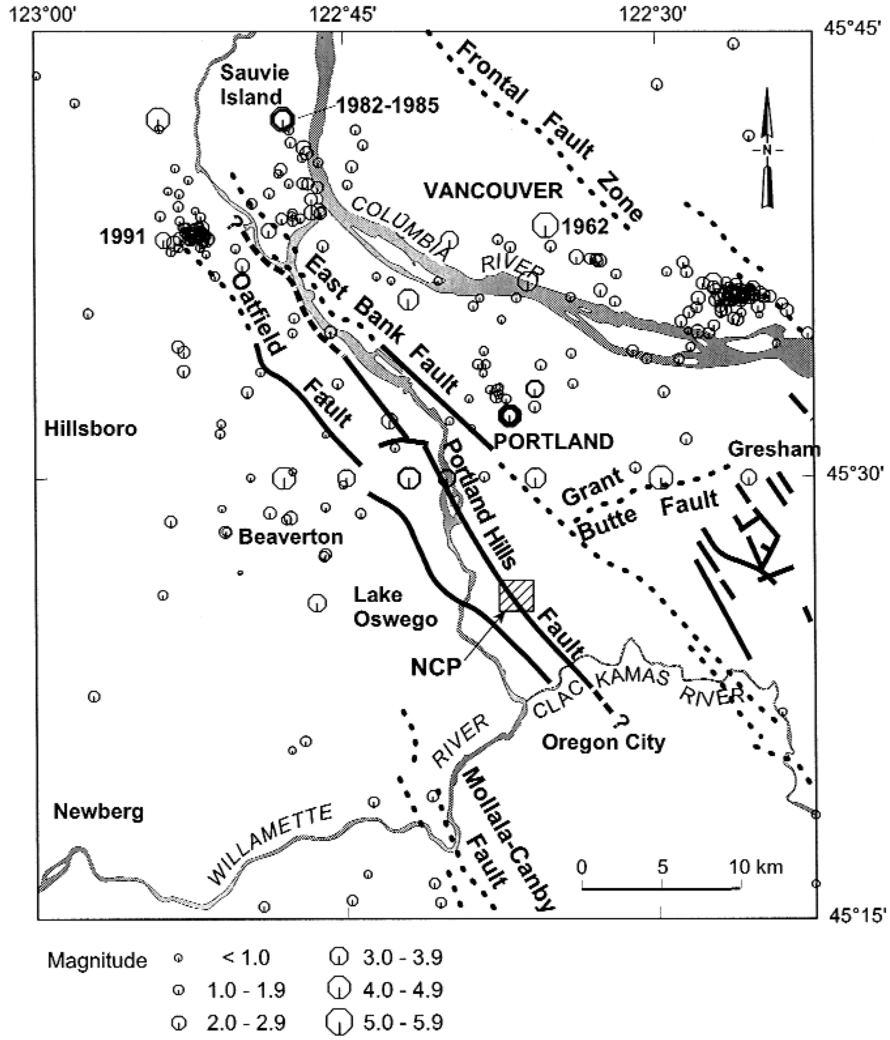


Figure 2. Portland Hills fault zone and historical seismicity in the vicinity of Portland, 1841 to 2000. Faults shown are those considered to be potentially active by Wong and others (2000b). Site NCP is also shown. Earthquake symbol size is a function of magnitude. The largest event shown is the 1962 M_L 5.5 earthquake. Smallest events are $M_L \leq 1.0$.

1968, an earthquake estimated to be M_L 3.7 in size was felt in Portland. The event is believed to have originated in east Portland but at a depth of 20 to 24 km.

The most significant local earthquake in Portland's history occurred on November 5, 1962. Yelin and Patton (1991) calculated a magnitude of M_W 5.2 for the event and Bott and Wong (1993) assigned a M_L 5.5 based on its felt area and other instrumental estimates. The earthquake was felt widely over an area of 70,000 km^2 in northwest Oregon and southwest Washington, causing damage typical for an earthquake of this size: broken windows, cracked and fallen chimneys, and cracked plaster. The main shock was followed by numerous small but unfelt aftershocks. With the exception of the 1962 earthquake, which was relocated by Yelin and Patton (1991) to a location in Vancouver (Figure 2), the large location uncertainties of the historical earthquakes with M_L >3.5 in the Portland area prior to 1982 prevent a determination of whether any of these events were associated with the Portland Hills fault or adjacent major structures.

PREVIOUS FAULT STUDIES

Numerous geologic and a few geophysical studies of the Portland Hills fault have been performed since the 1960s. The early studies stemmed from attempts to explain the presence of the Portland Hills, which are underlain by uplifted Tertiary rocks. A major obstacle in characterizing the Portland Hills fault is that nowhere has the fault been documented to be exposed at the ground surface. Given the heavy vegetation, urbanization, and catastrophic floods (i.e., the late Pleistocene Missoula floods ca. 12,000 to 15,000 years ago), there may be areas where the fault extends to the surface but has simply not been detected. The following summary is taken principally from Yelin and Patton (1991), Unruh and others (1994), and Blakely and others (1995).

The Portland Hills comprise a northwest-trending, asymmetric anticline that was uplifted principally in the late Miocene and Pliocene (after 6 Ma). Several models have been developed to explain the origin of the northeastern margin of the anticline, which forms an abrupt escarpment. Both Schlicker and others (1964) and Balsillie and Benson (1971) suggested that the escarpment (Figure 1) is the surface expression of a steeply northeast-dipping fault. Schlicker and others (1964) inferred that the fault was of normal slip. Beeson and others (1976) proposed that the fault was part of a Portland Hills-Clackamas River structural zone and that the zone accommodated right-lateral, strike-slip motion. They also suggested that the Portland basin was a pull-apart structure and that the west-bounding Portland Hills fault was a right-oblique fault. On 1:24,000-scale quadrangles of the Portland area, Madin (1990) showed the Portland Hills fault extending a distance of about 40 km along the Portland Hills (Figure 2). Yelin and Patton (1991) also inferred that the

Portland basin was a pull-apart basin and that the Portland Hills fault and their postulated Frontal fault zone to the east bound the basin (Figure 2). Their model was based in large part on a re-analysis of the 1962 Portland earthquake (M_W 5.2), which appears to have resulted from normal faulting within the Portland basin. In their model, the Portland Hills fault is a right-lateral, strike-slip fault. In contrast to previous models, Unruh and others (1994) interpreted the Portland Hills anticline as a fault-bend or fault-propagation fold and based this interpretation on surface mapping and sparse drill-hole data. In their model, the Portland Hills fault is a southwest-dipping, blind thrust fault.

In the most extensive study of faulting to date, Blakely and others (1995) performed a high-resolution aeromagnetic survey of the Portland area. On the basis of interpretations of the survey and an analysis of the contemporary seismicity, they identified two additional faults, the East Bank and Oatfield faults (Figure 2), which they include as part of the Portland Hills fault zone. Both faults were first identified by Beeson and others (1989, 1991) on the basis of geologic mapping. The Portland Hills fault, also an element of the Portland Hills fault zone, was not well imaged by the aeromagnetic data (Blakely and others, 1995). The East Bank fault was previously known through shallow well data that indicate ≤200 m of vertical displacement of the underlying volcanic basement. As mapped by Madin (1990) and Beeson and others (1991), the fault is overlain by Quaternary deposits. The Oatfield fault along the southwestern slope of the Portland Hills was also previously known from the studies by Beeson and others (1989) and Madin (1990).

The aeromagnetic data suggest that the Oatfield and East Bank faults are steeply dipping structures that exhibit principally reverse slip (Blakely and others, 1995). This slip would be consistent with earlier observations of folding and thrusting (Beeson and others, 1985, 1989, 1991; Unruh and others, 1994).

In an analysis of contemporary seismicity, Blakely and others (1995) noted that two sequences from 1982 to 1985 near Sauvie Island (M_L ≤2.8) and 1991 at the north end of the Portland Hills (M_L ≤3.5) may be associated with the Portland Hills fault zone, although they appear to have occurred at mid-crustal depths (15–20 km). Thus relating these events to mapped faults is problematic, given the uncertainties of the subsurface geometry of the faults and the hypocentral locations (Blakely and others, 1995). No other events appear to be associated with the fault zone, particularly along its central and southern extent (Figure 2). Focal mechanisms of the 1982 to 1985 and 1991 sequences exhibit both right-lateral and reverse slip (Blakely and others, 1995; Figure 3). A component of strike-slip motion along the Portland Hills fault zone is consistent with the pull-apart basin model.

No evidence for recent displacement on the fault had been observed prior to 1998. In a photogeologic investigation of the fault, Geomatrix Consultants (1993) did not observe evidence for Holocene or late Pleistocene activity, but the factors mentioned previously could obscure any surficial evidence (Figure 1). Balsillie and Benson (1971) noted several geomorphic features indicative of Pleistocene uplift of the Portland Hills (linear northeastern front of the Portland Hills, aligned triangular facets, and knickpoints in northeast-flowing streams), which may be suggestive of activity on the Portland Hills fault. Unruh and others (1994) judged the fault to be "potentially active" on the basis of their review of available data and geomorphic evidence for middle to late Quaternary uplift of the Portland Hills and homoclinal westward tilting of early to middle Pleistocene deposits in the Tualatin basin. The geomorphic evidence included recent stream incision and downcutting, minor deformation of Tualatin basin fill on the southwest flank, and thrust faulting of the Tertiary Troutdale Formation in the southern portion of the Portland Hills (Unruh and others, 1994).

In a seismic source characterization of the Portland Hills fault for the development of statewide ground shaking maps, Geomatrix Consultants (1995) considered two models: a relatively steeply (70°) west-dipping reverse or reverse-oblique fault and a blind shallow-dipping thrust fault. The latter model suggested by Unruh and others (1994) was assigned little weight. Although there was no definitive surficial evidence for the fault being seismogenic, Geomatrix Consultants (1995) adopted a relatively high probability of 0.70 that the fault was active and based this on possible deformation of late Pleistocene sediments and the topographic expression of the Portland Hills. They also estimated that potential rupture lengths for the Portland Hills fault range from 28 to 62 km (Figure 2). The latter value is based on lineaments observed on air photos to the north and south of the mapped trace. Slip rates of 0.05 to 0.2 mm/yr were estimated, considering the tectonic setting and regional kinematics (Geomatrix Consultants, 1995).

RECENT INVESTIGATIONS

The Portland Hills fault as well as the East Bank and Oatfield faults would pose the greatest seismic hazard to Portland because of their proximity and their potential to generate large-magnitude earthquakes (M_W ≥6.5) (Wong and Silva, 1998). Wong and others (2000b) characterized the Portland Hills fault in their development of scenario and probabilistic ground shaking maps for the Portland metropolitan area by revising the assessments of Geomatrix Consultants (1995). They assumed a higher probability (0.8) that the Portland Hills as well as the East Bank and Oatfield faults were seismogenic. The basis for this assessment, were the following observations:

1. Contemporary microseismicity has been observed in the vicinity of the Portland Hills fault, with the majority of events concentrated at depths of 5–20 km (Yelin and Patton, 1991; Blakely and others, 1995). Although no earthquakes can be definitively associated with the fault, the occurrence of events is suggestive that there are active structures nearby. As observed by many (e.g., Kafka and Levin, 2000), the presence of small earthquakes, more often than not, delineates areas where larger earthquakes are likely to occur. We believe the Portland Hills fault zone or specifically the Portland Hills fault is the likely source for future large earthquakes in the Portland area.

2. The few earthquake focal mechanisms in the Portland area and surrounding region indicate that northwest-striking structures such as the Portland Hills fault are favored to be seismogenic in a north-south tectonic compressive stress field (Yelin and Patton, 1991; Blakely and others, 1995; Wong, 1997) (Figure 3). The similarly oriented northwest-striking Mount Angel fault to the south may have been the source of the M_L 5.6 Scotts Mills earthquake of 1993 (Madin and others, 1993; Thomas and others, 1996).

3. Pratt and others (2001) acquired and interpreted single-channel marine seismic reflection data across the projections of the Portland Hills and East Bank faults where they cross the Willamette River near Ross Island and near the Multnomah channel, respectively. Unfortunately, the Ross Island profiles across the Portland Hills fault are uninterpretable. The data near the Multnomah channel appear to indicate that the East Bank fault coincides with a large paleochannel. The layered strata, including a late Pleistocene unconformity at the base of the paleochannel, may be cut by a nearly vertical fault. Thus the East Bank fault appears to have been active at least in the late Pleistocene (Pratt and others, 2001).

4. Finally, the apparent youthful geomorphic expression as evidenced by the abrupt escarpment on the eastern side of the Portland Hills is suggestive of recent activity on the fault. It is possible that this youthful morphology is the product of flood sculpting and scour, but it may also indicate late Quaternary and possibly current uplift of the Portland Hills.

Wong and others (2000b) based an estimated range of slip rates for the Portland Hills fault on (1) a qualitative comparison of its geomorphic expression with faults in other regions; (2) long-term slip rates for the Gales Creek and Mount Angel faults, which are located to the southwest and south of the Portland

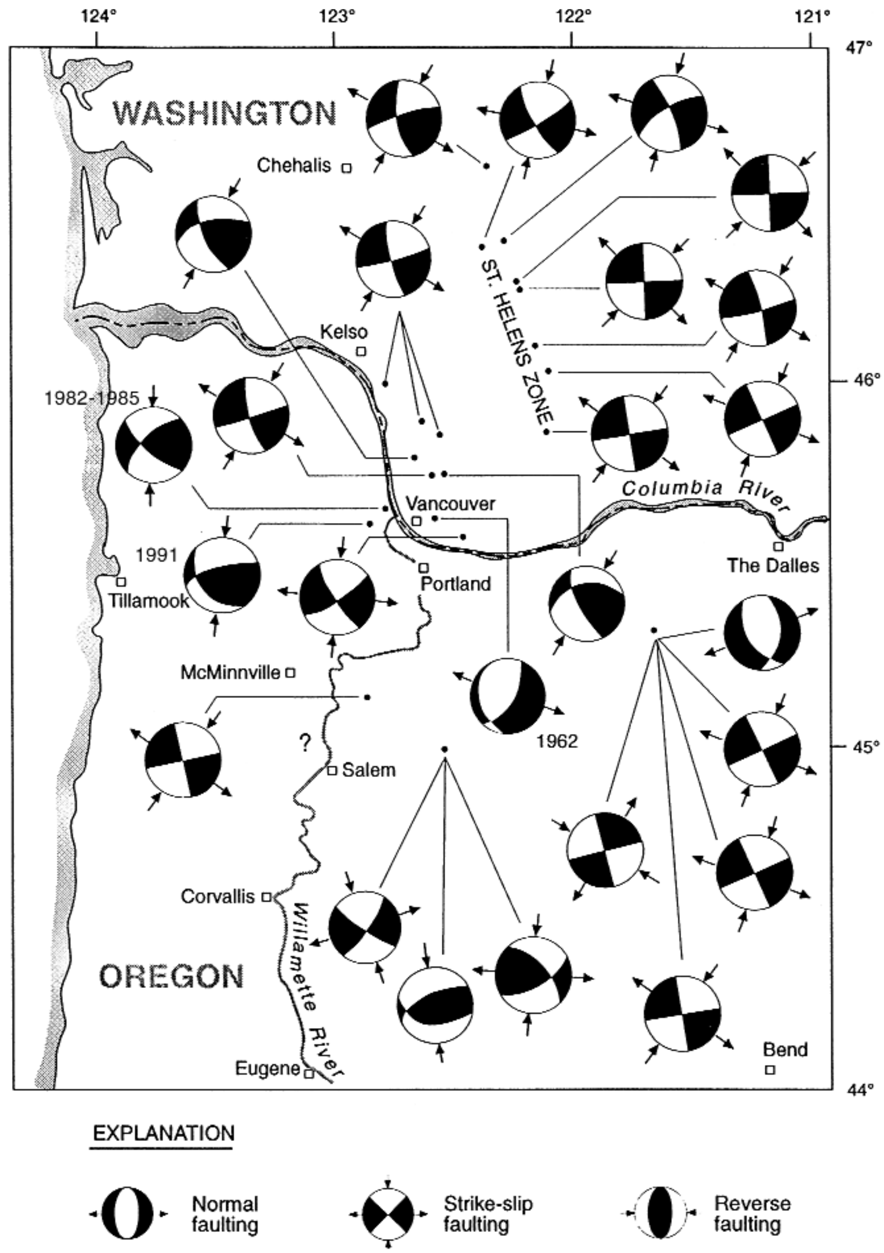


Figure 3. Crustal earthquake focal mechanisms of northwestern Oregon and southwestern Washington. Most of the mechanisms exhibit strike-slip and oblique-reverse faulting in response to a N-S to NE-SW-directed maximum compressive stress. Figure is modified from and data sources described in Wong (1997).

basin, respectively; (3) historical seismicity; and (4) estimated range of displacements by Pratt and others (2001). From detailed mapping, R.E. Wells (personal communication, 1997) estimated a long-term slip rate for the Gales Creek fault of about 0.24 mm/yr since 50 Ma and 0.6 mm/yr since 15 Ma. Wang and Madin (2001) have estimated a slip rate for the Mount Angel fault of approximately 0.23 mm/yr for the past 30 ka.

Bott and Wong (1993) calculated earthquake recurrence for the Portland region based on the historical seismicity record, which dates back to about 1850. Assuming a Gutenberg-Richter relationship, we find that the return period of earthquakes of M_L 6.5 and greater is about 1,000 years. For an average displacement of about 0.5 m, appropriate for a M_W 6.5 earthquake based on the relationship of Wells and Coppersmith (1994), the equivalent slip rate would be about 0.5 mm/yr, distributed across faults within the Portland region. If the Portland Hills fault zone (including the Portland Hills, East Bank, and Oatfield faults) and the Frontal fault zone are taking up most of this slip, the average slip per fault zone would be about 0.25 mm/yr.

Pratt and others (2001) estimate that the late Pleistocene (~15,000-yr-old) unconformity across the East Bank fault at the Multnomah channel may be displaced vertically "several" meters. Assuming that this apparent vertical displacement is at least 3 m, that would indicate a slip rate of about 0.2 mm/yr without accounting for any horizontal component of slip.

Wells and others (1998) suggested that the Cascadia forearc is migrating northward along the coast and is breaking into large rotating blocks. One of these blocks, the Oregon coastal block, is accommodating part of the 7–9 mm/yr of north-south shortening of the forearc. Wells and others (1998) also suggested that the shortening is taken up by deformation along block margins. The northeast boundary of the Oregon block is located near the Portland Hills fault zone (Wells and others, 1998).

To constrain maximum slip-rate values, we can use the convergence rate of 4–7 mm/yr proposed by Wells and others (1998) for the Oregon forearc. Of this total rate, R.E. Wells indicates that northwestern Oregon may be shortening at a rate of 2–3 mm/yr (personal communication, 1999). Within northwestern Oregon, the major fault systems appear to be the Portland Hills, the Gales Creek-Mount Angel, Mollala-Canby, and Frontal fault zones (Blakely and others, 1995, 2000; Wong and others, 2000b). If these four fault zones are taking up a significant portion of the 2–3 mm/yr of regional shortening and if the activity on the fault occurs at about the same maximum rate, the slip rates along them could range up to a maximum of 0.5–0.75 mm/yr. Such high rates seem unlikely except for possibly the Portland Hills fault, because they would result in much more pronounced geomorphic expression of the faults than is observed. Furthermore, these high slip rates assume that there is no aseismic component to the crustal deformation.

Based on the above observations, a range of slip rates of 0.05–0.4 mm/yr was adopted for the Portland Hills fault as well as the East Bank and Oatfield faults (Wong and others, 2000b). Using the relationship of Wells and Coppersmith (1994) to calculate an average displacement of 0.8 m for a M_W 6.8 earthquake), we find that the average recurrence interval would range from 2,000 to 16,000 yrs.

The maximum earthquake that the Portland Hills fault appears to be able to generate is in the range of M_W 6.8–7.2, as calculated from the potential rupture lengths of 28–62 km estimated by Geomatrix Consultants (1995). This is a significant range in magnitudes. Because the resulting hazards will also differ significantly from the low end to the high end of this range, it is critical that the extent of the Portland Hills fault and its possible segmentation and thus potential rupture lengths be better defined. In the modeling of the scenario ground motions for an event on the Portland Hills fault, Wong and others (2000a; 2000b) adopted a M_W 6.8 event rupturing 30 km of the fault, predominantly along its most geomorphically pronounced portion at the base of the Portland Hills.

The fault was assumed to rupture with oblique slip (50 percent reverse and 50 percent right-lateral strike-slip), dip 70° to the southwest beneath the hills, and extend to a depth of about 19 km (resulting in a fault width of about 20 km). Although focal mechanisms in the region exhibit predominantly strike-slip motion (Yelin and Patton, 1991; Blakely and others, 1995; Wong, 1997), with some showing reverse and oblique slip (Figure 3), the presence of the Portland Hills indicates that reverse faulting is the primary mode of deformation if uplift is still ongoing.

Future studies of the fault should also focus on constraining the dip of the fault. The assumed value of 70° is extremely uncertain. Because the dip controls the downdip width of the fault, the potential area available for rupture may be significantly larger, if the fault has a shallow dip (<50°).

The dip of the fault will also shed some light on the structural relationship between the Portland Hills and Oatfield faults. Wong and others (2000b) considered two possible structural geometries for the Portland and Oatfield faults due to the closeness of the faults (separated by 3–5 km; Figure 2) and their proposed respective westward and eastward dips as suggested by Blakely and others (1995): (1) the two faults each dip at about 70° and merge at a depth of about 5 km to form a single zone at greater depths Figure 4a), or (2) the two faults have steep dips (>80°) and are not structurally connected (Figure 4b). In the first case, i.e., if the two faults merge, they

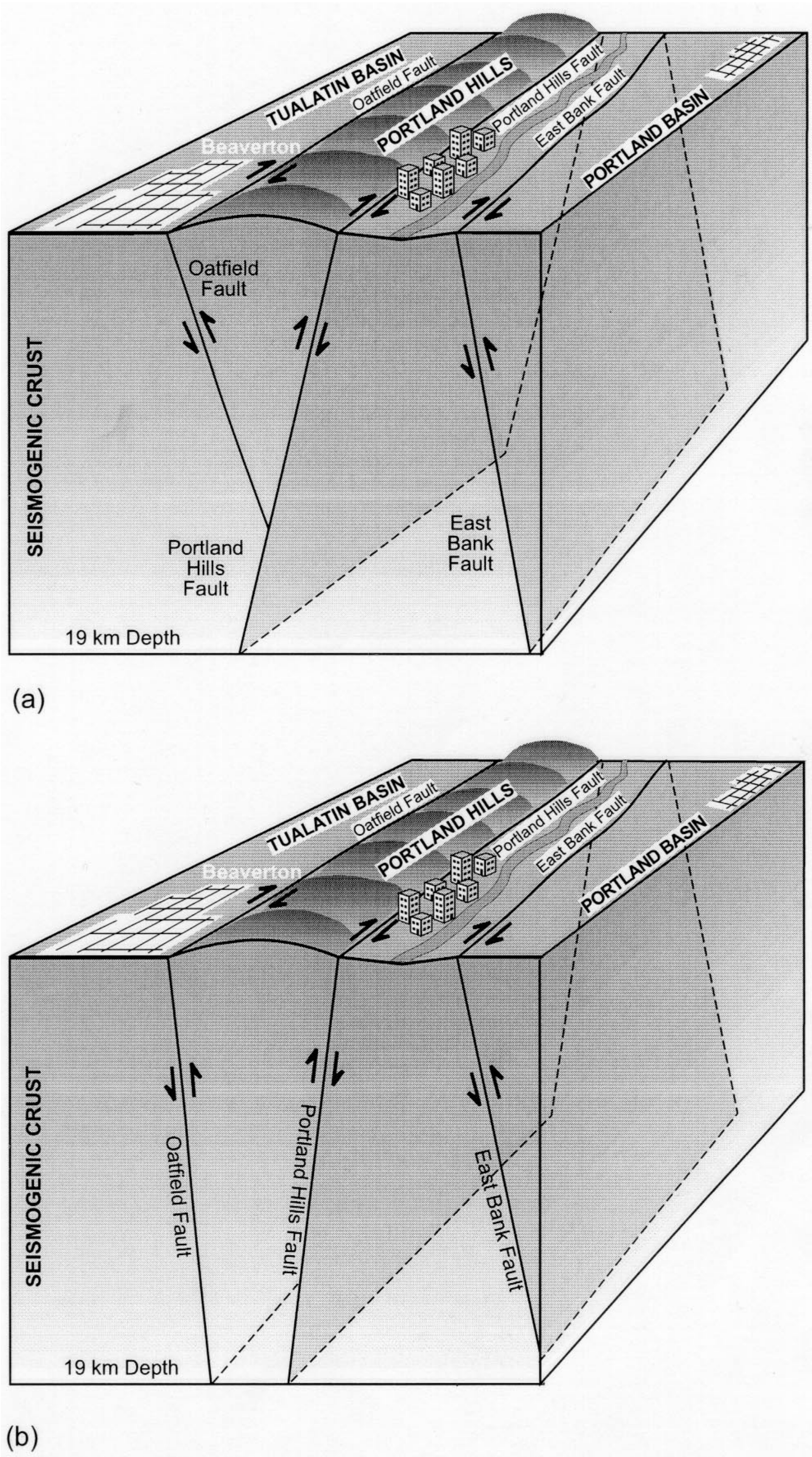


Figure 4. Schematic block diagram of the Portland Hills fault zone. Shown are two possible interpretations of its subsurface geometry. A third model is that the East Bank fault dips to the west and is structurally connected to the Portland Hills and/or Oatfield faults.

could be part of a flower structure provided they are predominantly strike-slip faults. If they are reverse faults, the Oatfield fault may be a back-thrust to the main Portland Hills fault.

The implication of both structural models is that in any given earthquake either one or both faults may rupture coseismically. If both faults rupture together in a single event, large near-field ground motions will be distributed over a wider area than if only a single fault were to rupture.

Furthermore, the proximity of the East Bank fault (Figure 2) suggests that it, too, might be structurally connected with the above faults. That is unlikely, however, at least according to Blakely and others (1995), whose interpretations of aeromagnetic data show the East Bank fault dipping away to the east (Figure 4).

CURRENT INVESTIGATION

With funding support from the U.S. Geological Survey National Earthquake Hazards Reduction Program, we employed multiple geophysical methods, including high-resolution seismic reflection, ground penetrating radar (GPR), and magnetic profiling to locate the Portland Hills fault at North Clackamas Park (NCP) south of Portland (Figure 2). We also incorporated data from nearby water wells to correlate the observed strata with horizons in the geophysical data and to aid in laying out the locations of the seismic lines.

Two high-resolution seismic profiles at the NCP site provide detailed images of the upper 100 m of the stratigraphic section, and enable us to locate significant offset in the Miocene-age Columbia River Basalt Group (CRBG) rocks and overlying sediments (Figure 5). Ground magnetic profiles along our seismic transects correlate with offset and orientation in the volcanic basement or CRBG rocks. The magnetic surveys, well logs, and ground reconnaissance show that CRBG rocks crop out near the southwest portion of

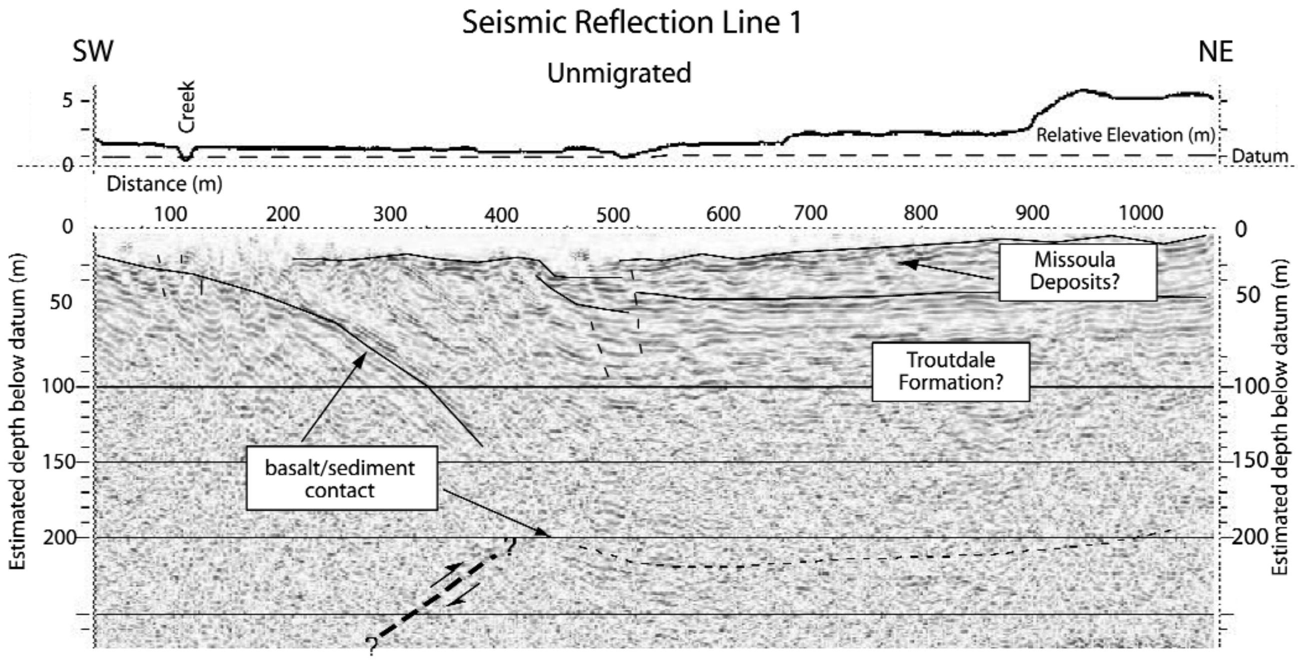


Figure 5. High-resolution seismic reflection profile at the North Clackamas Park.

the NCP site. Seismic, magnetic, and well-log information indicate that basalts dip shallowly to the northeast and are observed at depths greater than 100 m to the north of the site. The seismic data show a strong-amplitude, steeply (>20°) dipping horizon that is likely the top of the CRBG sequence (Figure 5). A well located less than 300 m to the northwest of the seismic line encountered basalt at a depth of more than 150 m. Reflections from younger sediments (possibly Tertiary Troutdale to uppermost Pleistocene Missoula flood deposits) also dip steeply. To the east, near the south-central portion of NCP, reflections associated with younger sediments appear flat lying, but are slightly folded synclinally and faulted toward the west. This major change in dip appears within the Pliocene to latest Pleistocene(?) sediments. The dipping strata are imaged to within about 10 m below the land surface (Figure 5).

We interpret these data to represent a major splay of the Portland Hills fault that offsets post-CRBG sediments. The change from flat-lying CRBG rocks and younger sediments to steeply dipping strata provides an indication of the fault location. The data do not, at present, provide unequivocal evidence for the style of deformation. However, the position of the offset CRBG marker is consistent with a southwest-dipping reverse fault which displaces the Portland Hills northeastward over the adjacent basin.

To date, evidence shows that post-CRBG sediments have been faulted. If the youngest faulted sediments imaged with high-resolution seismic-reflection methods are Missoula-flood-related deposits, then there was at least one episode of coseismic surface rupture in the past 15,000 to 12,000 years. The focus of our continuing investigation is to determine the age and extent of these deposits, to assess the number of times they have been displaced, and to determine the style of deformation.

CONCLUSIONS AND "WHAT IF?"

There are several lines of indirect evidence that suggest the Portland Hills fault is an active and seismogenic structure. Direct evidence includes the seismic reflection results at NCP, although the interpretation is still preliminary. We hope to collect more definitive evidence during field investigations during the coming summer. If doubt of the earthquake potential of the Portland Hills fault is removed, the current year's planned and future investigations will focus on characterizing the maximum earthquake potential of the fault, its subsurface dimensions and geometry, rupture characteristics, and the frequency of large-magnitude events. Regarding the latter, it will be critical to decipher the history of prehistoric earthquakes on the fault in an effort to provide some insight as to when the next event may occur.

The consequences of a future large earthquake on the Portland Hills fault could be severe. Wong and others (2000a) estimated that ground shaking, as characterized by peak horizontal acceleration, could exceed 1.0 *g* for a M_W 6.8 event[2]. (The peak horizontal acceleration recorded in the 1962 earthquake at the only existing strong-motion site was 0.10 *g*, in downtown Portland.)

[2] Earthquake ground motions are often expressed in terms of acceleration and the unit "*g*", which is the gravitational acceleration at the earth's surface equal to 980 cm/sec^2. The onset of light damage is at about 0.1 g.

If the Portland Hills fault were to rupture predominantly with reverse slip, an analogue for such an event would be the M_W 6.7 earthquake of 1994 in Northridge, California, which generated some of the strongest ground shaking ever recorded (as high as 1.9 *g*) and caused 58 deaths, and property damage of $20 billion. The source of the Northridge earthquake was a blind reverse fault which dips about 40°–50° to the south beneath the San Fernando Valley.

Unlike the Northridge fault, however, the Portland Hills fault is situated in the midst of a major metropolitan area, where the majority of older buildings do not meet current building code seismic design criteria, particularly those pre-code unreinforced masonry structures. Of special concern, as observed in the Northridge earthquake, is the potential for rupture directivity, which will be directed toward downtown Portland. The directivity effects will be greatest if the Portland Hills fault ruptures with reverse slip. Since directivity is a long-period effect (>1.0 sec), high-rise buildings, which are concentrated in downtown Portland, could be particularly susceptible to very strong ground shaking (These effects are not illustrated on the scenario maps of Wong and others [2000b] because they go out only to a period of 1.0 sec).

As future investigations proceed, it will be important to update the assumptions considered in the Portland Hills fault scenario ground shaking maps, (e.g., magnitude, slip, etc.) in order to provide the most realistic estimates of ground shaking possible so that adequate mitigation measures can be taken to prepare the citizens of the Portland metropolitan area for this potential disaster. Future studies of the East Bank and Oatfield faults and their relationship, if any, to the Portland Hills fault are also critically needed.

(Continued on page 50)

The Portland Hills fault at Rowe Middle School

by Ian, P. Madin, Oregon Department of Geology and Mineral Industries, and Mark A. Hemphill-Haley, Senior Geologist, URS Corporation

For decades, geologists have recognized that the Portland Hills fault is a major geologic structure that runs right through the Portland Metro area. The fault is responsible for the unusually straight and sharp edge of the Portland Hills north of downtown Portland, but is less obvious southeast of downtown. Scattered outcrops and data from water well logs were used to approximate the location of that southeast extension of the fault on recent geologic maps. Geologists from the Oregon Department of Geology and Mineral Industries (DOGAMI), URS Corporation (an engineering firm), and Boise State University began a research project in 2000 to study the Portland Hills fault in more detail. The study, funded by the U.S. Geological Survey through the National Earthquake Hazard Reduction Program (NEHRP), seeks to determine whether the fault is active, and therefore poses an earthquake threat to the region. In this case, "active" means that it has moved during the last 10,000 to 15,000 years.

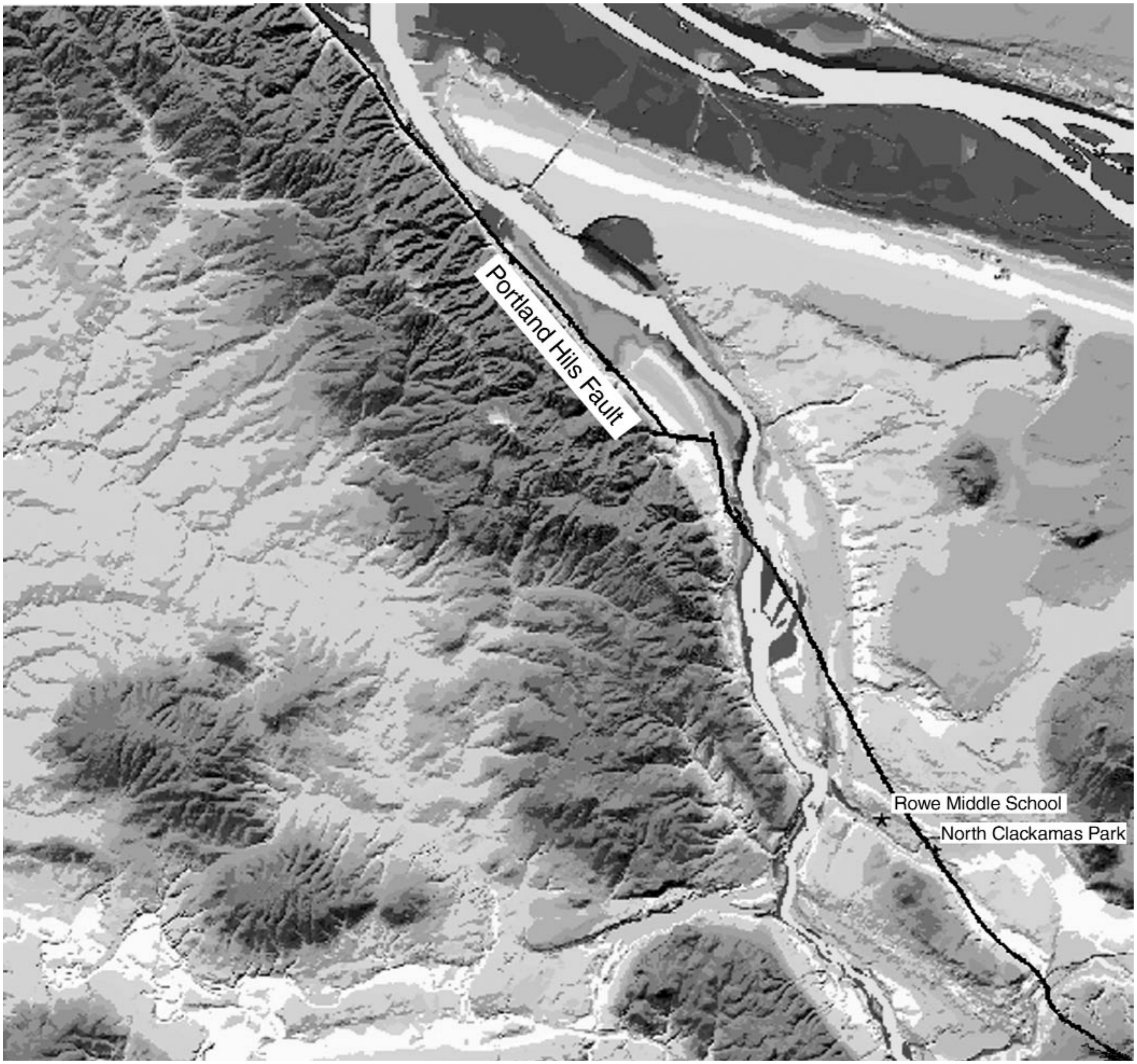
The NEHRP study used two geophysical methods to image the fault and was conducted in North Clackamas Park and on adjacent private property. The site was chosen because the inferred line of the fault passed through it, and the area was relatively undeveloped and quiet, which aided in the collection of good geophysical data. The resulting imagery confirmed the presence of a significant fault, located the main fault to within ~100 ft, and showed faulting and folding to within about 50 ft of the surface. It did not definitively show evidence of activity, because the seismic and magnetic techniques could not image the shallowest layers, and the age of those layers was unknown.

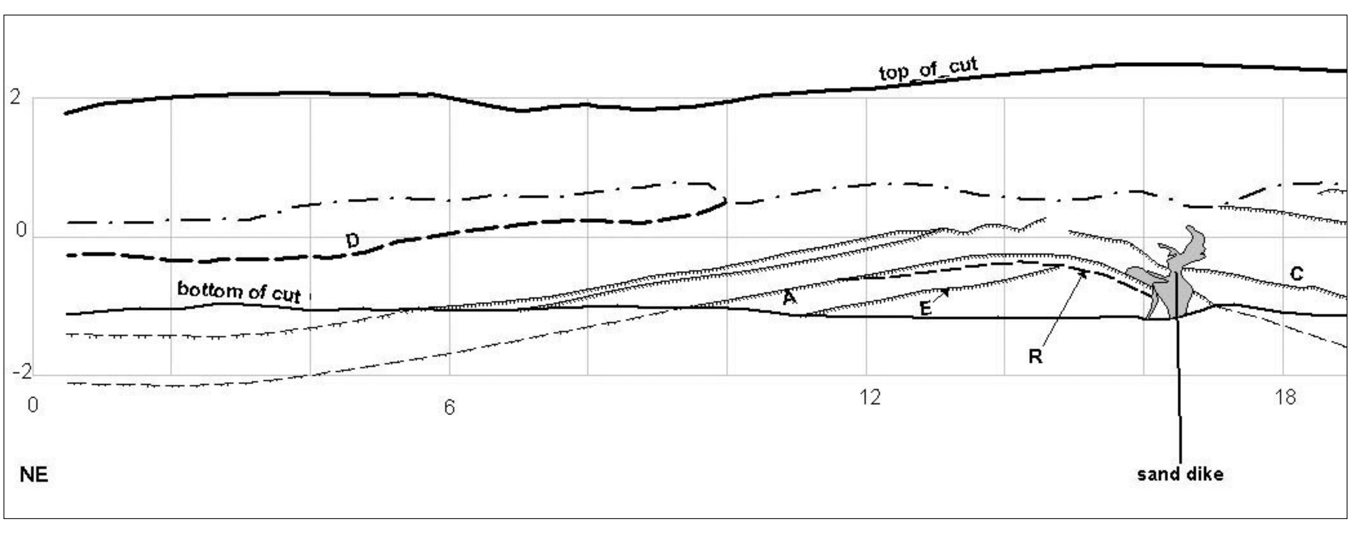
This May, a DOGAMI geologist was collecting more magnetic readings with a handheld instrument to try to map the fault line around the North Clackamas Park site. While collecting data at the site, he noticed sediment layers in a retaining-wall excavation, and these layers appeared to be folded. The deposits at this site are sand and silt layers left during the ice age by the Missoula floods and are 15,000 to 12,800 years old. Hence any faulting or folding of these sediments would point to an active fault.

A subsequent two-day examination and logging (by DOGAMI and URS geologists) of the sediments exposed in the retaining-wall face showed that the entire sequence of sediment layers is folded. We believe that this folding is evidence for an active fault beneath the site and that the fault is either the Portland Hills fault or a closely related fault. Preliminary interpretation of the log for the cut shows that the southwest end is about 5 ft higher than the northeast end, and the whole sediment sequence has been shortened about 3 ft. This suggests a total of 6 ft of movement. This is consistent with the assumption that, during the past 12,800 years, two earthquakes may have occurred on the fault.

We considered other geologic processes that might have caused the appearance of folded layers but concluded that they could not produce the arrangement we observed. We intend to use more geophysical studies at the site to confirm the presence of a fault beneath the site. An example of this approach is an earlier high-resolution magnetic survey across the fault, which shows an abrupt jump in the magnetic field strength coincident with the folded sediments. We believe this occurs because the depth to highly magnetic volcanic bedrock changes abruptly across the fault. ☐

(See illustrations on next two pages)


Portland Hils Fault
Rowe Middle School
North Clackamas Park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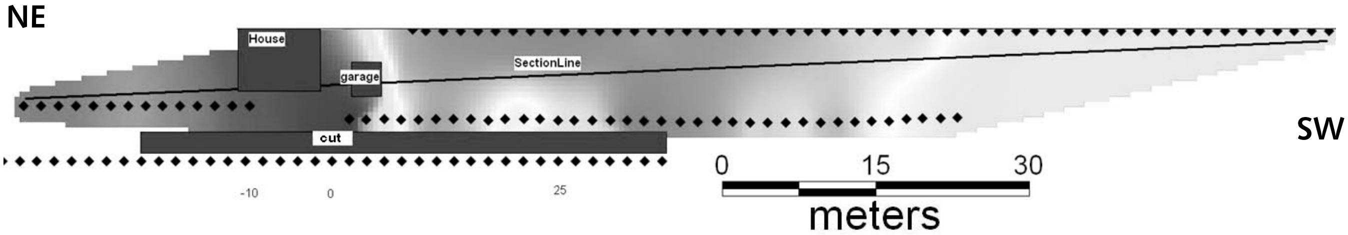
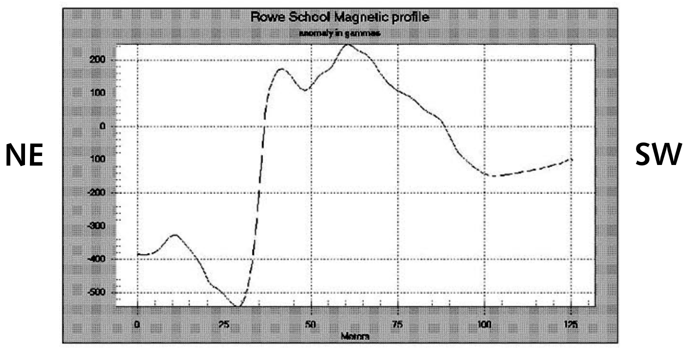




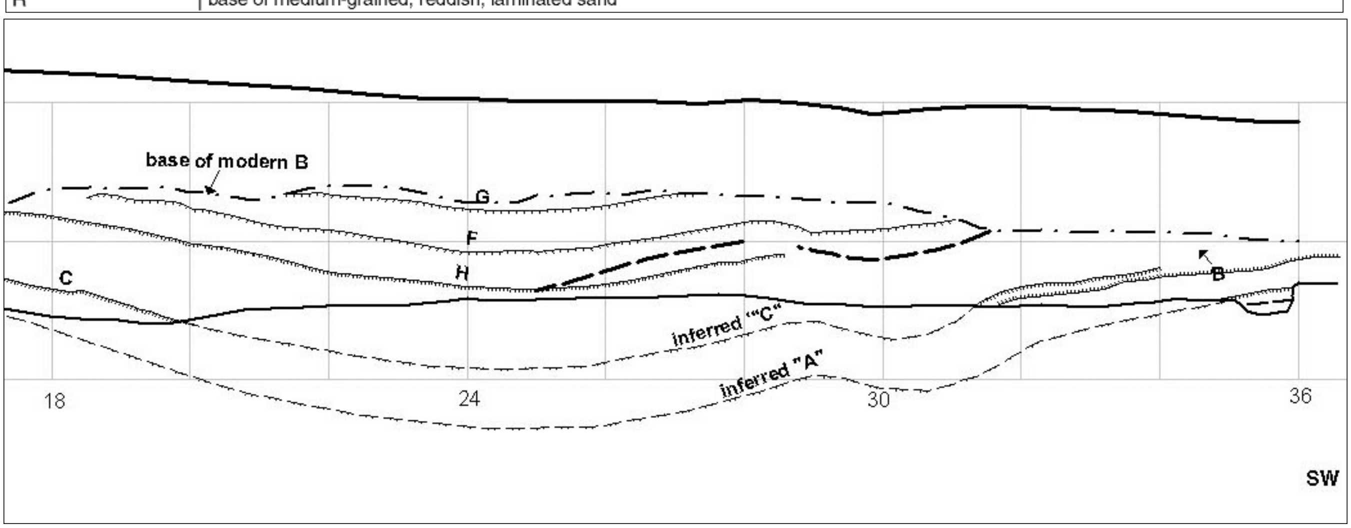
The fault at Rowe Middle School

These two pages show, far left, a location map of the new discovery site; on this page, top, a magnetic grid map and graph of the cut that revealed the new information; and, below this text, a description of horizons for the preliminary log of the cut, split across both pages at the very bottom.

The magnetic grid map shows the location of magnetic datapoints (black diamonds) with respect to the cut and includes cultural features. The postion of the sharp anomaly occurs at the same location as the sharp fold in the cut. Points not included in the grid were strongly affected by piles of rebar deployed along the cut for construction. The cross section of the magnetic grid shows a sharp and relatively high-amplitude (~700 gamma) anomaly.

The preliminary log of the cut shows a series of fine sand layers deposited by the late Pleistocene Missoula Floods. Each layer, or rhythmite, represents a single flood event, and the rhythmites are typically separated by paleosols, which are marked by accumulations of clay, iron oxides, and root casts. The log shows a stack of at least seven rhythmites, all of which appear to be folded in the same form. Some channeling is evident in the form of truncated paleosols but is generally restricted to one or two rhythmites. ☐

Horizon	Description
E	2-3 cm thick gray silty clay
base of modern B	irregular diffuse base of B horizon, marked by red-brown mottling, accumulation of disseminated brown clay and FeO, FeO veins
G	top of 8 cm hard paleosol with abundant red FeO
F	top of 10-20 cm thick strong paleosol, gray brown clay in lower half, clay and red FeO in upper half
B	top of 1-2 cm thick gray silty clayey layer, paleosol?
C	top of 5-8 cm thick moderately developed paleosol marked by accumulation of FeO and brown clay
H	top of 5-8 cm thick moderately developed paleosol marked by accumulation of FeO and brown clay
D	locally sharp, locally diffuse and burrowed contact between massive medium sand below and locally well-laminated medium reddish sand
A	top of strong, 10-15 cm thick paleosol, marked by accumulation of gray-brown clay and FeO
R	base of medium-grained, reddish, laminated sand



(Continued from page 47)

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