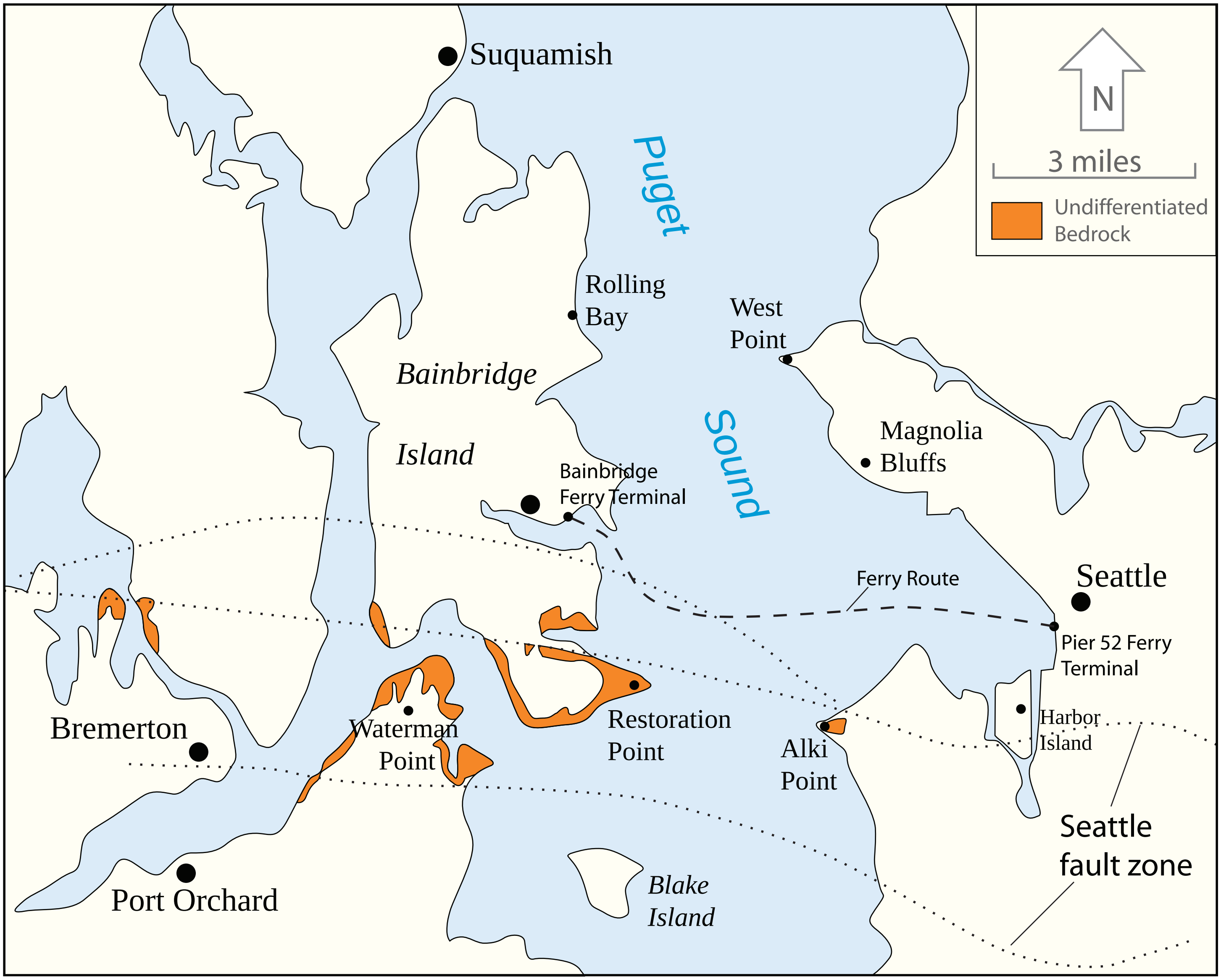
WASHINGTON STATE DEPARTMENT OF
Natural Resources



Earthquake Engineering Research Institute
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Building Resilient Communities
Through Policy and Mitigation

Field Trip Guide:
Geologic Hazards in Seattle

Friday, February 15, 2013

by:

Tim Walsh
Chief Geologist, Hazards Section

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Tour Description

This field trip will travel along the Seattle fault on the Bainbridge Island ferry. Figures 1 and 2 give a general sense of the regional tectonic setting. Following our departure from Seattle to Bainbridge Island, we will discuss visible features and lines of evidence for earthquakes along the Seattle fault on the starboard side of the ferry, looking north.

- *Seattle landslides*:
  The coastal bluffs around Puget Sound are especially prone to slope instability because of their unique terrane, geology and climate. We will discuss the Magnolia Bluffs area (see cover sheet for location), which experienced severe damage from landslides during the winter storms of 1996/1997 (see "*Puget Sound Bluffs: The Where, Why, and When of Landslides Following the Holiday 1996/97 Storms*" in this guide for detailed information).
- *LiDAR and other geophysical methods used to find active faults*:
  LiDAR, short for Light Detection and Ranging, is a useful tool in detecting linear geologic features through heavy forest cover (Figure 3). Use of LiDAR and applications of geophysical techniques, such as seismic reflection, gravity and aeromagnetic surveying (Figure 4) are instrumental in providing evidence for the presence of active faults near Seattle.
- *Restoration Point*:
  Discussed in more detail on the return trip, we will introduce the history of Restoration Point on Bainbridge Island (location shown on cover sheet) as it relates to discovery of the Seattle fault.
- *Landslides along the eastern shores of Bainbridge Island*:
  Like most coastal areas along the Puget Sound, Bainbridge Island contains abundant landslides, some of which are visible from the ferry. One landslide event in particular (Figure 5) in Rolling Bay in the winter of 1997 will be discussed.
- *Trenching across active fault scarps*:
  Once fault scarps are discovered, trenching is performed to try to determine the age(s) of events. Numerous trenches on and around Bainbridge across scarps of the Seattle fault are discussed (see posters on display and Figures 6 through 12).

Our return trip from Bainbridge to Seattle will be spent on the port side of the ferry, looking south.

- *Restoration Point*:
  We will examine the evidence for earthquakes on the Seattle fault, viewing the topographic expression of the geology of Restoration Point (Figure 13).
- *Mercer Island Seismically-Induced Landslides*:
  We will discuss the area of Mercer Island, located just east of Seattle, where there is additional geological evidence for seismic slip on the Seattle fault (Figure 14).
- *Alki Point*:
  Alki Point, (location shown on cover sheet) provides further evidence for seismic slip on the Seattle fault (Figure 15).
- *Harbor Island and tsunami hazard in Elliott Bay*:
  As we near the ferry terminal, we will discuss the implications of earthquakes and tsunamis on Harbor Island (Figure 15), Elliott Bay (see poster on display) and (time-permitting) the elevated portions of the Alaskan Way viaduct (Figure 16).

Evidence for Seismic Slip on the Seattle Fault Zone

During this excursion, you will see geologic evidence for a prehistoric earthquake on the Seattle fault. Geologists concluded that the Seattle area was struck by a large earthquake about 1000 years ago, based on diverse lines of evidence that were reported in a series of articles in Science (1992, v. 258). The evidence, all dating to about 1000 years ago, includes:

- sudden uplift and subsidence adjacent to a major reverse fault near Seattle (the Seattle fault),
- tsunami-laid sand on two historical tidal marshes in central and northern Puget Sound, several landslides that slid into Lake Washington in the same season of the same year as the tsunami in Puget Sound, and landslides of approximately the same age in Lake Sammamish
- a layer of graded sediment (turbidite) in Lake Washington, and
- a series of rock avalanche-dammed lakes in the eastern Olympic Mountains.

Today, you will see sites where geologists collected evidence for sudden uplift and subsidence that accompanied this large earthquake 1000 years ago.

The evidence for earthquake-induced uplift about 1000 years ago in central Puget Sound consists of geomorphic and stratigraphic features that record sudden changes in the relative elevation of sites along the coast. The most dramatic and conspicuous of these features is a raised wave-cut platform at Restoration Point on Bainbridge Island, 5 km west of Seattle. Geologists proposed that uplift of this platform was the result of seismic slip on the Seattle fault, which extends westward across Puget Sound from Seattle. The field trip will cross Puget Sound by ferry, following the course of the fault. The main fault is not exposed at the surface. Several subsidiary faults do break the surface on Bainbridge Island, at Waterman Point in Kitsap County, and just south of Alki Point.

Exposures of bedrock are uncommon in the central Puget Sound region and are confined to a west trending belt extending from the Seattle-Renton area to Bremerton (see cover sheet figure). North of this belt, the top of bedrock is as much as 1 km below the surface. The abrupt increase in depth to bedrock as well as a steep gravity gradient and data from seismic reflection profiles suggest that a west-trending fault (the Seattle fault) lies along the north side of this zone. The Seattle-Bainbridge Island ferry closely follows the inferred course of the fault.

Winslow Marsh-Stratigraphic Evidence of Subsidence

As the ferry approaches Bainbridge Island, it passes south of a submerged bar at the mouth of Eagle Harbor and then turns northward to follow the coast into Eagle Harbor and the ferry dock. South of Eagle Harbor, houses at the foot of the wooded hill above the beach are built on a continuation of the raised marine platform at Restoration Point. After entering Eagle Harbor you can see a small marsh (Winslow marsh) just west of Wing Point on the north side of the entrance to the harbor. There is no raised platform on the north side of the harbor, and peat below the surface of the marsh preserves evidence of subsidence at this site about 1000 years ago. This contrast with the uplift at nearby Restoration Point is a key to inferring the source of the earthquake about 1000 years ago. We will not visit Winslow marsh, but we discuss its importance in earthquake studies below.

Brian Sherrod, a geologist with the University of Washington, led a field trip similar to this one in 1992, and wrote: “Winslow marsh is a small (about 1 hectare) brackish coastal marsh slightly above high tide in the sheltered cove of Eagle Harbor. A low sand and gravel beach berm borders the harbor side of the marsh. The berm ponds a small freshwater stream that flows through the marsh, forming several shallow pools of slightly brackish water that percolate through the berm. In summer and fall the surface of the marsh is commonly free of standing water, but in winter and spring several centimeters of water may stand on the surface. About 2 meters of peat and organic-rich aquatic sediments lie below the marsh surface, and record a rise in relative sea level during the past 2,000 years. Seeds, pollen, and diatoms in a clay sediment at the base of the marsh indicate that the site was a freshwater bog or swamp about 1900 years ago; similar assemblages of fossils in the overlying organic sediment indicate a stable environment of fresh to possibly slightly brackish water until about 1000 years ago. Scarce diatoms and foraminifera with brackish to marine salinity preferences in the gyttja were probably washed or blown to the site. The marine fossils suggest that the site was only slightly above the highest tides. Peat that overlies the gyttja is dominated by fossil assemblages characteristic of brackish and saltwater tidal marshes. Within the peat, radiocarbon dated leaf bases of Triglochin maritima, a common plant of brackish and saltwater tidal marshes in Washington, show that tidal marine water inundated the site more frequently by 700 to 900 years ago. These findings show that the elevation of this site either stayed the same or subsided slightly 1000 years.”

Early History of Significant Observations of the Seattle Fault Zone

On Restoration Day (May 19), 1792, Vancouver landed at the point on Bainbridge Island now named for "that memorable event", and noted that it was a "projecting point of land, not formed by a low sandy spit, but rising abruptly in a low cliff about ten or twelve feet from the water side" (Vancouver, 1798).

James Kimball (1897) noted this "Restoration Point uplift" and called it part of a "post-Glacial re-elevation". He further commented that the "promontory of Restoration point is limited to that once insulated area. As a comparatively recent event, this area has been so far re-elevated as to connect its base with the main island (Bainbridge). This is strikingly indicated not only by a complete erosion of the sandstone series directly across the strike from the head of Blakely Harbor, and its replacement by alluvial material, but also by the raised beach which is a part of such replacement. This occurrence is well exhibited by extensive clam beds six to twelve feet above tide and two and one-half feet below the top of the marginal plateau, and uncovered in the gullies as far back as 100 feet inland...Considering the habitat of these bivalves, along with the uniformity in hight (sic) of the baseleveled margin, and its alluvial extension on opposite sides of the original islet, the measure of regional re-elevation locally indicated may be estimated as not less than 25 feet."

In 1941, Harvard Geography Professor Erwin Raisz published the most detailed physiographic map of the Pacific Northwest states (Raisz, 1941). He was struck by a very distinct lineation on the map that he considered to be a major fault cutting all the way across Washington from the Olympic Mountains to the Wallowa Mountains (hence the Olympic-Wallowa Lineament) and described its location in the Seattle area as running through Elliott Bay, the north end of Mercer Island, and along Issaquah Creek (Raisz, 1945). These are areas that we now consider part of the Seattle fault zone.

The 1949 Puget Sound earthquake caused Weikko Heiskanen (1951) to speculate that the earthquake and others in the region might be related to a gravity anomaly later to become known as the Seattle low. The force of gravity in Seattle is about 100 milligals (1/10,000 of the earth's total field) less than it is in Renton (Figure 4).

In 1965, Frank Danes, a physics professor at the University of Puget Sound, and 9 high school students used the previously existing gravity measurements and added many more new ones to develop the most detailed map of the Seattle low yet available. Danes and others (1965) combined their gravity anomaly map with aerial magnetometer mapping and geologic mapping and concluded that "the most active of them (faults) is a double fault striking approximately at azimuth 105 degrees through Hood Point, Bremerton, southern Seattle, and Renton."

Pat Rogers (1970) gathered more gravity and magnetic data and mapped the deformation at Alki Point and Restoration Point—he named this the Seattle-Bremerton fault and said that the evidence was "overwhelming" that it is a major fault.

In 1978, Howard Gower (1978; Gower and others, 1985) went back to Restoration Point and radiocarbon dated the fossils shells of the uplifted beach previously noted by

Kimball. The age of about 3,200-3,300 years demonstrated that this was indeed a geologically young uplift and therefore this must be an active fault.

Bob Bucknam and colleagues subsequently refined the age of the uplift and began making detailed maps of both uplift and subsidence related to faulting (Bucknam and others, 1992). Since then, with the recognition that the Seattle fault is active and highly dangerous, numerous studies have been undertaken on the fault, some of which you will hear about today.

References Cited

Bucknam, R. C.; Hemphill-Haley, Eileen; Leopold, E. B., 1992, Abrupt uplift within the past 1700 years at southern Puget Sound, Washington: Science, v. 258, no. 5088, p. 1611-1614.

Danes, Z. F.; Bonno, M.; Brau, J. E.; Gilham, W. D.; Hoffman, T. F.; Johansen, D.; Jones, M. H.; Malfait, Bruce; Masten, J.; Teague, G. O., 1965, Geophysical investigation of the southern Puget Sound area, Washington: Journal of Geophysical Research, v. 70, no. 22, p. 5573-5580.

Gower, H. D., 1978, Tectonic map of the Puget Sound region, Washington, showing locations of faults, principal folds, and large-scale Quaternary deformation: U.S. Geological Survey Open-File Report 78-426, 22 p., 1 plate, scale 1:250,000.

Gower, H. D.; Yount, J. C.; Crosson, R. S., 1985, Seismotectonic map of the Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1613, 1 sheet, scale 1:250,000, with 15 p. text.

Heiskanen, W. A., 1951, On Seattle earthquakes and gravity anomalies: Seismological Society of America Bulletin, v. 41, no. 4, p. 303-305.

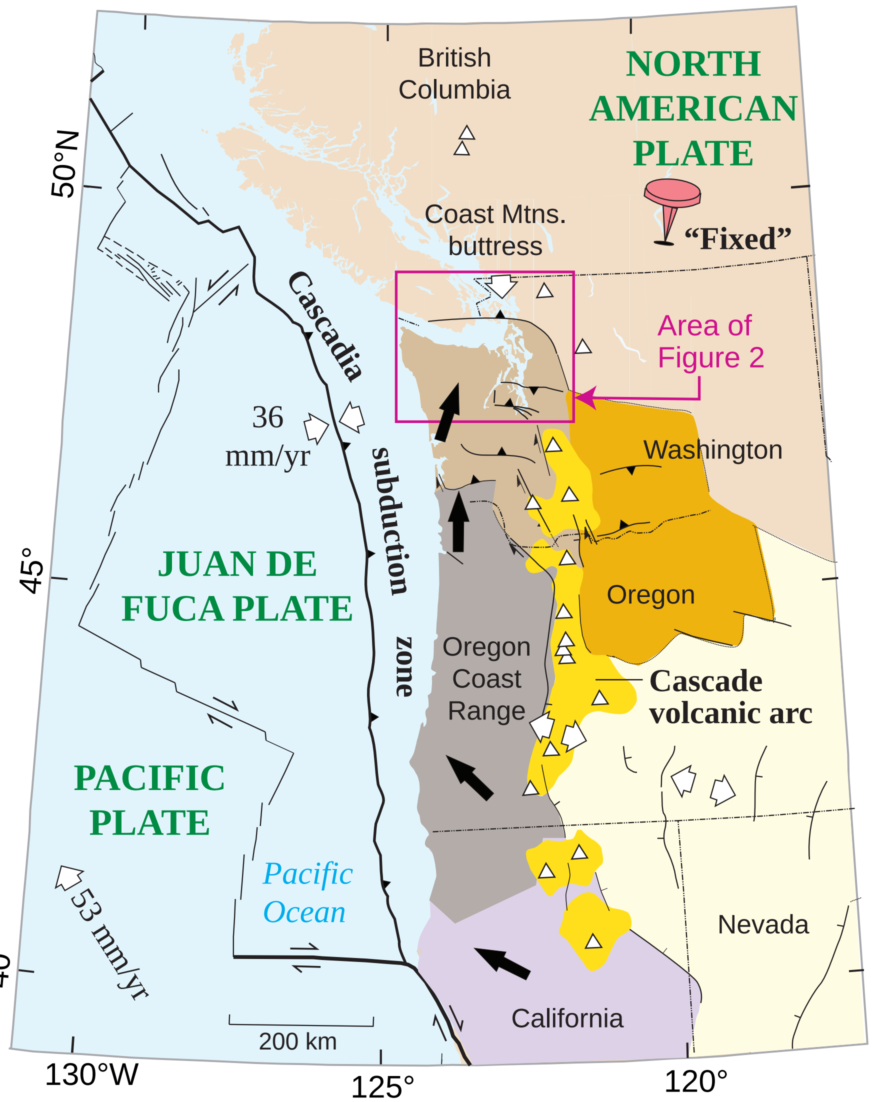
Kimball, J. P., 1897, Physiographic geology of the Puget Sound basin [in 2 parts]: American Geologist, v. 19, no. 4, p. 225-237 [part 1]; v. 19, no. 5, p. 304-322 [part 2].

Raisz, Erwin J., 1941, Landforms of the northwestern states: [Privately published by the author, Harvard University], 1 sheet, scale 1:1,500,000.

Raisz, Erwin J., 1945, The Olympic-Wallowa lineament: American Journal of Science, v. 243A [Daly volume], p. 479-485.

Rogers, W. P., 1970, A geological and geophysical study of the central Puget Sound lowland: University of Washington Doctor of Philosophy thesis, 123 p., 9 plates.

Vancouver, George, 1798, repr. 1992, A voyage of discovery to the north Pacific Ocean, and round the world; in which the coast of north-west American has been carefully examined and accurately surveyed--Undertaken by His Majesty's command, principally with a view to ascertain the existence of any navigable communication between the north Pacific and north Atlantic Oceans; and performed in the years 1790, 1791, 1792, 1793, 1794, and 1795: G. G. and J. Robinson



Thrust fault (teeth on upthrown block)

Fault

Fault (bar on downthrown side)

Transform fault (arrows show direction of relative movement)

Quaternary volcano

Figure 1. Tectonic setting of Cascadia subduction zone. Western Washington region (brown), between fixed North America and Oregon Coast Range, is undergoing transpression. This transpression creates folds and reverse faults across Puget Sound. Bold arrows indicate motions of tectonic blocks inferred from geologic and geodetic data. Modified from Wang and others (2003) and Wells and others (1998), courtesty of Brian Sherrod, University of Washington Department of Geological Sciences. Box shows area of Figure 2.

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Structural Framework of Northwestern Washington

Legend

- Quaternary deposits
- Sedimentary rocks (Paleogene to Neogene)
- Cascade Igneous rocks (Oligocene and younger)
- Crescent Formation and other Eocene volcanic rocks
- Basement rocks (pre-Tertiary)
- Quaternary volcano
- Structural basin
- Thrust fault (teeth on upthrown block), black where Holocene movement is known or suspected
- Fault, black where Holocene movement is known or suspected
- Fault (bar on downthrown side), black where Holocene movement is known or suspected
- Concealed fault, black where Holocene movement is known or suspected
- Transform fault (arrows show direction of relative movement), dashed where concealed

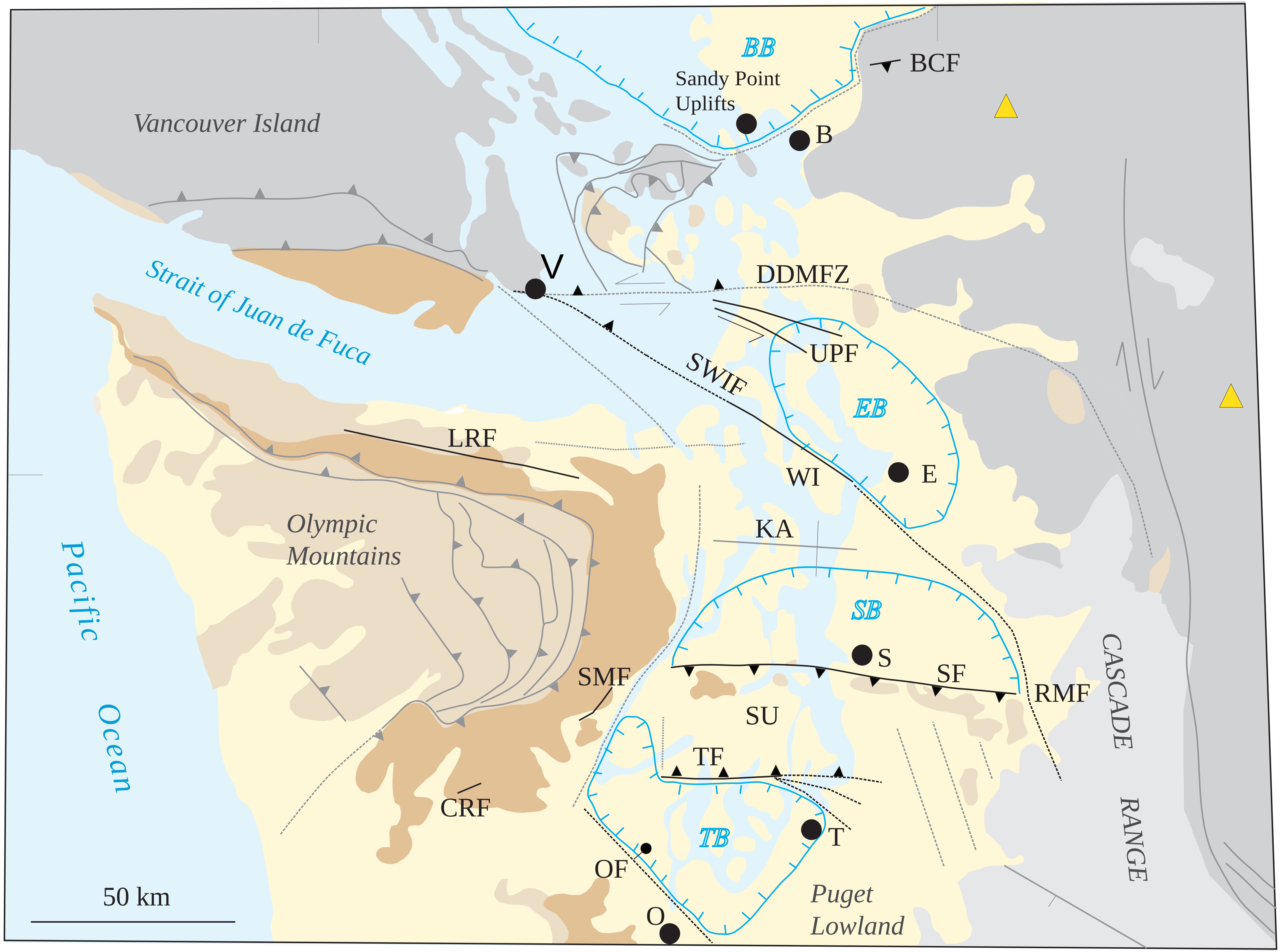

Figure 2: Schematic geologic map of northwestern Washington showing the Puget Lowland and flanking Cascade Mountains, Coast Range and Olympic Mountains. Abbreviations for cities are as follows: B, Bellingham; O, Olympia; S, Seattle; T, Tacoma; E, Everett; V, Victoria. Abbreviations for faults (heavy lines) and other geologic features are as follows: BB, Bellinham Basin; CRF, Canyon River fault; DDMFZ, Darrington-Devils Mountain fault zone, fault; EB, Everett Basin; KA, Kingston arch; LRF, Little River fault; OF Olympia fault; RMF, Rattlesnake Mountain fault, SB, Seattle basin; SF, Seattle fault; SMF Saddle Mountain faults; SU, Seattle uplift; SWIF, Southern Whidbey Island fault; TB, Tacoma basin; TF, Tacoma fault, UPF, Utsalady Point and Strawberry Point faults; CRF, Canyon River fault; BCF, Boulder Canyon fault. Geology from maps and compilations of Tabor and Cady (1978), Washington Public Power Supply System (1981), Gower and others (1985), Walsh and others (1987), Whetten and others (1988), Yount and Gower (1991), Tabor and others (1993), Dragovich and others (2002), and Johnson and others (2004).

Modified from figure courtesy of: Brian Sherrod, University of Washington, Dept. of Geological Sciences

Puget Sound Bluffs: The Where, Why, and When of Landslides Following the Holiday 1996/97 Storms

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From late December 1996 to early January 1997, a series of winter storms delivered snow, freezing rain, warm rain, and wind to the west coast, producing floods, snow and ice damage, and landslides from Washington to central California. Individual weather systems like these arrive almost annually; the consequences of their combination are somewhat more remarkable, but nonetheless occur every few years somewhere in the region. The region's long history of slope failure following heavy precipitation events is discussed in Tubbs (1974), Thorsen (1987), Miller (1991), and Evans (1994).

In the Pacific Northwest, the autumn months had above-normal precipitation, building high soil moisture and heavy snowpacks. In late December, a cold continental air mass sat over northwest Washington, while a series of warm wet storms began moving in from the Pacific Ocean. The incoming moisture first fell as snow north of the cold front and freezing rain south of it. In the southern Puget Sound region and the Columbia Gorge–Portland area, ice storms brought down trees and power lines, while snow accumulated from about Olympia northward, reaching depths of up to 3 ft in north King County.

Then on January 1 and 2, warm air, combined with locally heavy rains, quickly melted much of the low-elevation snow. This caused flooding in most streams in the Puget Lowland and in many of the rivers draining the Olympics and the Cascades.

The combination of pre-existing soil moisture, heavy rain, and rapid snowmelt brought soils to or near saturation. This had different effects, depending on the terrain. On the gentler drift plains, perching of water on tills and emergence of ground water from shallow aquifers caused lingering flooding of low-lying areas. But in the steep bluffs and ravines that border Puget Sound, Lake Washington, and the larger river valleys, lateral movement of ground water toward the free faces caused elevated pore-water pressures that triggered hundreds of landslides. A selection of these landslides are presented in this report.

Following a disaster declaration by President Clinton for most counties in Washington, the Federal Emergency Management Agency (FEMA) made funds available for identification, investigation, and remediation of the landslides, among other emergency needs. Division of Geology and Earth Resources geologists were asked by the Washington State Emergency Management Division to help the City of Seattle with damage assessment. Helicopter flights and several days of on-the-ground visits provided an overview of storm effects. The Division submitted oral and written reports to the City of Seattle and worked with other local geologists and landslide experts to examine new slides and slide-prone areas that threatened structures and transportation corridors. At the same time, private consultants assisted homeowners in repairing the damage and provided advice on slope stabilization techniques.

Figure 1. Map of the City of Seattle showing landslide critical areas (shading) and the location of some of the landslides that occurred during the December 1996–January 1997 storms (black dots). Compiled from City of Seattle information.

This article is a photographic essay that provides a geologic explanation for these landslides. In Seattle and to the north, the areas of Magnolia, West Seattle, and Whidbey Island were particularly hard hit (Figs. 1, 13). Captions for Figures 2–12 and 14–21 describe the setting of the landslides that

Figure 2. This house, which has been the subject of several news stories, is located on East Boston Terrace in the Capitol Hill area of Seattle. It hangs precariously over the headscarp of a reactivated old landslide. Careful construction engineering preserved the structure but not the front yard, leaving the driveway suspended. The failure of the front yard destroyed part of the road below. Note the exposed pipes, climbing ivy no longer rooted (below the tall window on the right), and tension cracks migrating into the neighbor's yard to the left in the photo. After this picture was taken, a retaining wall was built in front of the house (Seattle P-I, Feb. 6, 1997); a retaining wall behind the house was built during the original construction. This house is in the same drainage as, and a few hundred feet upslope of, a house destroyed by a landslide in 1942. That landslide killed one resident and seriously injured another.

Figure 3. This boating supply store on Harbor Avenue SW stands in a line of commercial and residential structures at the base of the bluff on the east side of Duwamish Head. Many debris flows were generated along the upper portions of the bluff as a result of the December storms. At this site, a fairly small debris flow (approx. 200 yd^3) hit the back of the building and split into two lobes, one flowing north around the outside of the building, the other pushing through and out the front of the building. (See also the cover photo.) The area without vegetation on the bluff behind the store is a layer of sand that failed when it became saturated by ground water perched on the underlying clay. An explanation of this common geologic situation is given in Figures 20 and 21.

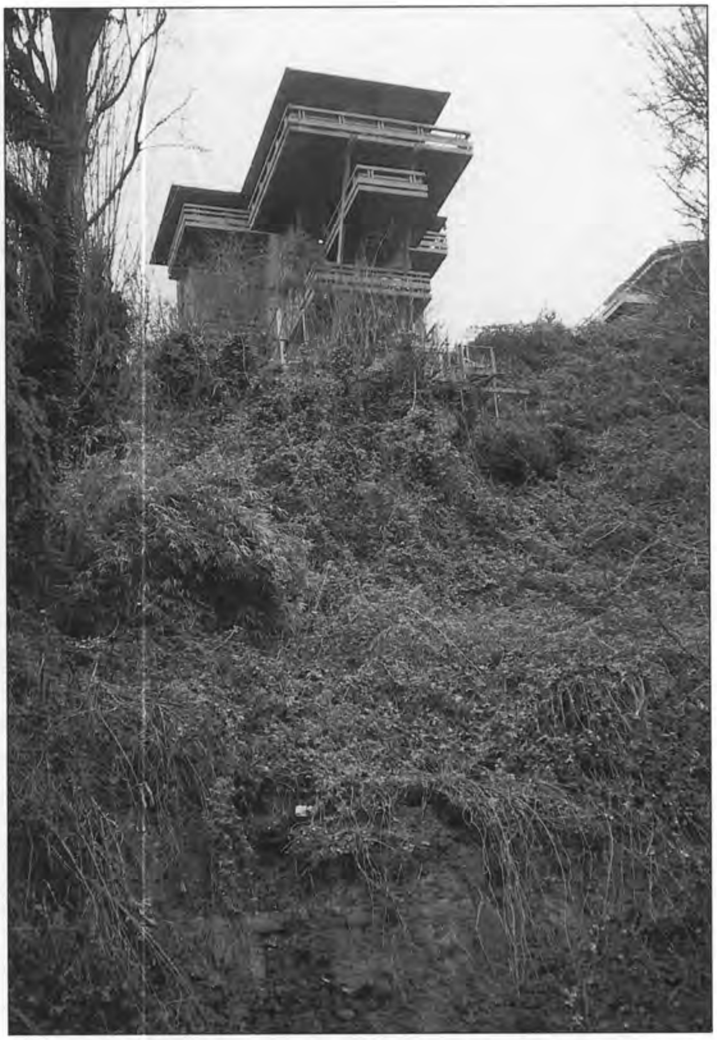


Figure 4. The "Anderson house" (known by the name of its designer) is cantilevered over the slope above Ferry Avenue SW, north of the bluff shown in Figure 3. Below it, and about 15 feet above the street, a small debris flow initiated in saturated material (here colluvium) covering clay deposits. Clay layers can be seen in the lower part of the photo. Slides like this commonly increase in size through headward erosion.

Figure 5. This view to the east shows three homes along Alki Avenue SW in West Seattle that were affected by a growing deep-seated landslide. The largest displacement occurred west (toward the viewer) of the low house on the left. Note the person (circled) standing on the down-dropped portion of the slide in front of the headscarp. Also visible is the displacement of the deck of the large house in the center. The tension crack delineating the headscarp continues through the deck area in the center house and into the backyard of the house to the right (south). The dark line extending from the house on the left is a tightline for drainage (see p. 29). Another segment of the headscarp is visible to the left of the tightline.

Figure 6. This photo shows one of the larger Seattle landslides along Perkins Lane on the southwest side of the Magnolia neighborhood. This is an area of continuing large-scale instability. Immediately following the February 1996 storms, a 1,500-yd^3 landslide (Harp and others, 1997) slid from the upper portion of the bluff into the back yard of the home on the right. Seattle engineers attempted to mitigate the problem by regrading and revegetating the upper slope. However, the February landslide was a shallow manifestation of a deep-seated rotational failure that formed, or might have already existed, in the sand, gravel, and silt deposits of the bluff at this site. This deep-seated slide was reactivated in December 1996, damaging at least five houses. These three are now uninhabitable. The white plastic sheeting on the slope was probably placed there in an attempt to prevent water from infiltrating the soil. This site is representative of the geologic conditions shown in Figures 20 and 21C.

Figure 7. This house in West Seattle (lower right), and a portion of the road that runs behind it, are built on fill, commonly failure-prone when saturated. Note the down-dropped (and previously patched) section of the road between the white signs. Tension cracks start to the left of this area and extend to the right, under the house. Fill material at the lower right corner of the house appears to be displaced. Also note the recent debris flows in the drainage below the road (lower left center of this photo). These may have been caused by excessive runoff onto colluvium and fill.

Figures 8A & B. *(this and facing photo)* This landslide at the intersection of Ferry Avenue SW and California Way SW, just to the north of the "Anderson house" (Fig. 4), illustrates geologic conditions that contribute to many Seattle landslides. Sand exposed in the upper bluff (barely visible in the upper left corner of B) has been sloughing onto the bench (visible in the upper portion of both photos) and then sliding along that bench to the lower bluff's edge (see Figs. 20, 21). These photos were taken several days after the initial landslide. Sand was still slowly creeping out over the clay toward the face of the slope. Despite the large amount of recent precipitation, much of the upper part of the sand unit remained well drained and dry. Roots exposed above the person (circled) in B are being stretched and torn because they are at the contact (dashed line) between the sand and the impermeable clay, from which ground water is seeping (more visible in A). The clay layers just above the fallen tree in A remain intact. This landslide blocked the intersection and forced its closure for more than a week.

Figures 9A & B. This shallow landslide, just north of the intersection of Ferry Avenue and California Way SW (Fig. 8), occurred following the storm of February 1996. Subsequent regrading and covering with plastic sheeting stabilized this portion of the slope enough to prevent shallow failure during the December 1996 storms. However, disruption of the pavement and sidewalk at the base of the slide (B) suggests that the slope may be moving along a deeper failure surface and may still (or again) be active. Notice the tilted street lamp. Although the plastic serves to prevent shallow failures, it does little to prevent a deep-seated failure, such as that shown in Figure 6. Just below California Way are several homes and businesses; at the time of the inspection, a sign indicated that more building is proposed. In A, snow, more than a week old, is still lying at the base of the plastic.

Figure 10. This view to the west over the Magnolia Bridge, a major artery into downtown Seattle, shows the landslide that forced the closure of the bridge and the "red-tagging" (condemning or declaring uninhabitable) of at least five homes along the headscarp of the slide. This slide occurred after the rains had ceased. Notice the displaced bridge trusses, the debris on the house at the base of the slope, and the broken water main just below the fallen truss and above the house.

Figure 11. The owners of the house under construction in the center of this photo recognized the potential for instability at the site. The "shotcrete" (concrete sprayed on the slope) on the face of the slope was intended to protect the sandy upper part of the slope from surface erosion, but failed, probably due to excessive hydrostatic pressure. The shotcrete seems to hang like a curtain over the bluff face, with the left portion having fallen away.

Figure 12. This slide, one of many that occurred along a stretch of railroad tracks north of Carkeek Park, lies within an older, larger slide scar. Past slides along these tracks have temporarily halted train traffic many times. Such slides have knocked railroad cars into Puget Sound, at times resulting in injuries or hazardous spills. Trip wires are strung just above the retaining wall along the tracks. An interrupted circuit signals when (but not precisely where) landslides occur. Figures 21 through 26 illustrate the different mechanisms responsible for landsliding along this stretch of bluff. Development at the top of the bluff can contribute to and is affected by the slides. Coastline modifications such as the bulkhead (built in the 1890s to support the railroad bed) also affect slope and near-shore processes. The bulkhead does not prevent landslides, but does control the rate and nature of redistribution of slide debris in the near-shore zone. Material dumped into the Sound by railroad crews cleaning the tracks is rapidly redistributed out of the narrow and steep intertidal zone and offshore by wave energy reflected off the bulkhead.

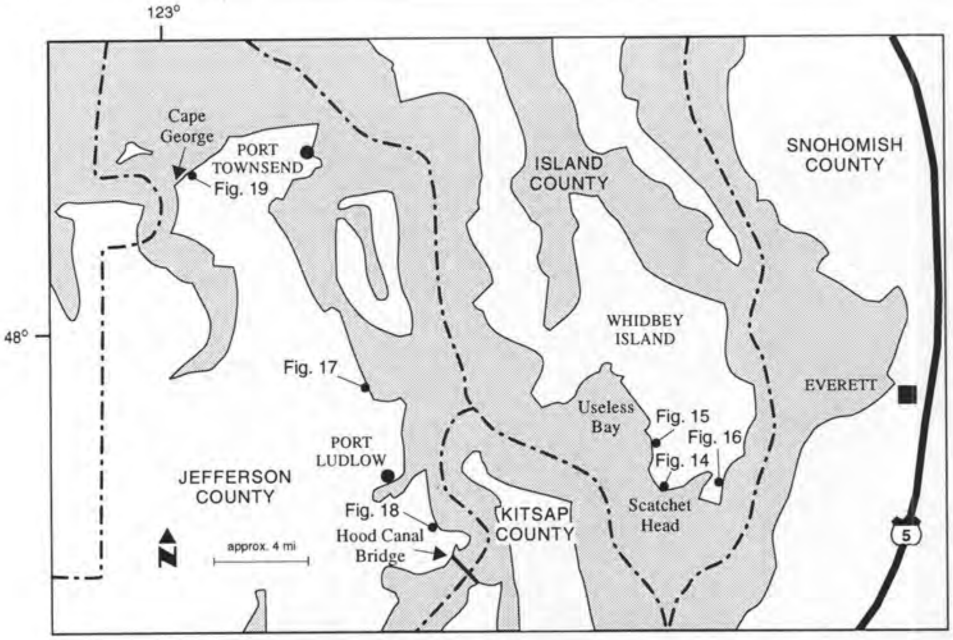


Figure 13. Locations of landslide damage shown in Figures 14 through 19.

Figure 14. At Scatchet Head at the southern end of Whidbey Island, mudflows temporarily block access to these beach-level homes during wet winters. The upper bluff is porous glacial outwash sand that dries out in summer. The silt that forms the lower bluff (below dashed line) and perches ground water is damp and green year round. The top of the silt is approximately at the position of the dashed line. The scarp in the background and the partially forested bench are characteristic of such slide areas where percolating ground water is perched above the less permeable silts. The sands are weaker than the silts and slide readily when saturated. Similar situations are present north of Carkeek Park and in the Golden Gardens area of Seattle, among other places. (See Figs. 20, 21.)

Figure 15. Slide activity such as this in the Useless Bay area of Whidbey Island can cause periodic retreat of the bluff edge by as much as 20 feet or so in seconds. During this recent slide, a portion of the fence in front of the large house was lost. Such episodes commonly are preceded and followed by decades of little erosion, making estimates of average bluff retreat rates potentially meaningless. In this location there are multiple impermeable silt layers that perch water, in contrast to conditions like those at Scatchet Head (Fig. 14), where water is concentrated above one impermeable "perching" layer. Slides here can be triggered by an abundance of water (as in the December/January storms) or by wave erosion at the base of the bluff. A rainstorm may simply be the "last straw". In many locations around the sound, water from winter rains is accumulated inland of bluffs and may cause landslides to occur months later as it slowly migrates toward the bluff. In the mid-1970s in the Golden Gardens area of Seattle, slides occurred well into summer after a series of exceptionally wet winters.

Figure 16. Several beach homes on the east side of southern Whidbey Island had close calls from debris avalanches. Debris avalanche tracks and deposits here will soon be colonized by alders. Stripes or patches of alder trees that are all of the same age can indicate areas where slide activity occurred in the past; the age of the trees indicates approximately when the slide(s) occurred. In the 1950s and '60s, many beach-level developments like this were constructed on fill behind bulkheads. Material for the fill was commonly hosed off the slopes or bulldozed from the bluffs. This may have contributed to continuing slope instability by destabilizing the toe of the slope.

Figure 17. Fortunately, homes here were built with adequate setback— for these failures. The depth of a failure surface can influence the rate of retreat of the edge of the upland surface. In this slide west of Port Townsend, shallow debris avalanching (far left) has caused no significant edge retreat yet. The mid-bluff bench on the right indicates a relatively deep-seated slide of upper-bluff sediments only. (See Fig. 21B.) The surface of failure for the middle slide is even deeper, "daylighting" at (or below?) beach level (Fig. 21B, C), and has caused the most retreat. At many sites along the coastal bluffs, sedimentary units are not laterally continuous, and conditions can be quite different over a distance of 100 feet or less.

Figure 18. This shoreline home between the Hood Canal Bridge and Port Ludlow lost its front yard during the December/January rainstorms and snowmelt. Bedrock exposed on the beach below the bluff shown in this photo was resistant to wave erosion. However, the glacially polished bedrock perched ground water in the gravelly sand above the steeply sloping contact here. Runoff from rapid snowmelt was apparently funneled down the driveway from upslope development. The area to the left of this landslide (out of view) was probably buttressed by a large maple stump kept alive by sprouts. (The area still farther left also failed.) Glacially compacted silts or bedrock form a barrier to roots and ground water. Where this condition exists in the Puget Lowland, shallow debris avalanches can be common. The overlying permeable saturated soil cannot be anchored to the substrate by the weak toehold of the roots of trees and other vegetation.

Figures 19A & B. Continuing slide activity has made this home near Cape George in Jefferson County uninhabitable. At this site, the perching layer is a small area of ancient lakebed silt that lies beneath the house at about mid-bluff level, now covered with grass dropped from the back lawn. This part of the bluff remains green year round. Note the old slide mass at beach level (lower left), now covered by alder trees that are all of approximately the same age (here, perhaps 25 years old). Also note the arcuate line of boulders seaward of these trees. Such a pattern of boulders, which are commonly accompanied by steeply tilted silt and clay beds, can indicate an old slide surface at or below beach level. **B.** *(right)* This closeup shows recent slide debris on the bench, as well as the exposed septic tank (the white rectangle below the right side of the house and drainfield pipe in A); the tank has since fallen to the beach. Poorly located septic systems often contribute to slope instability. The dark strata at the upper part of the bluff are gravels and are not saturated here. It is possible that drainfield effluent percolated downward and bluffward to destabilize this slope or that deeper ground water caused the problem at this location. Wave erosion has likely been a contributor at this site as well. Trying to maximize a view by building close to the bluff line can be a costly and potentially hazardous mistake.

occurred in these areas. We also discuss what area residents can do to avoid such serious consequences and prepare for the effects of future rains and snows. At the end of the article is a list of helpful books and articles.

GEOLOGY BY EXAMPLES

Seattle Area Stratigraphy

Several different mechanisms contribute to the instability of coastal bluffs in the Puget Sound region. The resulting landslides can range in size from small, shallow soil slips to large, deep-seated rotational slump-earthflows. Most of those resulting from the February 1996 and holiday 1996/97 storms were some variation of the ones shown earlier in this article and described in the following text and accompanying sketches.

The typical undisturbed stratigraphy in the central Puget Sound area consists (from the top down) of a thin soil layer overlying relatively impermeable till (hard pan), permeable sands, and/or nearly impermeable clays and silts (Fig. 20). However, in many areas, the stratigraphy can be more complicated (Figs. 15, 17).

Throughout much of the Seattle area, till of Vashon age (approximately 13,000 years old), approaching thicknesses of up to 30 ft, forms a relatively strong and resistant cap that covers much of the highlands and protects softer underlying layers from erosion. Although till is in many places impermeable to ground water, fractures and gullying in the till surface allow percolation into the lower sedimentary layers. Till commonly overlies advance outwash deposits locally known as the Esperance Sand.

The Esperance Sand was deposited by streams issuing from the ice sheet while it was located some distance to the north. It is highly permeable (well-drained) and poorly consolidated. In typical Esperance Sand deposits, the upper part may be dry, even in winter, whereas ground water flows rapidly through its basal zone, where the water is perched on underlying clays and silts. Water saturation builds pore pressure, which in turn reduces soil strength and allows the sand to mobilize and slide along the surface of the clay (Fig. 21). In some places, the sand is so poorly consolidated that it collapses on itself and flows like a fluid. Permeability within the Esperance Sand varies laterally and vertically, and ground water piping can occur along weak zones. Gullies form where piping intersects the surface.

The compact clays and silts underlying the Esperance Sand were deposited in a proglacial lake that existed before the ice advance into the Puget Sound area. The name "Lawton Clay" is applied to this thinly and parallel-bedded clay and silt unit. The Lawton Clay perches ground water, forming the slippery surface on which the Esperance Sand can slide (Fig. 21B, C). The clay unit, generally more competent, remains in place, with only minimal seasonal retreat. With each passing winter, the sand portion of the bluff retreats at a faster rate than the clay and the resulting landform is the characteristic stepped or benched bluff (Fig. 21C). Deep-seated failures can occur where a failure surface extends into the clay unit. (For discussions of these and other relations between ground water and landslides, see Tubbs, 1974; Dunne and Leopold, 1978; Freeze and Cherry, 1979; Thorsen, 1987; and Evans, 1994.)

Any of these Pleistocene units may overlie knobs and fault blocks of impermeable Tertiary bedrock. The upper surfaces of these bedrock protrusions may also perch water and act as glide planes for landslides (Fig. 18).

Processes along the Burlington Northern–Santa Fe (BNSF) Railroad North of Carkeek Park

The landslides that occurred along the BNSF Railroad tracks (Figs. 12–26) provide excellent examples of the different types of failures and the different slope retreat rates discussed above and seen throughout the storm-damaged areas (Fig. 21). It is important to understand and anticipate these landslides, as they have been and will continue to be responsible for damage along the Puget Sound shoreline.

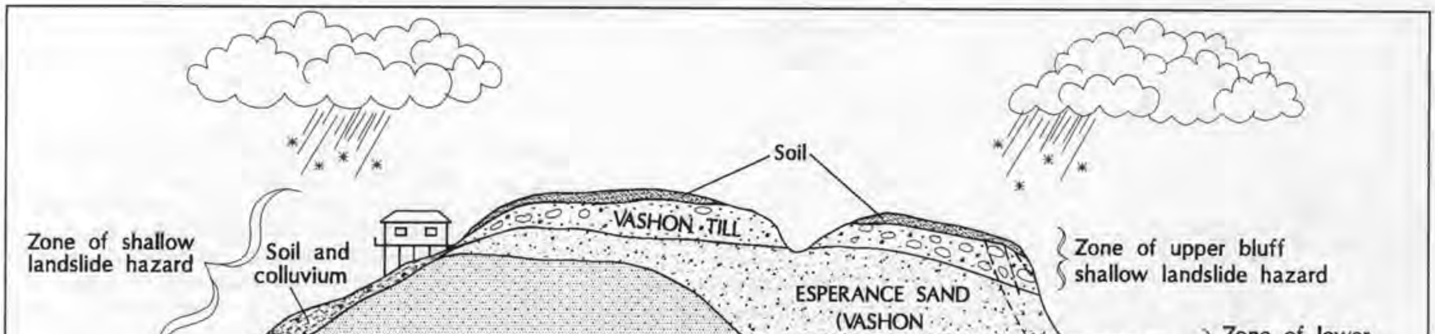
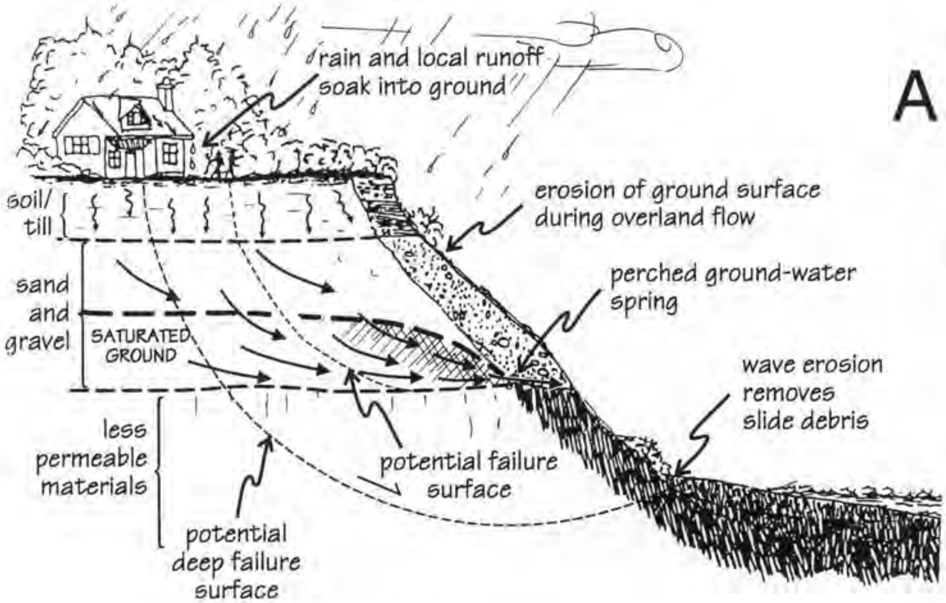
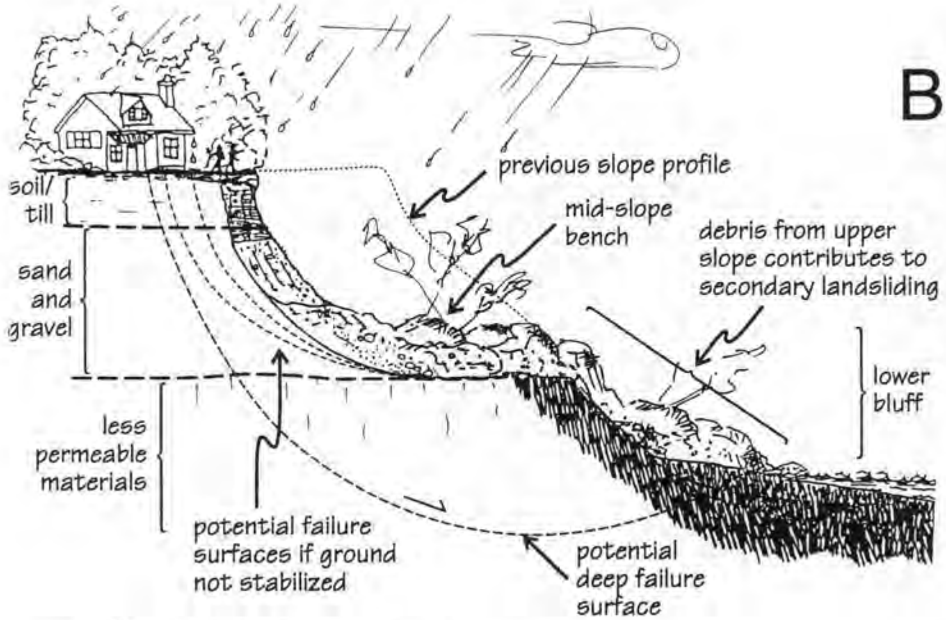


Figure 20. This is an idealized cross section of the characteristic stratigraphy in the Seattle area that is responsible for landsliding. These units are not necessarily laterally continuous over long distances, and they can be more complex, with several water-perching layers. However, the general geologic and hydrologic principles are similar. The Esperance Sand and Lawton Clay are unit names restricted to the Seattle area, but similar sequences are present elsewhere in the Puget Lowland. (Adapted from Tubbs, 1974.)



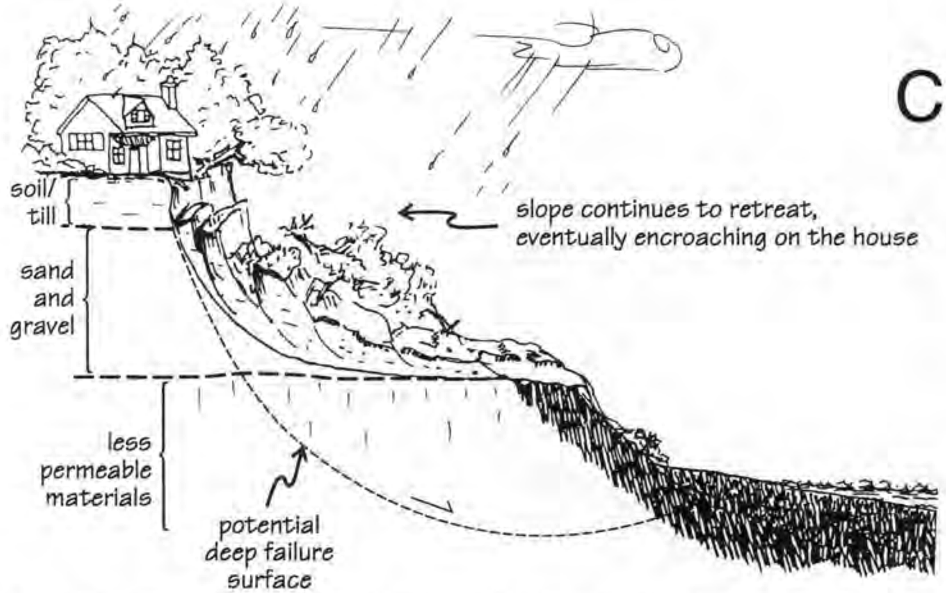
A

At the beginning of an idealized cycle, the bluff has a uniform slope. Water infiltrates the surface soils and perches above the relatively impermeable materials at the base of this sandy sequence. Saturation creates pore-water pressures that reduce the effective strength of these materials.



B

Runoff and precipitation introduced by the sources shown in **A** have infiltrated and weakened the sediments, causing failure of the unconsolidated upper sand unit. Once mobilized, the sand moves (sometimes episodically, sometimes continuously) along the contact with the underlying less permeable unit on the mid-slope bench, often cascading as a secondary landslide off the bluff formed by the lower unit. This migration of material across the bench decreases the buttressing of the upper bluff. Failure surfaces can be deep (those that project into the lower, less permeable materials) as well as shallow.



C

Benched bluff retreat continues. Movement of slide debris toward the lower bluff further destabilizes the upper bluff, causing continued sloughing onto the bench. Either failure of the upper bluff onto the bench or failure of the slide debris off the lower bluff can trigger a cycle of movement. Movement along a deep-seated surface can reset this sequence of events.

Figure 21. This sequence of sketches shows the idealized, potentially cyclical process by which bluffs in the northern Puget Sound area are forming and retreating.

Figure 22. This view to the south shows a few of the many recent debris flows along the section of the railroad tracks north of Carkeek Park (Fig. 1). Exposed in the lower half of the bluff face are dense water-perching clays and clayey silts, which have not moved at this location. These maintain a steep bluff face that is often wet due to ground water seeping from the contact with the overlying sand. The weaker overlying sands have a much gentler slope. In the upper middle part of the photo, one can see the headscarps of older, vegetated landslides that have progressed farther back into the highlands. These features illustrate the continuing differential retreat rates of the upper and lower portions of the bluff (see Fig. 21C). The home in the left center of the photo sits in one of these landslide scars. This view shows the bulkhead that protects the toe of the slope from wave erosion (discussed in Fig. 12).

Figure 23. This view to the south (and Figs. 24–26) of the bluff along the railroad tracks (60–80 ft below) shows a fresh exposure in the Esperance Sand (Fig. 20). Shallow failures in this unit created a sand slurry (Fig. 25) that flowed onto the bench in the lower right of the photo. This location is just south of the area shown in Figure 22.

Figure 24. These tilted trees are those shown on the right in Figure 23. They indicate back rotation of the bench along a larger, deeper seated failure surface. Tension cracks in the sand surrounding the base of the trees (Fig. 25) show that this movement took place after the sand slurry was deposited.

Figure 25. This closeup of the sand slurry deposit (Fig. 24) shows that sand flowed onto the bench from left to right in the photo (now uphill). Partial drying of the sand and subsequent rotation of the bench resulted in the formation of these tension cracks parallel to the back edge of the bench (upper left of photo). Note footprints for scale.

Figure 26. In this view to the north, the large tension crack near the outer edge of the bench indicates active movement. The geologist in the foreground is standing in the crack; the other is at the north end of the crack. The railroad tracks are about 60 ft below and to the left.

WHAT CAN BE DONE TO IDENTIFY AND AVERT POTENTIAL LANDSLIDES?

As the Growth Management Act and its enabling regulations state, avoidance is the safest approach when it comes to land-use practices in areas of unstable slopes. However, in many places urban growth has already encroached on these slopes. If you live at the edge of a bluff or in an area that has experienced landslides in the past, there are some things you can do to reduce the rate of bluff retreat and improve the stability of the slope with respect to shallow failures and surface erosion. Deep-seated failures are more difficult to control, but it is clearly beneficial to reduce infiltration and surface runoff from roofs and driveways and to fix clogged or leaking storm drains.

Listed at the end of this article are several publications that provide useful information on amelioration of unstable bluff slopes. Figures 27 through 29 show examples of stabilization efforts in the Seattle area, not all of which were successful. The following lists offer landslide identification criteria and prevention and mitigation techniques.

Identification of Landslide Hazard Areas

These are some characteristics that may be indicative of a landslide hazard area:

- Active bluff retreat – Continuing sloughing or calving of bluff sediments, resulting in a vertical or steep bluff face with little to no vegetation.
- Pre-existing landslide – Landslide debris within an arcuate head scarp.
- Tension cracks – Ground fractures along and/or near the edge of the top of a bluff or ravine.
- Structural damage – Settling and cracking of building foundations near edge of a bluff or ravine; also separation of steps or porch from the main structure.
- Toppling, bowed, or jackstrawed trees – Disruption of the ground surface by active movement causes trees to lean and/or fall in different directions or to grow in a curve instead of straight.

Figure 27. Shotcrete, shown here, has been used (not always successfully) to prevent surface erosion and headward migration of the bluff edge. The drainage must be directed away from the base of the cover so that the shotcrete will not be undermined by surface erosion. The drainage must also be continually maintained in order to be effective. In this location, there is extensive erosion occurring at the base of the shotcrete cover. If the material behind it is washed away, the shotcrete will fail, as seen in Figure 11.

Figure 28. These two apartment buildings in the Duwamish Head area of West Seattle, just south of the intersection of Ferry Avenue and California Way SW shown in Figures 4 and 8, are built at the head of a small ravine on unconsolidated sand deposits. The February 1996 storm resulted in a shallow debris slide in that ravine. As a result, drainage from all the roofs and balconies is now collected in nonperforated pipes and directed away from the steep slope. This is called tightlining, and it is also effective along beach bluffs. There were no slides directly below these buildings as a result of the December/January storms.

- Gullying and surface erosion – Dissection of the bluff edge by natural drainage or discharge from pipes, culverts, and ditches.
- Springs – Mid-slope ground-water seepage from the bluff face; particularly noteworthy are increases in flow.

Safeguarding Against Landslide Hazards

The following are some measures that can be taken to mitigate or avoid landslide hazards:

- Use setbacks – Expect natural slope processes to continue, and provide adequate construction setback for structures in landslide hazard areas.
- Reduce surface erosion – Keep drains and culverts clear. Avoid discharge onto the slope—direct surface water/runoff (especially from impermeable surfaces) to the base of the slope in nonperforated pipe. This is called tightlining.
- Reduce ponding and infiltration – Limit opportunities for water to pond on the surface by draining or regrading. Consider connecting to city sewers instead of installing or replacing septic systems.
- Maintain and improve vegetation – Trees and shrubs provide root strength to hold the soil in place and help dewater the slope. If they are removed, root strength will be gone within 2 to 12 years and will not be easily restored.
- Protect bluff from surface erosion – Apply erosion mats, plastic sheeting, or other erosion-control material where vegetation will not take hold.

DISCUSSION

The Puget Lowland bluffs have experienced landslides for thousands of years. Bluff retreat is a normal process. Some of the small-scale, but still potentially destructive, retreat occurs

Figure 29. A resourceful homeowner in the area north of Carkeek Park, along the BNSF Railroad, used metal roofing material to cover the upper portion of the slope below his house. However, the lower part of the slope failed as a debris flow onto the railroad tracks during the December/January storms, probably because energy from runoff water was not properly dissipated, thereby causing erosion below the roofing material. Subsequently the lower slope was covered with strips from large rolls of plastic sheeting. Placing the plastic required the use of technical climbing equipment by skilled workers seen here to the left of the sheeting.

as continuous raveling and sloughing. The larger landslides tend to be more episodic. When heavy winter precipitation is added to bluff sediments, unstable parts of the slope tend to fail. (See, for example, Thorsen, 1987.) The frequency over time and space of these failures increases during and after particularly heavy precipitation. In some places, human activities (such as poor construction practices) have exacerbated the rate of bluff retreat by landsliding.

By learning to recognize old landslides and studying the effects of construction and landscaping near and on slide-prone areas, we may be able to plan for the slides to come.

In 1990, the legislature passed the Growth Management Act (amended 1991) requiring the enactment of local ordinances that govern the development of unstable coastal bluff areas. RCW 36.70A.170 requires that "on or before September 1, 1991, each county, and each city, shall designate where appropriate:...critical areas". These include "geologically hazardous areas", which are areas that "because of their susceptibility to erosion, sliding, earthquake, or other geological events, are not suited to the siting of commercial, residential, or industrial development consistent with public health or safety concerns" (RCW 36.70A.030).

The regulations (365-190-080 WAC) state that:

"geologically hazardous areas...pose a threat to the health and safety of citizens when incompatible commercial, residential or industrial development is sited in areas of significant hazard. Some geological hazards can be reduced or mitigated by engineering, design, or modified construction practices so that risks to health and safety are acceptable. When technology cannot reduce risks to acceptable levels, building in geologically hazardous areas is best avoided. This distinction should be considered by counties and cities that do not now classify geological hazards as they develop their classification scheme.

(b) Counties and cities should classify geologically hazardous area as either:

(i) known or suspected risk.

(ii) no risk.

(iii) risk unknown – data are not available to determine the presence or absence of a geological hazard."

Ordinances identifying geologically hazardous areas are now in place in most cities and counties of Washington. Of the recent slides in Seattle, none occurred at a site developed solely under the new ordinances, suggesting that they may be providing a safeguard against slide hazards. Nevertheless, Seattle declared a 90-day moratorium on development in landslide hazard areas to assess the adequacy of the steep slopes ordinance. For information on designated steep-slope hazard areas in your community, contact your local planning agency or building department.

If you are uncertain about the conditions surrounding or underlying your home or property, consult the listed references or any of the many others available at your library or local jurisdictional offices. If you are still unsure, seek geotechnical advice from a professional geologist or geotechnical engineer.

ACKNOWLEDGMENTS

We acknowledge funding support for this project through Linda Burton-Ramsey from the Washington State Emergency Management Division. Assistance in the office and in the field was generously offered by Gerald W. Thorsen, consulting geologist; John Peterson and T. J. McDonald of the City of Seattle; Newell Lee, Jr., (helicopter pilot) of the Washington Department of Transportation; Tom Badger, local geologist; and Steve Palmer, Washington Division of Geology and Earth Resources. Sketches of slope profiles in Figure 21 were drawn by Leonard Palmer. Jari Roloff and Keith Ikerd provided graphic support.

REFERENCES AND FURTHER READING

Best, M. E.; Steele, C. L., [Feb. 14,] 1997, Hazard mitigation early implementation strategies for severe winter storms, flooding, mud and landslides, DR-1159-Washington: Federal Emergency Management Agency, Region 10, and Washington Emergency Management Division, 22 p.

(Describes results of damage assessments conducted from Jan. 7–17; mentions forthcoming reports and meetings.)

Dunne, Thomas; Leopold, L. B., 1978, Water in environmental planning: W. H. Freeman & Co. [San Francisco], 818 p.

Evans, Stephen, 1994, Draining Seattle—WPA landslide stabilization projects, 1935–1941: Washington Geology, v. 22, no. 4, p. 3-10.

Freeze, R. A.; Cherry, J. A., 1979, Groundwater: Prentice-Hall [Englewood Cliffs, N.J.], 604 p.

Galster, R. W., chairman, 1989, Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, 2 v.

Gray, D. H.; Leiser, A. J., 1989, Biotechnical slope protection and erosion control: Robert E. Krieger Publishing Company [Malabar, Fla.], 271 p.

Harp, E. L.; Chleborad, A. F.; Schuster, R. L.; Reid, M. E.; Wilson, R. C., 1997, Landslides and landslide hazards in Washington State due to the February 5–9, 1996 storm: U.S. Geological Survey administrative report, 29 p., 1 plate.

Kockelman, W. J., 1986, Some techniques for reducing landslide hazards: Bulletin of the Association of Engineering Geologists, v. 23, no. 1, p. 24-52.

(Discusses nonstructural hazard mitigation; written mostly for local governments.)

Menashe, Elliott, 1993, Vegetation management; A guide for Puget Sound bluff property owners: Washington Department of Ecology Shorelands and Coastal Zone Management Program Publication 93-31, 46 p.

Miller, D. J., 1991, Damage in King County from the storm of January 9, 1990: Washington Geology, v. 19, no. 1, p. 28-37.

Myers Biodynamics Inc., 1993, Slope stabilization and erosion control using vegetation—A manual of practice for coastal property owners: Washington Department of Ecology Shorelands and Coastal Zone Management Program, Publication No. 93-30, 42 p.

Myers Biodynamics Inc., 1995, Surface water and groundwater on coastal bluffs—A guide for Puget Sound property owners: Washington Department of Ecology Shorelands and Coastal Zone Management Program, Publication No. 95-107, 64 p.

Nuhfer, E. B.; Proctor, R. J.; Moser, P. H., 1993, The citizens' guide to geologic hazards: American Institute of Professional Geologists, 134 p.

Oregon State Board of Geologist Examiners, 1992, Guidelines for preparing engineering geologic reports in Oregon: Oregon State Board of Geologist Examiners, 8 p.

Scullin, C. M., 1983, Excavation and grading, code administration, inspection, and enforcement: Prentice-Hall, Inc., 403 p.

(Although focused on Orange County, Calif., this book contains much information relevant to the Pacific Northwest. It is available from the International Conference of Building Officials, 5360 Workman Mill Rd., Whittier, CA 90601-2298.)

Slosson, J. E.; Larson, R. A., 1995, Slope failures in southern California—Rainfall threshold, prediction, and human causes: Environmental & Engineering Geoscience, v. 1, no. 4, p. 393-401.

Thorsen, G. W., 1987, Soil bluffs + rain = slide hazards: Washington Geologic Newsletter, v. 15, no. 3, p. 3-11.

(Describes typical bluff retreat and slides in the Puget Lowland.)

Tubbs, D. W., 1974, Landslides in Seattle: Washington Division of Geology and Earth Resources Information Circular 52, 15 p.

(Discusses 1972 landslides and includes a map showing slide locations and the "hazardous zone".)

See also: URL: www.geoengineers.com/ic52.htm

Turner, A. K.; Schuster, R. L., editors, 1996, Landslides—Investigation and mitigation: National Research Council Transportation Research Board Special Report 247, 657 p.

Washington Department of Ecology, 1978–1980, Coastal zone atlas of Washington: Washington Department of Ecology, 12 v.

(These volumes contain colored maps that show landslides and relative slope stability.)

Washington Emergency Management, Oregon Emergency Management, Federal Emergency Management Agency Region 10, [undated], Homeowner's landslide guide for hillside flooding, debris flows, erosion, and landslide control: Washington Emergency Management, Oregon Emergency Management, Federal Emergency Management Agency Region 10, unpaginated pamphlet.

(Photocopies available through the Washington Division of Geology and Earth Resources.)

Wold, R. L., Jr.; Jochim, C. L., 1989, Landslide loss reduction—A guide for state and local government planning: Colorado Geological Survey Department of Natural Resources Special Publication 33, 50 p.

(Also available as Federal Emergency Management Agency Earthquake Hazards Reduction Series 52.) ■

Photo Credits

Wendy Gerstel – 3–5, 9B, 23–29

Leonard Palmer – 19B

Hugh Shipman – 2, 6, 7, 10–12, 22

Gerald W. Thorsen – 14–19A

Tim Walsh – 8A, 8B, 9A

Note added in proof: As this issue was going to press, another rainstorm hit the Puget Sound area and caused at least 30 more landslides.

Burke Museum Closes to Prepare New Exhibits

The Burke Museum will close its doors April 28 to renovate and install exhibits. It will reopen this coming November. "Life and times of Washington State—A trek through geologic time" and "Pacific voices—Worlds within our community" are two long-term exhibits being prepared for November.

Errata

- The price for Open File Report 96-6, Preliminary bibliography and index of the geology and mineral resources of Washington, 1991–1995, (announced in the previous issue) should indicate $1.03 tax.
- The cover photo and the photos on p. 22 in the previous issue were taken by Tim Walsh of our staff.
- In the previous issue, the article "A Field Guide to Washington State Achaeology" contains at the end of the last sentence "and also briefly discusses Ringold Formation correlatives throughout the region, setting the stage for future regional sedimentologic interpretations." This phrase wandered in from somewhere else and does not actually belong with the field guide.

N A T U R A L R E S O U R C E S

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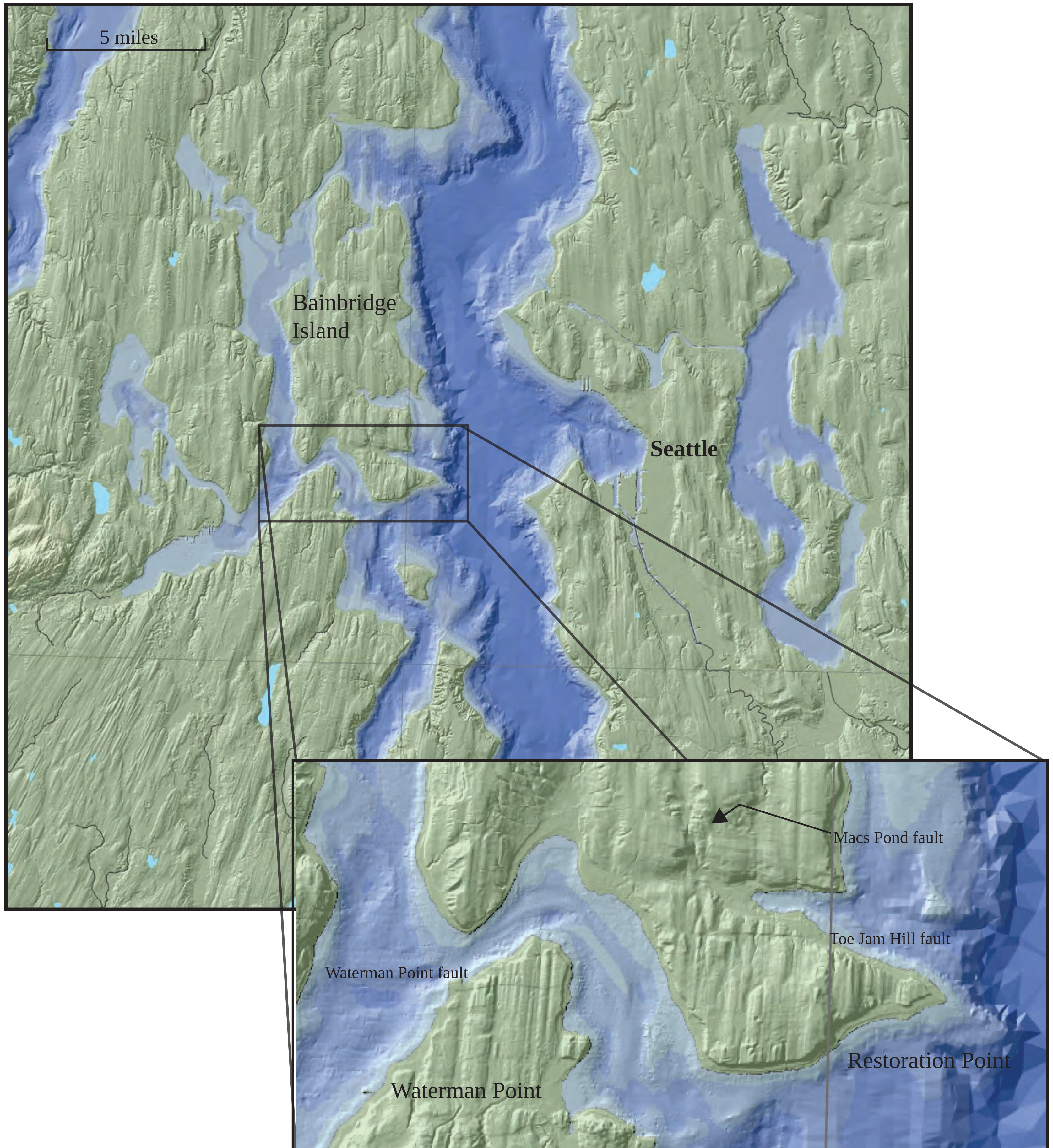
INSIDE THIS ISSUE

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands
Kaleen Cottingham - Supervisor

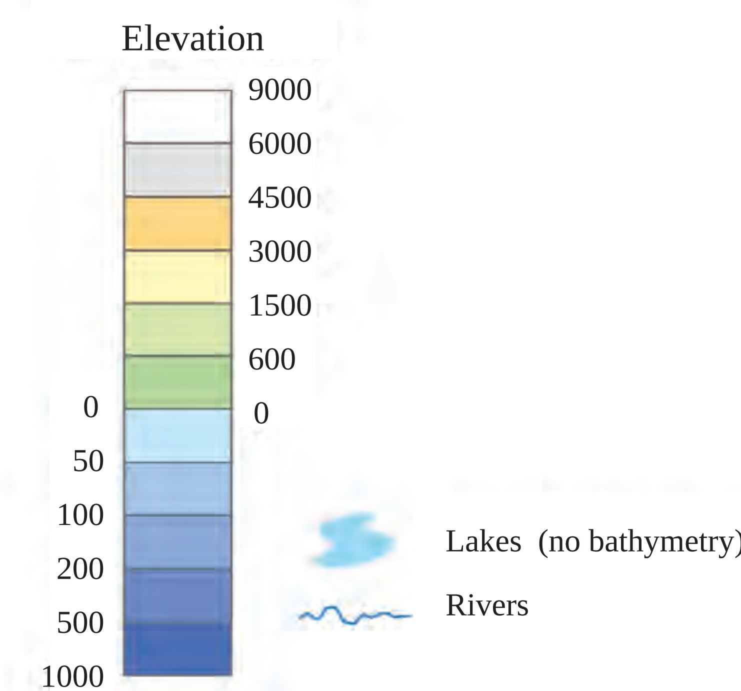


Combined Bathymetry and Topography of the Puget Sound,Washington State

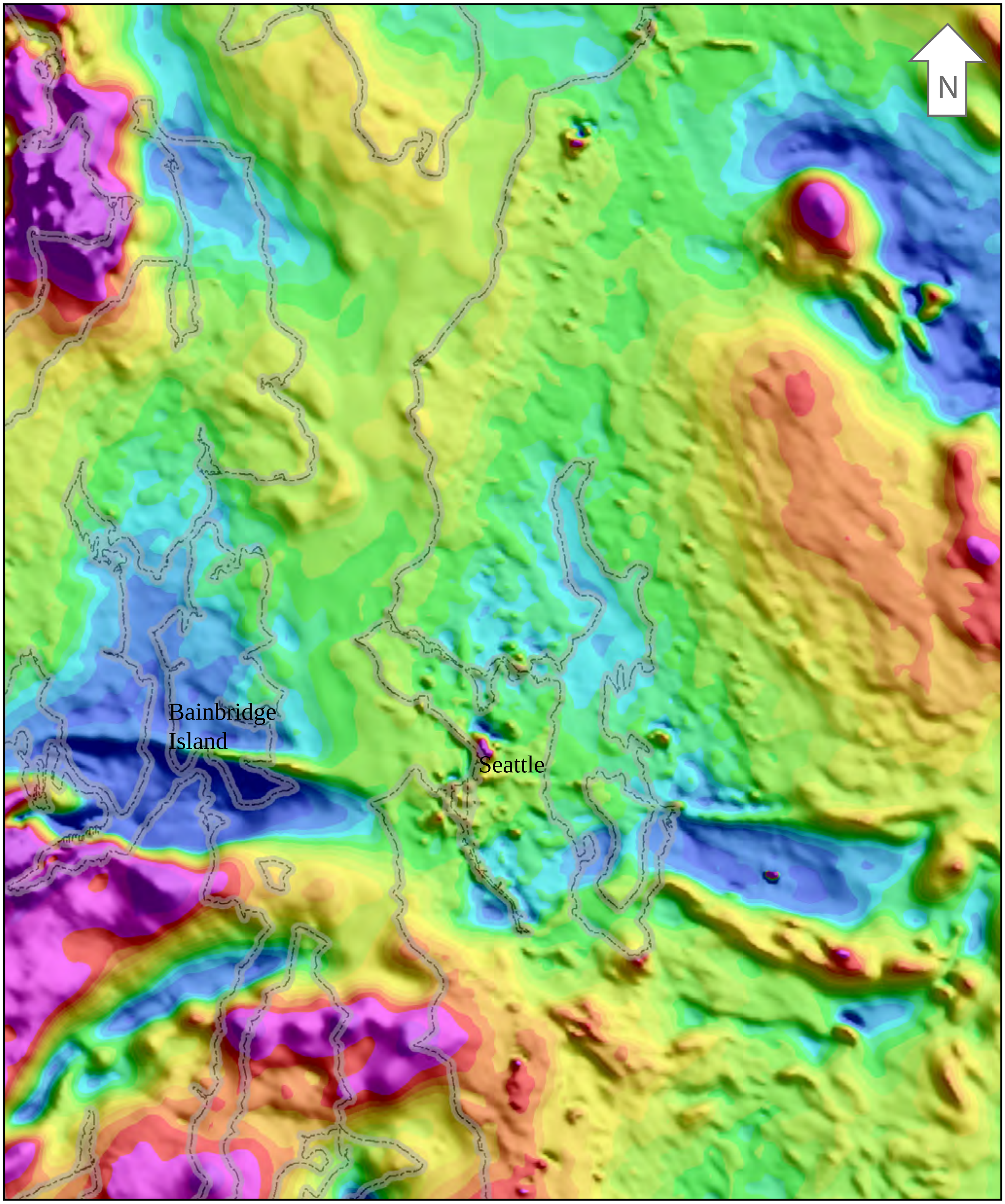
modifield from Finlayson (2005)

This map is a composite image of LiDAR baythymetry and topography from multiple sources of the best data available. The advantage of LiDAR over traditional aerial survey methods is accuracy, due to its ability to survey the actual ground surface through the overlying forest canopy. The application of LiDAR over recent years in the state of Washington has led to the discoveries of numerous active fault scarps, that may otherwise have gone undetected due to heavy forest cover.

The inset map (lower left) of Restoration Point on Bainbridge Island and Waterman Point to the west. Clearly visible are what were confirmed to be (through subsequent trenching) east-west trending, active fault scarps of the Seattle fault system.

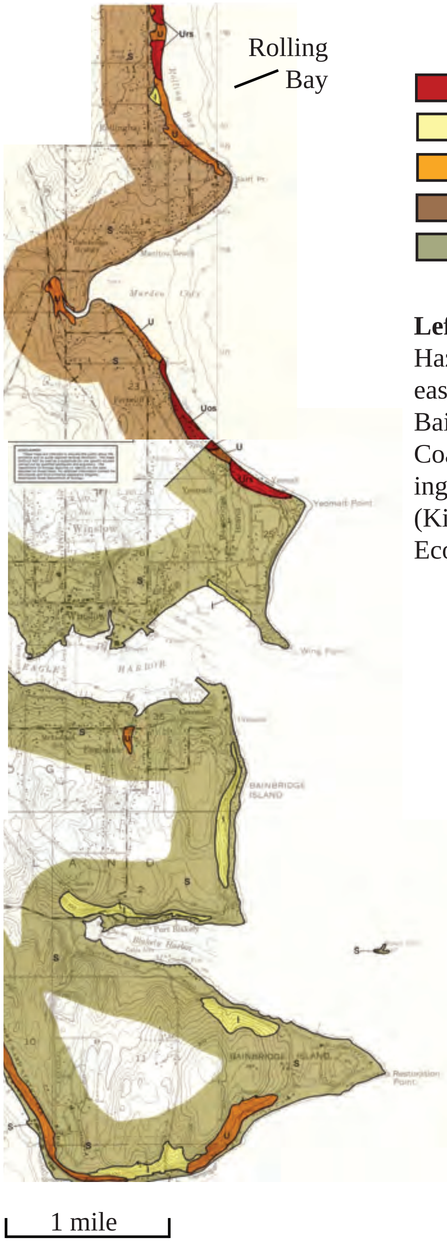


Aeromagnetic Survey Map of the Puget Lowland



Aeromagnetic survey map of the Puget Lowland, showing the low anomoly (dark blue) created by the Seattle fault zone. Modified from Blakely, R.J. et.al., (1999), U. S. Geological Survey OFR 99-154.

Rolling Bay, Bainbridge Island

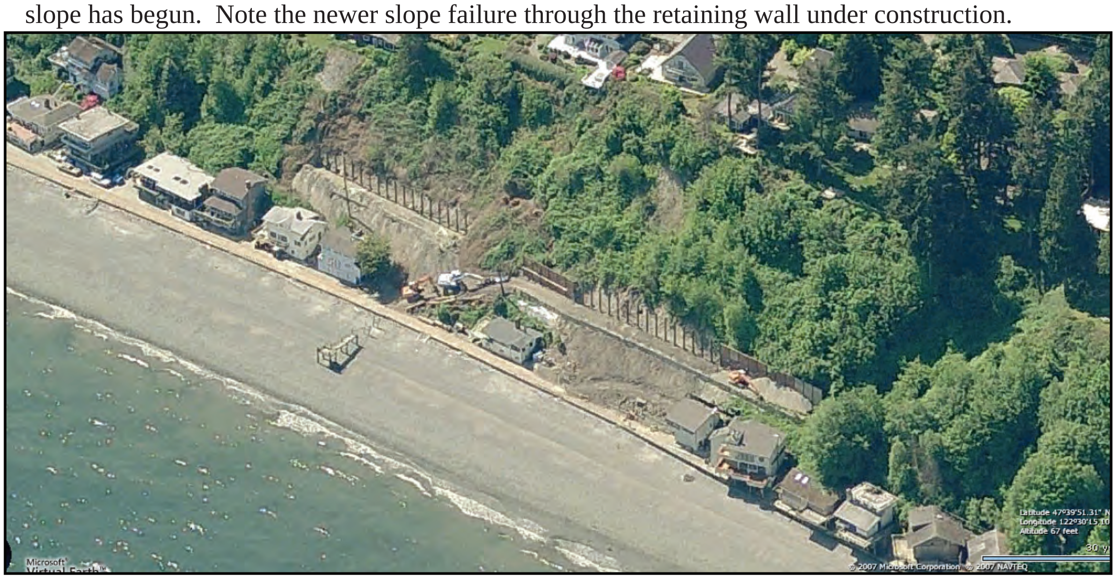


- Unstable Recent Slide
- Intermediate
- Unstable
- Unstable Old Slide
- Stable

Left: Modified Landslide Hazard Mapof the south-eastern coastal slopes of Bainbridge Island, from the Coastal Zone Atlas of Washington, Volume 10, 1979 (Kitsap County), Dept.of Ecology.

Right:
Frontal and oblique aerial views to the west-southwest of the landslide at Rolling Bay Walk on Bainbridge Island that occurred on January 19, 1997. (photographs by the Department of Ecology (top) and T. Tamura, The Seattle Times (lower)). This house was built after another house two lots away was destroyed by a previous landslide event in the spring of 1996. And sadly, the event shown here killed a family of four, all of whom were home at the time of the landslide.

Below:
Oblique aerial view of the same area after the debris was removed and remediation of the slope has begun. Note the newer slope failure through the retaining wall under construction.



After locating the fault, what next?

After using aeromagnetic and gravity surveys, seismic reflection profiling, aerial photography, and/or LiDAR to locate the trace of a fault (its intersection with the earth's surface), more detailed information can often be obtained by trenching. This entails digging a trench, generally perpendicular to the fault, to create a fresh exposure of the fault in three dimensions. Trenches are commonly more than 10 ft deep and 30 ft long. Examples are shown on the following pages. These trenches allow for detailed mapping of the fault and the geologic units that are offset by it. Using radiocarbon or other age-dating techniques, the age of rock or soil that is cut by the fault or buried by it can be determined, providing limiting ages of faulting. For instance, if a peat deposit that is dated at 1,100 years old is cut by the fault, then the earthquake happened more recently than 1,100 years ago. Unfortunately, this doesn't tell us how much more recently. Conversely, if a soil that developed on top of debris shed from the fault scarp (colluvium) is 1,100 years old, then the earthquake had to have happened more than 1,100 years ago. Unfortunately, this doesn't tell us how much longer ago. Sometimes we have to date charcoal, which may already have been five or six hundred years old when it was buried by colluvium or deposited on top of it. Because these dating uncertainties are almost always present, the time of occurrence of prehistoric earthquakes is generally only approximately known. If evidence for multiple earthquakes can be found on several trenches on a given fault, however, a statistical average of recurrence intervals, or average time between earthquakes, can be obtained and applied to the probabilistic earthquake hazard maps that are the basis of the building codes.

Trenching Across Active Faults in Washington

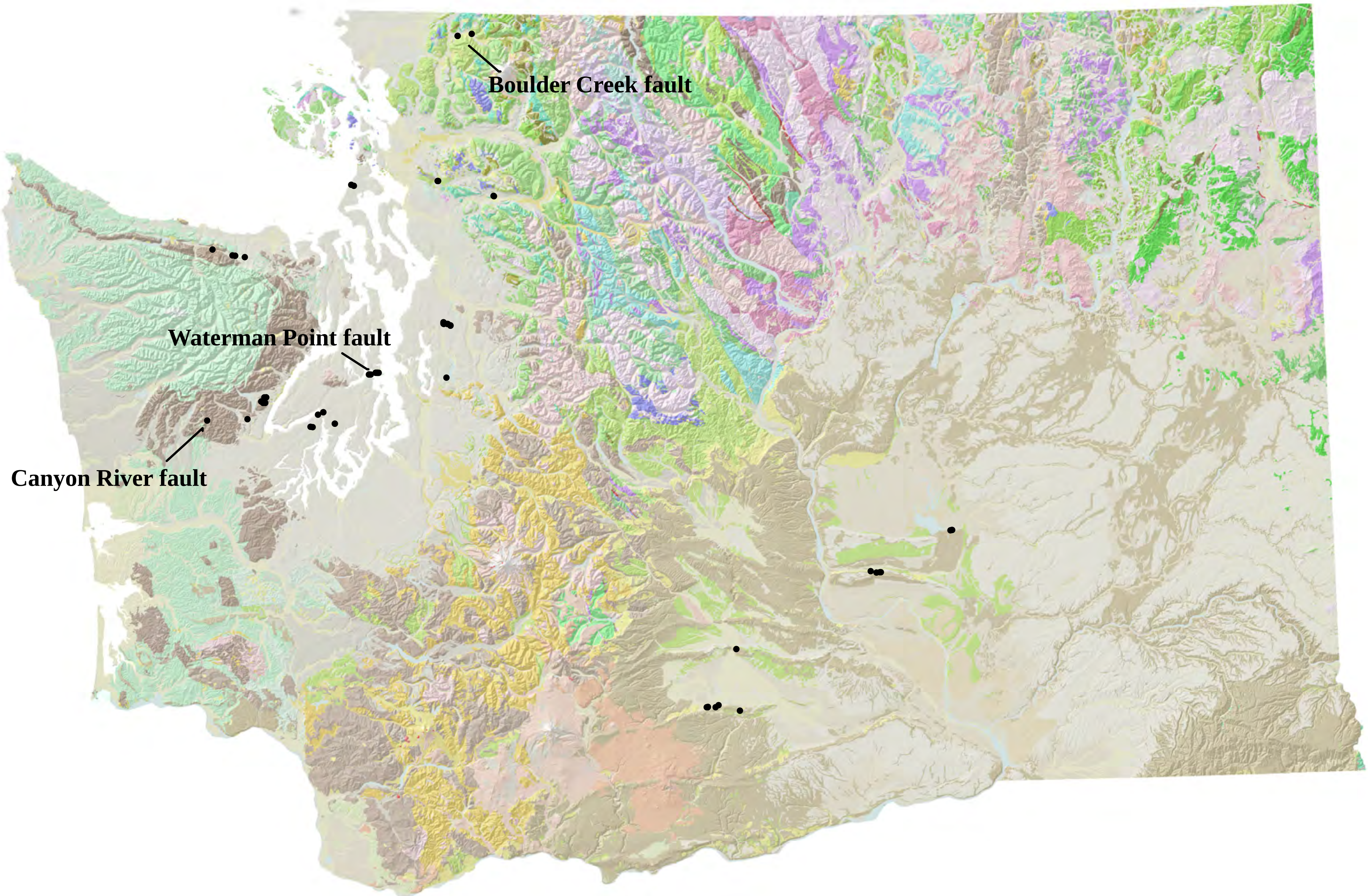


Figure 6: Location of fault trenches in Washington; labels of faults reflect trenches shown in Figures 7-11.

Figure 7. Trench on Canyon River fault, looking south. The blue-gray basalt at the head of the trench is thrust up over the gravel in the foreground and to the left, moving about 20 ft in one earthquake.

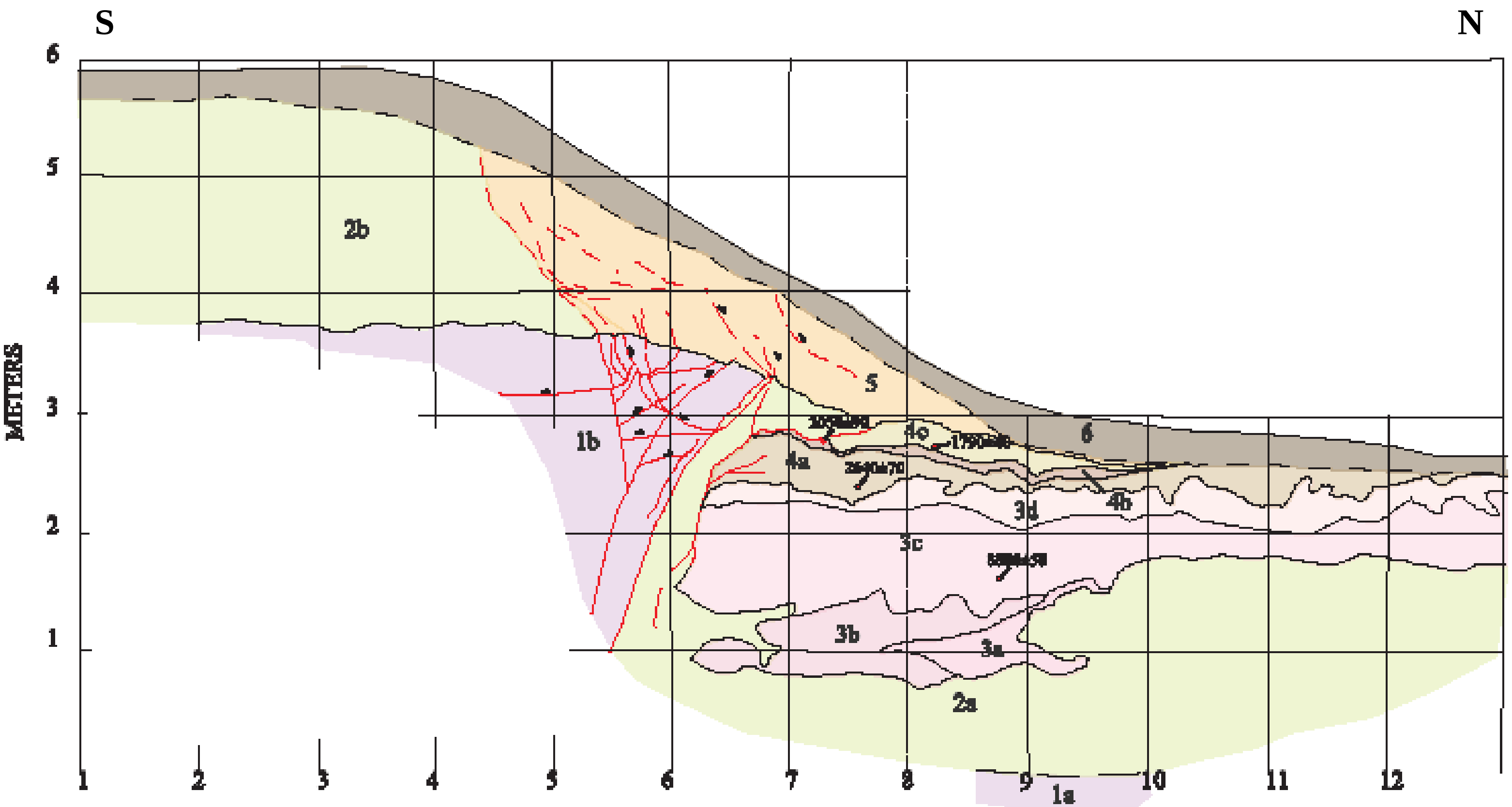


Figure 8. Log of trench in figure 7. Faults shown in red. Inferred correlative units on opposite sides of the fault have the same number but different letters.

Figure 9. Nettle Grove trench on the Waterman Point fault looking northwest. Fault is highlighted by color contrast at black arrow in center of photo. From U. S. Geological Survey Miscellaneous Field Studies Map MF-2423.

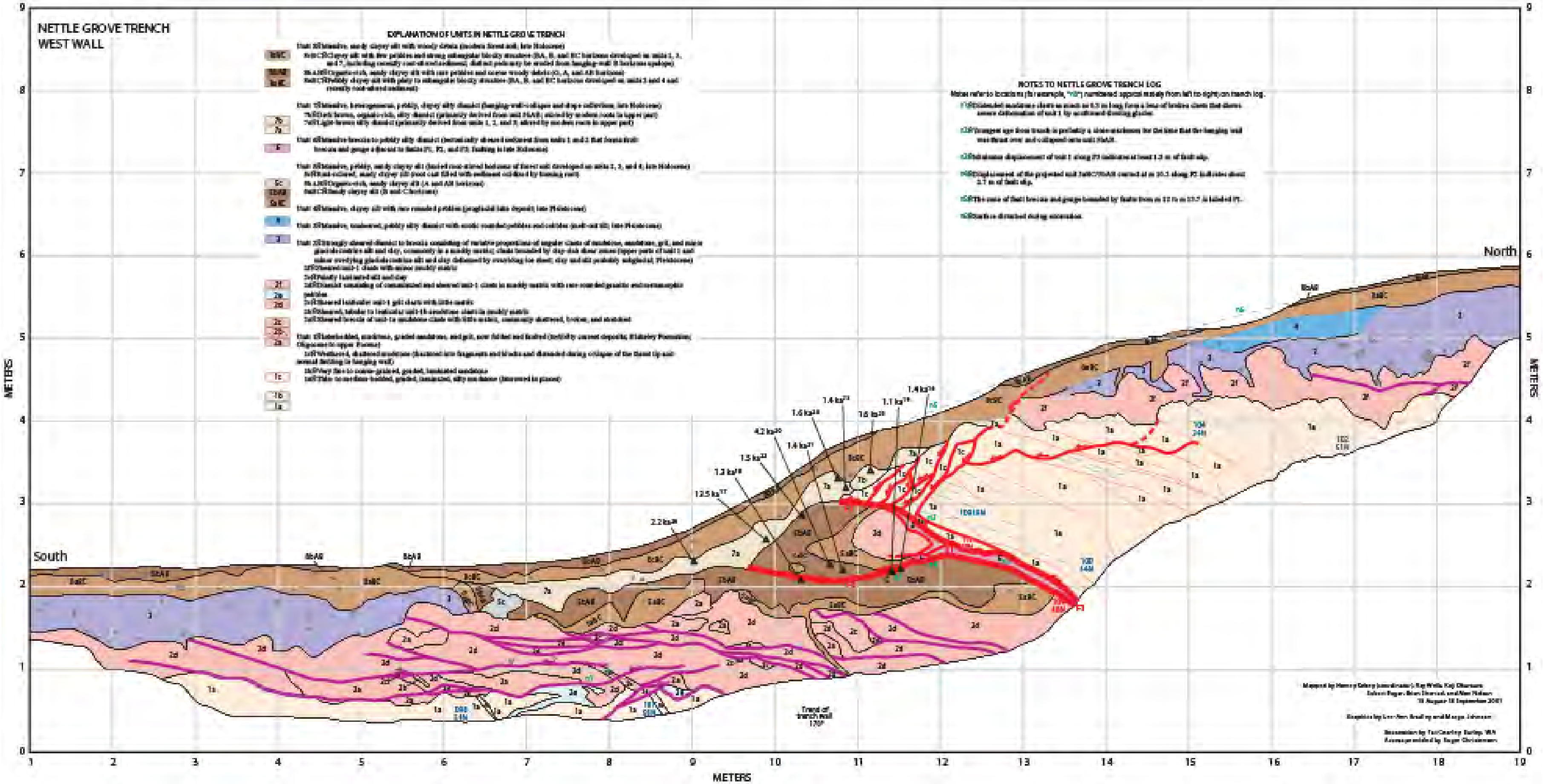


Figure 10. Log from Nettle Grove trench

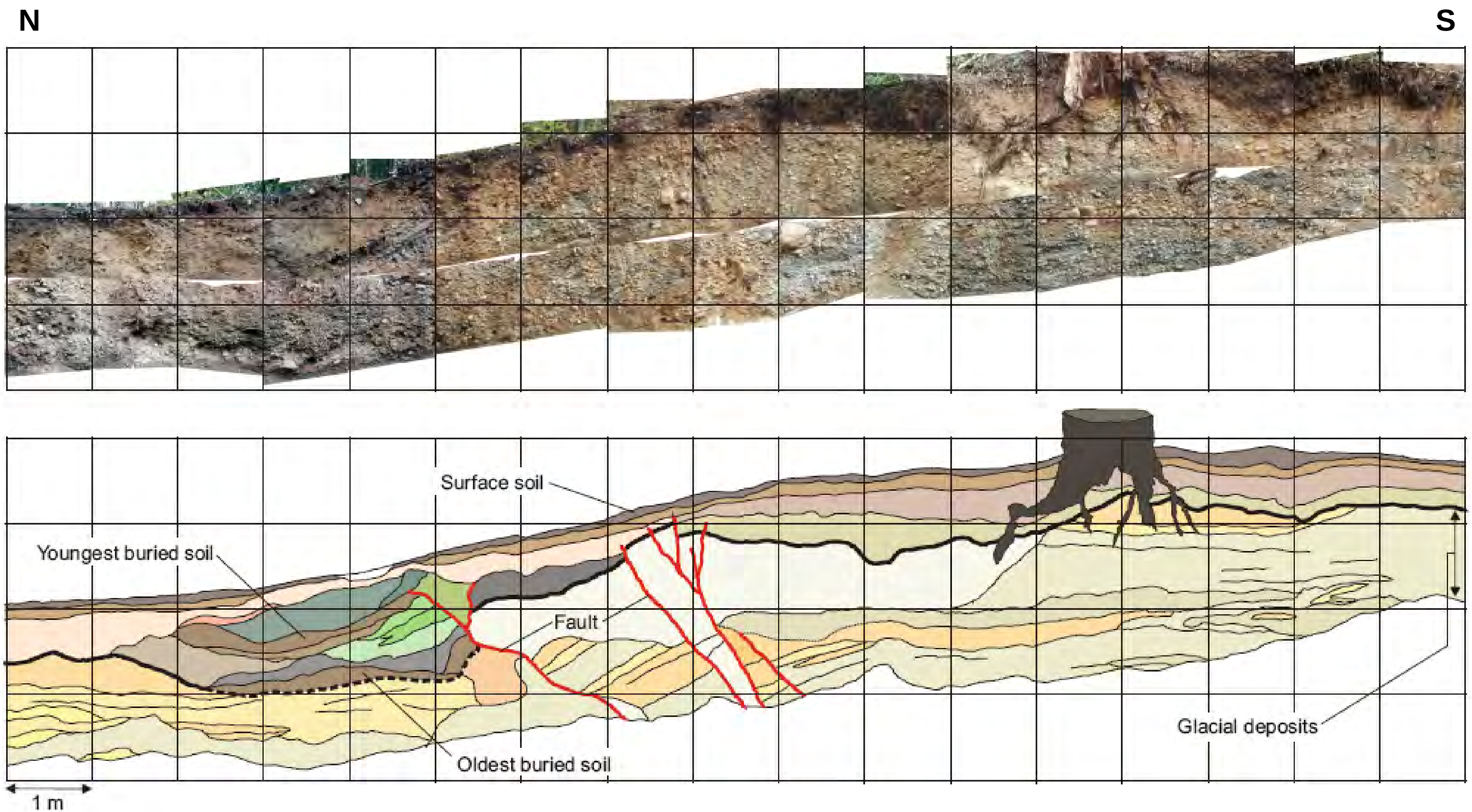
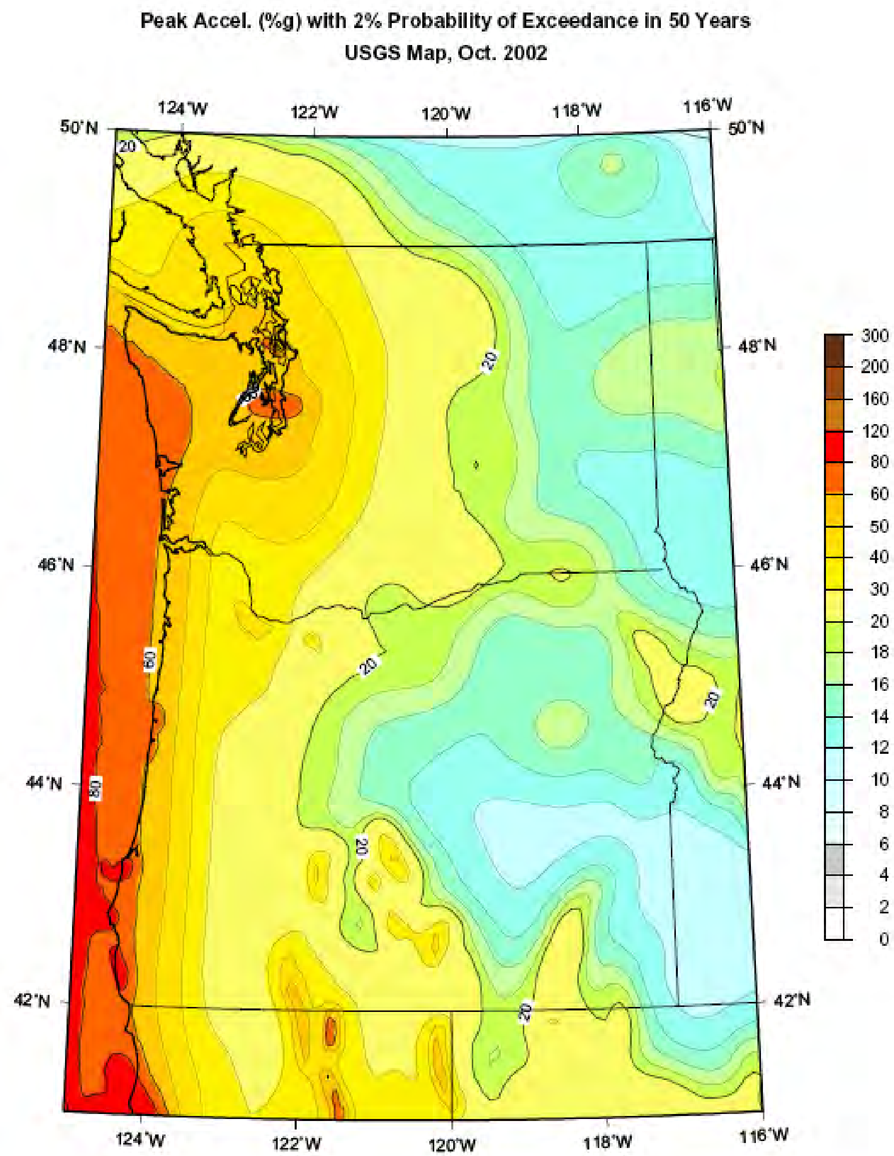


Figure 11. Trench and log of the Hornet trench on the Boulder Creek fault in Whatcom County.

Figure 12. Probabilistic hazard map of the Pacific Northwest (http://earthquake.usgs.gov/research/hazmaps/products_data/2002/wus2002.php). This is one of the inputs to seismic design standards in the International Building Code, which is in force in Washington State. Colors reflect forces to be designed for as a percentage of the force of gravity. For instance, 50% means that a building should be designed to withstand a force equal to half its weight. Bullseyes around Seattle and southern Whidbey Island reflect information garnered from trenches such as these.



Restoration Point

Oblique aerial photo of Restoration Point, courtesy of the Washington Department of Ecology, Shorelands and Environmental Assistance Division.

Photo of near-vertical bedding exposed on uplifted wave-cut platform.
Photo by Pat Pringle

The low-lying bedrock peninsula of Restoration Point juts eastward into the Sound from the west, mirroring Alki Point to the east. This bedrock peninsula was uplifted about 7 meters during an earthquake on the Seattle fault about 1000 years ago. Notice the elevated wave-cut platform in the upper photo. The peninsula may owe its existence to bedrock that is more resistant to erosion than the unconsolidated Quaternary deposits that flank most of Puget Sound. Restoration Point appeared anomalous to Captain George Vancouver, who named the peninsula in 1792. Vancouver commented "...we arrived off a projecting point of land, not formed by a low sandy spit, but rising abruptly in a low cliff about ten or twelve feet from the water side. Its surface was a beautiful meadow covered with luxuriant herbage..." (Lamb, 1984, A voyage of discovery to the North Pacific Ocean and round the world [Journals of George Vancouver]: London, the Hakluyt Society, 4 vols., 1752 p.).

In addition, the marsh (indicated in the upper photo) shows evidence of rapid uplift. Cores taken from within the marsh reflect the rapid change from saltwater to freshwater environments about 1000 years ago.

Conversely, Winslow marsh, located to the north of the ferry terminal, contains fossil evidence suggesting either slight subsidence or maintaining the same elevation within the same time period.

Mercer Island Seismically-Induced Landslides

Below and Right: 1920-era timber recovery of drowned forests from massive, ancient, earthquake-induced landslides off Mercer Island in Lake Washington.

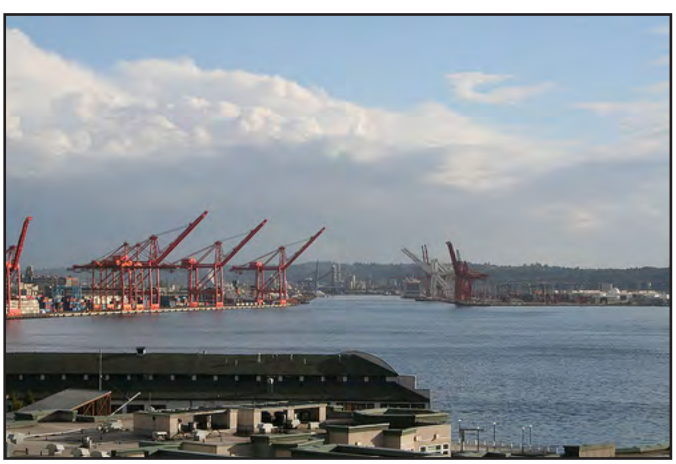
>1160±35
Location of seimically-induced landslide with radiocarbon age.
Data obtained from Adams, J., (1992), Paleo-seismology: A search for Ancient Earthquakes in Puget Sound, Science, Vol. 258.

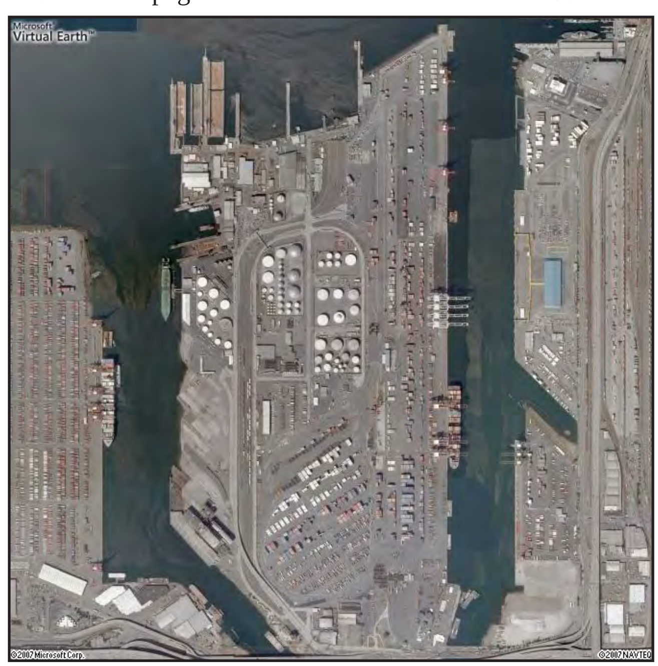
Alki Point

Alki Point protrudes westward into Puget Sound (see cover map), a virtual mirror image of Restoration Point on Bainbridge Island directly to the west. Like Restoration Point, bedrock is exposed in the intertidal zone, consisting of steeply-dipping Tertiary sandstone and siltstone of the Blakely Formation. Although landforms are obscured by dense urban development, building excavations on the point have exposed an uplifted marine terrace incised into bedrock approximately 4 meters above high tide . Conversely, located at the northern end of Elliott Bay and directly north of Alki Point, West Point shows evidence of between 1 and 5 meters of subsidence 1000 years ago. Aerial photo courtesy of the Washington Department of Ecology, Shorelands and Environmental Assistance Division.

Harbor Island

Harbor Island (shown below), located about 1/8 mile from the Pier 52 ferry terminal, is composed entirely of hydraulic fill, and is therefore susceptible to liquefaction during earthquakes. The next page contains a vivid account from Bob Norris, a now retired USGS seismologist, who experienced this phenomenon first-hand on Harbor sland shortly after the M6.8 Nisqually Earthquake in 2001. The epicenter of the Nisqually quake was about 60 km southwest of Seattle. A large-magnitude earthquake along the Seattle fault would be catastrophic for the port of Seattle.





Narrative of strong ground shaking and liquefaction on Harbor Island (south of downtown Seattle) during the Nisqually earthquake

Editor's Note:

The following is one of the most exciting scientific descriptions of the Nisqually earthquake that I have read. It recounts the strong shaking produced by the earthquake, and most interestingly, describes the formation of a sand boil in the Port of Seattle on Harbor Island. Sand boils result from the liquefaction of sand layers that contain abundant water. This description by Bob Norris, a seismologist with the U.S. Geological Survey, is one of the few known observations of the formation of a sand boil by a scientist. Bob wrote his account about 6 days after the earthquake on March 6, 2001.

This is a narrative of my observations of strong ground motion and a sand blow I observed on Harbor Island from the Nisqually earthquake.

Harbor Island is located on the south shore of Elliot Bay, south of downtown Seattle. The island consists largely of artificial fill and overlies former tidal flats of the Duwamish River delta. In common with other sites on artificial fill, Harbor Island shows high site response during earthquakes. (I can now verify that from personal experience.) For this reason, the USGS maintains a portable digitally recording seismograph on the island.

At 10:54 AM on February 28, I was driving along 11th Ave. SW on Harbor Island en route to the seismograph site to download seismic data and perform routine maintenance. The instrument is located in a small outbuilding that contains fire control equipment for a complex of oil tanks nearby. I had just entered the gravel driveway that gives access to the site when the truck started yawing from side to side as if I'd just driven diagonally over a large speed bump. I thought I had driven over something I hadn't seen, and went through several seconds of confusion because the truck was still rocking sharply after I had stopped. It wasn't until I looked up and saw some electrical wires overhead swaying and their support poles leaning back and forth that I realized this was not only an earthquake, but an unholy BIG earthquake! I was utterly amazed that all this ground motion could go on so quietly-- I could hear things creaking and clanging from all the swaying, but the ground itself was silent.

When I stopped gawking and resumed thinking, I remembered the wires overhead and gunned the truck into an open area about 60 feet ahead, which looked like a safe area to wait it out. At this point, about 1520 seconds into the strong ground motion, its amplitude seemed relatively constant and although the ride was bumpy I had no problem steering the truck into the open area. It seemed the worst was over, but as I stopped the truck again the amplitude of shaking abruptly increased. In less than a second the truck was rocking so violently I lost sight of everything outside and could do nothing but hold on and hope my flying head didn't hit anything. This violent phase was brief, perhaps 5-7 seconds, but long enough to give me a mild strain in my neck. If it went on much longer, this could turn from an exciting professional experience to a survival situation. I remembered I was next to an oil tank farm and had a visualization of the huge oil fire in Valdez, Alaska after the 1964 quake, which I could have done without.

When it eased enough for me to be able to look around again, perhaps 25-30 seconds after the strong shaking began, I saw the dozen or so 200 foot tall cargo cranes that line the waterways of Harbor Island quivering and flexing in place, resembling huge steel giraffes trying to dance. I remember hoping no one was in them. It was at least another minute before I felt safe enough to get out of the truck. Outside, there was a pervasive background din of car and industrial alarms going off all over the city. As I walked over to a crew of ARCO people in hardhats about 100 yards away to see if they were all right, I could plainly feel the asphalt under my feet gently moving back and forth with about a 2-3 second period. We traded our stories for a short time, perhaps 2 to 3 minutes, then I walked back to the truck. At this time I could still feel subtle ground motion if I stopped walking.

Since my cell phone was out and I no longer felt in danger there, I thought I might as well get the earthquake data from the seismograph. I estimate that what happened next occurred at least 5 minutes after the onset of strong shaking at that point, perhaps as long as 10 minutes, but that's probably an upper limit.

I had just opened the door of my truck to get my laptop and notebook when I was distracted by a wet swishing sound coming from the ground nearby. I looked over to its source and saw a smooth dome of brown fluid, perhaps a foot and a half wide and high, issuing from the ground a few yards away from the southeast corner of the fire control house where the seismograph was located. This dome lasted perhaps two seconds, then grew and burst into a muddy geyser. This geyser issued three or four very fluid splashes over the next few seconds, about a yard high each, then it widened and collapsed into a column about half that wide that discharged a tremendous volume of muddy water. This flood emerged much faster than it could spread, so that within a few seconds the flow front had become a surge several inches high, like a small wave travelling up a dry beach. Its velocity was near 3ft/second as far as I could tell. Within an estimated 30 seconds, the surge had grown into a shallow rotating pool about 25 feet across with bits of suds floating on it, still vigorously fed by the column of water at the original breakout site.

I confess I didn't think it was a liquefaction feature at all; the delayed onset, the limited amount of sediment in the water, and the high flow rate convinced me it was a water main break-- particularly as it occurred near a building containing fire control equipment. In fact, I was annoyed because I thought the growing pool might engulf the driveway and strand me there, or prevent me from getting to the seismograph and downloading data! The feeder column remained centralized at the breakout site but began to gradually wane after a couple of minutes. I walked over to get a closer look and was surprised to find the water was relatively clear; I could see to a depth of a couple of inches in the pond.

Unfortunately, I paid no further attention to it and focused on getting data from the seismograph. When I left the site about 90 minutes later, I noticed that the column had dwindled to a disturbed patch of water in the now-quiet pool, which had approximately doubled in size.

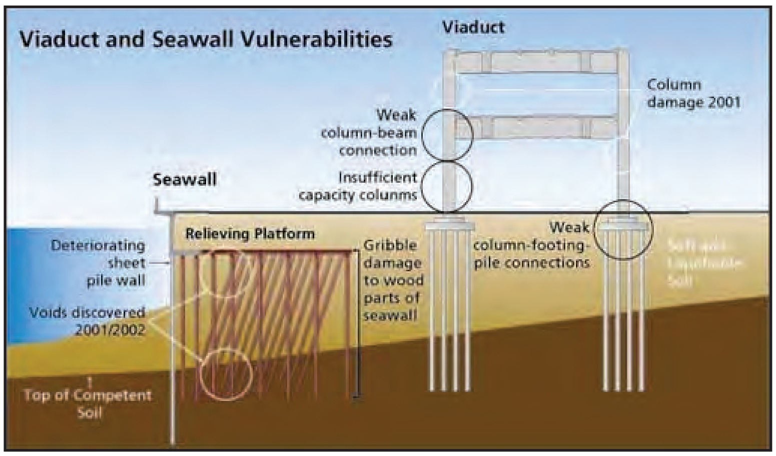
After learning that this was indeed a sand blow, I returned to the site as soon as time allowed- about 3 days after the quake. Its deposit consisted mostly of dark sand-sized material, much coarser than the fine muds emitted by similar features along First Avenue South. This may explain why the eruption was so fluid; the sand added relatively little viscosity to the water and quickly settled out once the water had surfaced. The vent that I had witnessed forming had been filled in with gravel by the property owners, who had cordoned off the area. The area covered by emitted sand was approximately 45-50 feet in maximum diameter. I was surprised to see several other vents in the sand (closer to where my truck had been!); these may have erupted shortly after the initial vent and were submerged before I could see them.

This was only one of many sand blows that occurred on Harbor Island. I was luckier to get out of there than I realized; subsurface piping had opened an oblique collapse pit about 3 feet wide and of uncertain depth, only a few feet from where my truck had been parked.

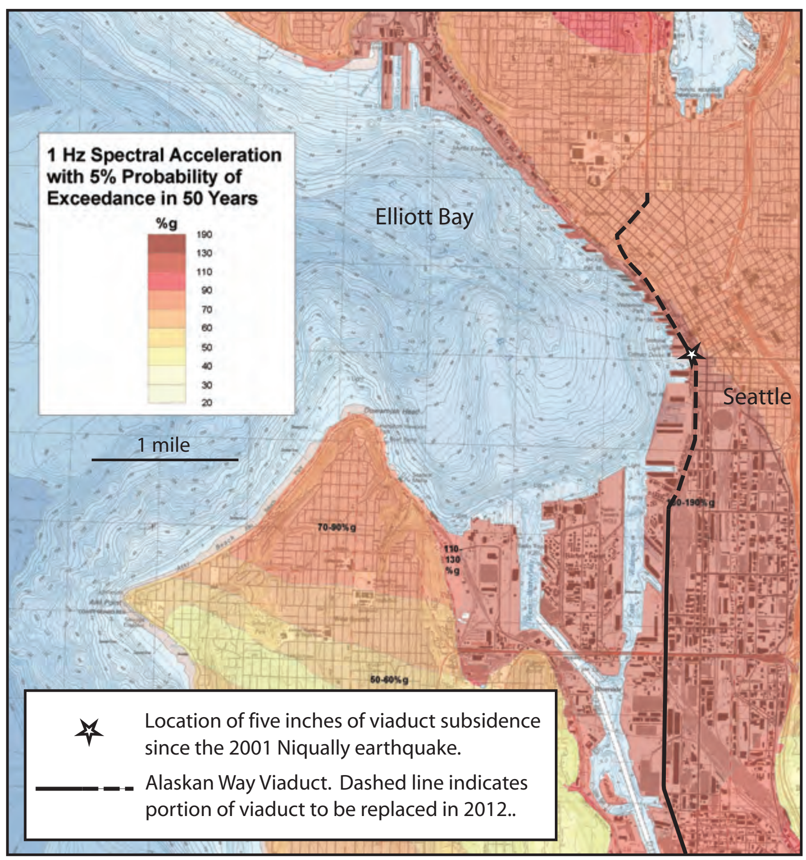
Bob Norris

Alaskan Way Viaduct

Right: Photograph viewed to the southeast of the Alaskan Way Viaduct, aging and weak elevated structure used by 110,000 vehicles per day. The structure was built on hydraulic fill in the 1950's, and was not engineered to sustain a major eartquake. It was not (nor can it be) retrofitted for current seismic design, and thus, it required major structural repair after the 2001 Nisqually earthquake. Numerous vital municipal utilites are housed by the viaduct, all of which would be lost should the viaduct fail. Plans are in effect to replace the viaduct completely beginning in 2012 (see dashed line in bottom figure).



Left: Diagram showing vulnerabilities of the aging Alaskan Way Viaduct and seawall. The seawall was built in the 1930's to hold the hydraulic fill placed on top of tideflat deposits along the waterfront. Image courtesy of the Washington Department of Transportation.



Right: Map showing the location of the Viaduct in relation to potential seismic hazard. This map shows the seismic hazard of a 5% Probability of Exceedance in 50 years. The limits of the two darkest red zones are coincident with the limit of artificial fill. Features within artificial fill, such as the waterfront, the viaduct and Harbor Island, have the highest amount of seismic hazard associated with them. Routine monitoring of the structure revealed that since the 2001 Nisqually earthquake, select sections of the viaduct (indicated with a star on the map) have settled 5 inches. Image modified from the United States Geological Survey SeismicHazard Map of Seattle.