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ABSTRACT

Airborne laser mapping confirms that Holocene active faults traverse the Puget Sound metropolitan area, northwestern continental United States. The mapping, which detects forest-floor relief of as little as 15 cm, reveals scarps along geophysical lineaments that separate areas of Holocene uplift and subsidence. Along one such line of scarps, we found that a fault warped the ground surface between A.D. 770 and 1160. This reverse fault, which projects through Tacoma, Washington, bounds the southern and western sides of the Seattle uplift. The northern flank of the Seattle uplift is bounded by a reverse fault beneath Seattle that broke in A.D. 900–930. Observations of tectonic scarps along the Tacoma fault demonstrate that active faulting with associated surface rupture and ground motions pose a significant hazard in the Puget Sound region.

Keywords: Holocene, scarp, Puget Sound, paleoseismology, fault.

INTRODUCTION

A tectonic scarp along a fault, as a geomorphic signature of surface rupture, demonstrates the fault's capacity to produce earthquakes. In addition, by providing clues to the frequency and size of past earthquakes, the scarp may help define the hazard that the fault poses. Until 1998, scarps played little role in defining seismic hazards around Puget Sound, northwestern continental United States. This subduction-zone region, home to three million people, faces earthquakes from a multitude of sources, the nearest of these being faults within the overriding North American plate (Fig. 1). Geologists used to despair over finding scarps from such faults because the landscape around Puget Sound is covered with 16 ka glacial deposits, forests, and houses. Recent, detailed topographic maps based on airborne laser surveys show that the region has no fewer than seven scarps in two urban fault zones. Four of these scarps have histories of postglacial earthquakes that have been confirmed by trenching and radiocarbon dating (Wilson et al., 1979; Nelson et al., 2002) (Figs. 2B, 2C). Here, as an example, we show that near-surface rupture produced Holocene scarps along a geophysical lineament that bounds an area of shoreline uplift and subsidence and projects through the city of Tacoma.

Near-surface faults in the Puget Sound region accommodate contraction of western Washington between the Coast Ranges of Oregon and British Columbia (Wells et al., 1998) (Fig. 1). The contraction has produced east-trending uplifts, basins, and associated reverse faults that traverse Puget Sound (Fig. 2B). The faults, which separate areas of coastal uplift and subsidence (Fig. 2C), were first identified from geophysical lineaments (Danes et al., 1965). New geophysical data (Brocher et al., 2001) confirm that one fault zone passes beneath Seattle and another beneath Tacoma (Figs. 2D–2F). The Seattle fault zone marks the northern edge of an area of crustal uplift, the Seattle uplift, whereas the Tacoma fault zone bounds this uplift on the south (Pratt et al., 1997; Johnson et al., 1999; Brocher et al., 2001; Blakely et al., 2002). The two zones probably have similar structural relief—as much as 10 km since the Eocene for the Seattle fault—because they coincide with geophysical anomalies of similar amplitude.

TACOMA FAULT ZONE GEOPHYSICS

The Tacoma fault zone consists of several geophysical lineaments along the southern and western flanks of the Seattle uplift. Two prominent geophysical lineaments (lineaments C and G in Figs. 2D–2F) are the signature of the Tacoma fault zone, and extend at least 50 km from Hood Canal through the city of Tacoma (Brocher et al., 2001). Two lesser lineaments broaden the signature along the eastern part of the fault zone (labeled lineaments D and E in Figs. 2D–2F). Anomaly amplitudes increase to the west along the prominent lineaments, interpreted as a westward increase in structural relief accommodated by the Tacoma fault zone (Brocher et al., 2001). Along the western end of the fault zone (near lineament C), inferences from seismic tomography and seismic reflection data suggest 6–7 km of north-side-up structural relief on the top of Eocene basalt.

LIDAR MAPPING OF FAULT SCARPS

To study the recentness of movement on the Tacoma fault zone, we looked for fault scarps by means of lidar (light distance and ranging).

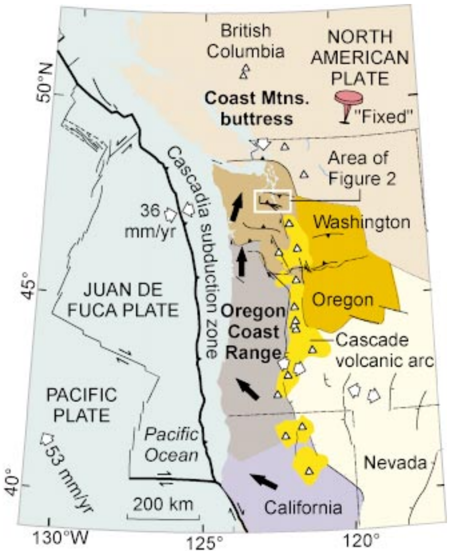

Figure 1. Tectonic setting of Cascadia subduction zone. Western Washington region (brown), between fixed North America and Oregon Coast Range, is undergoing transpression, which creates folds and reverse faults across Puget Sound. Bold arrows indicate motions of tectonic blocks inferred from geologic and geodetic data. Modified from Wells et al. (1998) and Wang et al. (2003).

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Geology; January 2004; v. 32; no. 1; p. 9–12; DOI 10.1130/G19914.1; 4 figures.

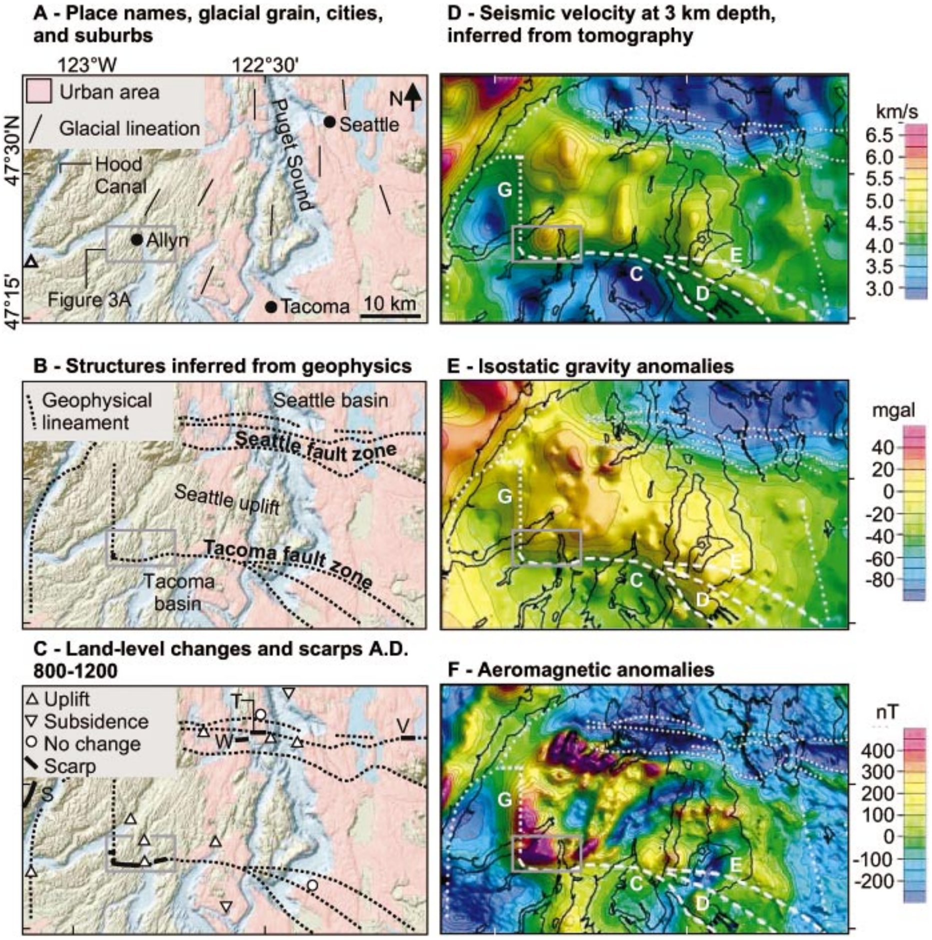

Figure 2. Summary of geological and geophysical evidence along Tacoma fault zone. A: Geographical features referred to in text. B: Map of central Puget Sound showing traces of geophysical anomalies crossing densely populated urban corridor around Seattle and Tacoma. C–F: Geophysical data and locations of geophysical lineaments C, D, E, and G discussed in text. C: Evidence for past earthquakes within region includes deformed shorelines and Holocene fault scarps revealed by lidar mapping within Seattle and Tacoma fault zones. Previously studied scarps: T—Toe Jam fault (Nelson et al., 2002); V—Vasa Park (Sherrod, 2002); W—Waterman Point (Haugerud et al., 2003); S—Saddle Mountain (Wilson et al., 1979). D: Tomographic seismic velocity model at 3 km depth. E: Isostatic gravity map. F: Aeromagnetic map. Base map is modified from Finlayson et al. (2001), and paleoseismic data from Seattle fault zone are summarized from published sources (Atwater and Moore, 1992; Bucknam et al., 1992; Sherrod, 2000).

This airborne laser mapping uses two-way traveltimes of laser light pulses to detect as little as 15 cm of relative relief on the forest floor. (Additional information on lidar mapping in Puget Sound and Web-viewable topographic images are available at http://www.pugetsoundlidar.org.) The lowest returns of laser pulses yield digital elevation models of the ground surface (Haugerud and Harding, 2001; Haugerud et al., 2003).

Lidar mapping along the Tacoma fault zone reveals fault scarps near Allyn, Washington. These south-facing scarps—invisible on aerial photographs (Fig. 3A) but conspicuous in lidar images (Figs. 3B, 3C)—cut across glacial lineations left by the last glacial advance into Puget Sound ca. 16. ka (Porter and Swanson, 1998). The scarps are as high as 4 m.

FAULT-SCARP EXCAVATION

An excavation across one scarp, named Catfish Lake scarp, showed evidence of postglacial folding and a small amount of faulting. The excavation exposed late Quaternary glacial sediments (till, sand, and gravel-filled channels) deposited by last-glacial ice sheets (Booth, 1994), and an oxidized surface soil developed on till (Fig. 3D). Deformation observed in the till is consistent with both glacial ice flow and movement on the Tacoma fault. However, a platy B/E horizon of the surface soil is displaced by a fault (F3) with ~30 cm of reverse offset. Folding of till fabrics is defined by stratified pebbles and imbricated clasts. Pebble layers in the north half of the trench are almost horizontal, whereas similar layers in the south half of the trench dip to the south. Imbricated clasts are more steeply inclined to the north on the north side of F3 and are almost subhorizontal to the south of F3. The break between the two fabric orientations occurs near F3, the fault that offsets a Holocene soil horizon, and both fabrics suggest anticlinal folding. No organic material suitable for radiocarbon dating was present. Folded and faulted glacial deposits show that most of the deformation and scarp height (>2 m) postdate deposition by the ice sheet, which ended in this area ca. 16 ka (Porter and Swanson, 1998).

EVIDENCE FOR COASTAL DEFORMATION

The scarps coincide with deformed shorelines that straddle the fault and point to an earthquake between A.D. 770 and 1160 (Figs. 3B and 4). A raised tidal flat observed along the north side of the fault in Case Inlet suggests late Holocene uplift (Fig. 3B). Differences between the modern and raised shoreline elevations, taken from profiles of the lidar data, show ~4 m of uplift. Uplifted tidal-flat deposits observed at several sites along the north side of the fault contain marine fossils. Paleoecology of the tidal-flat deposits and overlying upland soils requires at least 1.5 m of uplift to change a tidal flat into a freshwater swamp or meadow (Bucknam et al., 1992; Sherrod, 1999, 2001). Plant fossils within the tidal-flat deposits and from overlying freshwater peat limit uplift to between A.D. 770 and 1160. Microfossils recovered from sediments beneath an intertidal marsh at Dumas Bay show that the site remained in the upper intertidal zone while sites to the west were uplifted. The area south of the fault subsided between A.D. 980 and 1190, as shown by a radiocarbon age on the outermost rings of a tree stump (Douglas fir) found in growth position partially exposed on a modern tidal flat at Wollochet Bay (Fig. 4).

Radiocarbon ages from uplifted and submerged coastal sites along the Tacoma fault constrain the timing of deformation between A.D. 770 and 1160. An age from leaf bases of *Triglochin maritima* that grew on a freshly uplifted tidal-flat surface at Lynch Cove constrains uplift to shortly before A.D. 880–980. Similarly, freshwater peat deposited between A.D. 1000 and 770 at Burley overlies sand vented onto a raised tidal flat, implying that the ground shook hard enough to liquefy during uplift. At other sites, ages on freshwater swamp peat deposited over tidal-flat deposits loosely constrain uplift between A.D. 890 and 1410. A single age from a submerged tree south of the fault constrains subsidence to between A.D. 980 and 1190.

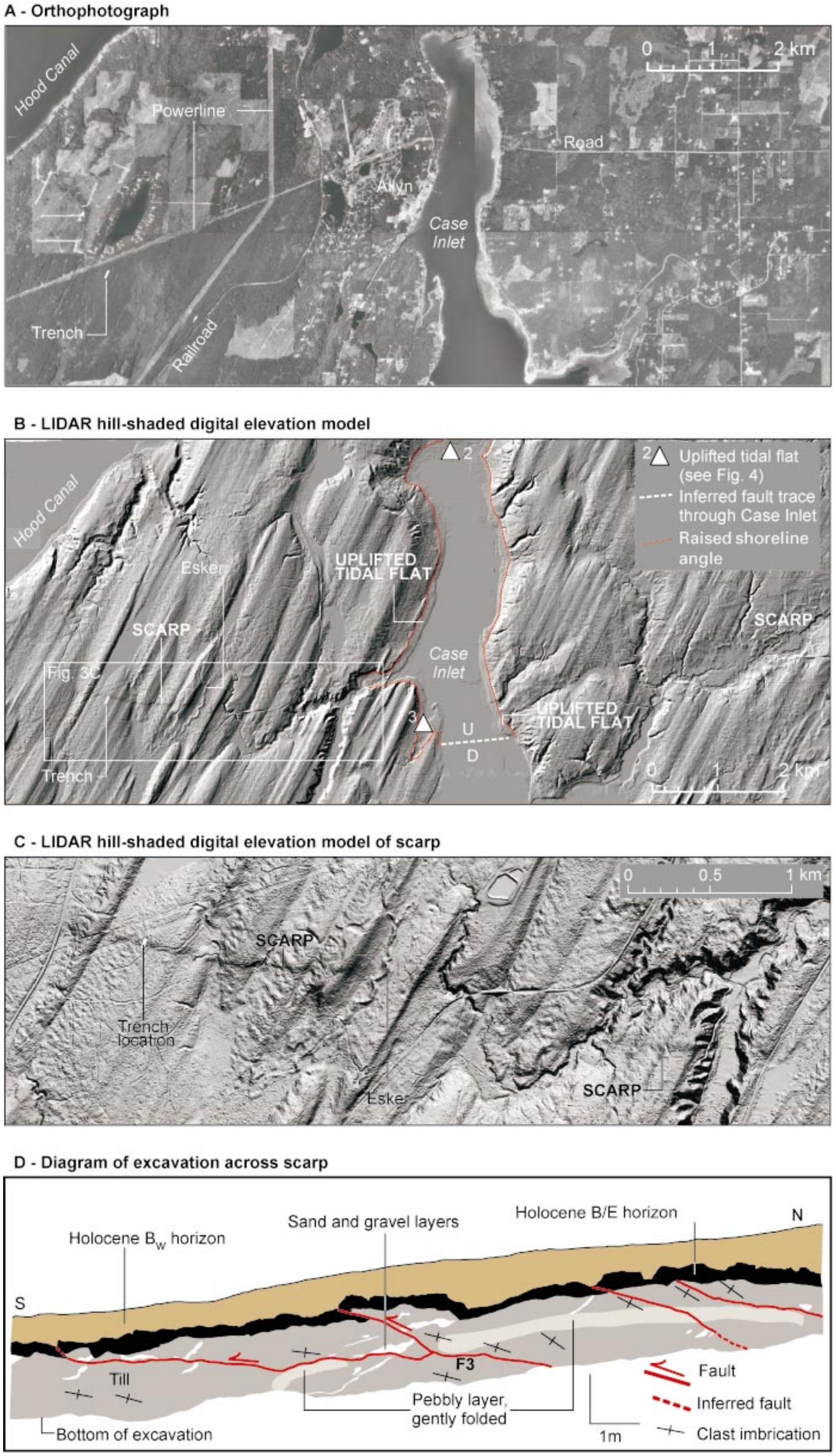

Figure 3. Digital images of ground surface along Tacoma fault and excavation log across Holocene scarp. A: Digital orthophotograph of study area where lidar mapping revealed several scarps. Dark areas covering most of photograph are dense, second- and third-growth forests of Douglas fir. B: Hill-shaded digital-elevation model of lidar data from same area shown in A. Image is illuminated from azimuth of 315° and 40° above horizon. C: Small-scale lidar image of area within white box shown in B, showing northeast-trending glacial striations and scarp cutting across striations. D: Diagram of trench wall across Catfish Lake scarp.

IMPLICATIONS FOR SEISMIC HAZARDS POSED BY THE TACOMA FAULT

We conclude that coastal uplift and surface rupture along the Tacoma fault are the result of a large earthquake between A.D. 770 and 1160. The A.D. 770–1160 age range for a paleoearthquake on the Tacoma fault includes times of coseismic uplift and subsidence at many sites around Puget Sound. A well-known earthquake raised shorelines as much as 7 m along the Seattle fault zone between A.D. 900 and 930 (Bucknam et al., 1992; Atwater, 1999), and shores of southern Puget Sound subsided at A.D. 860–940 (Sherrod, 2001). Therefore, either the Tacoma fault earthquake coincided with a single large event in A.D. 900–930, or it represents a separate earthquake of about that age. In either case, the Seattle and Tacoma fault zones likely ruptured at about the same time in the late Holocene to raise the Seattle uplift by several meters.

Our results show that the Tacoma fault is active and joins the Seattle fault on the list of shallow faults in the Seattle-Tacoma metropolitan area with Holocene movement. On the basis of geophysical mapping, the fault extends at least 50 km from Hood Canal to Tacoma. We conservatively estimate a maximum credible event on the Tacoma fault by comparing regressions of fault-rupture length and moment magnitude relationship (Wells and Coppersmith, 1994). Under the assumption that the fault can rupture along its entire known length of 50 km, it is possible for the Tacoma fault to generate an earthquake on the order of $\mathbf{M} \sim 7$. Surface ruptures from shallow earthquakes are not known in the 170-yr-long historic period in Puget Sound, yet lidar mapping reveals several scarps on the Seattle and Tacoma fault zones (Nelson et al., 2002; Sherrod, 2002; Haugerud et al., 2003). Recognizing that surface rupture occurs on shallow faults crossing urban areas in Puget Sound will help shape future seismic hazard plans and mitigation in the Seattle-Tacoma metropolitan region.

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REFERENCES CITED

Atwater, B.F., 1999, Radiocarbon dating of a Seattle earthquake to A.D. 900–930: Seismological Research Letters, v. 70, p. 232.

Atwater, B.F., and Moore, A.L., 1992, A tsunami ~1000 yr ago in Puget Sound, Washington: Science, v. 258, p. 1614–1617.

Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y., 2002, Location, structure, and seismicity of the Seattle fault zone, Washington:

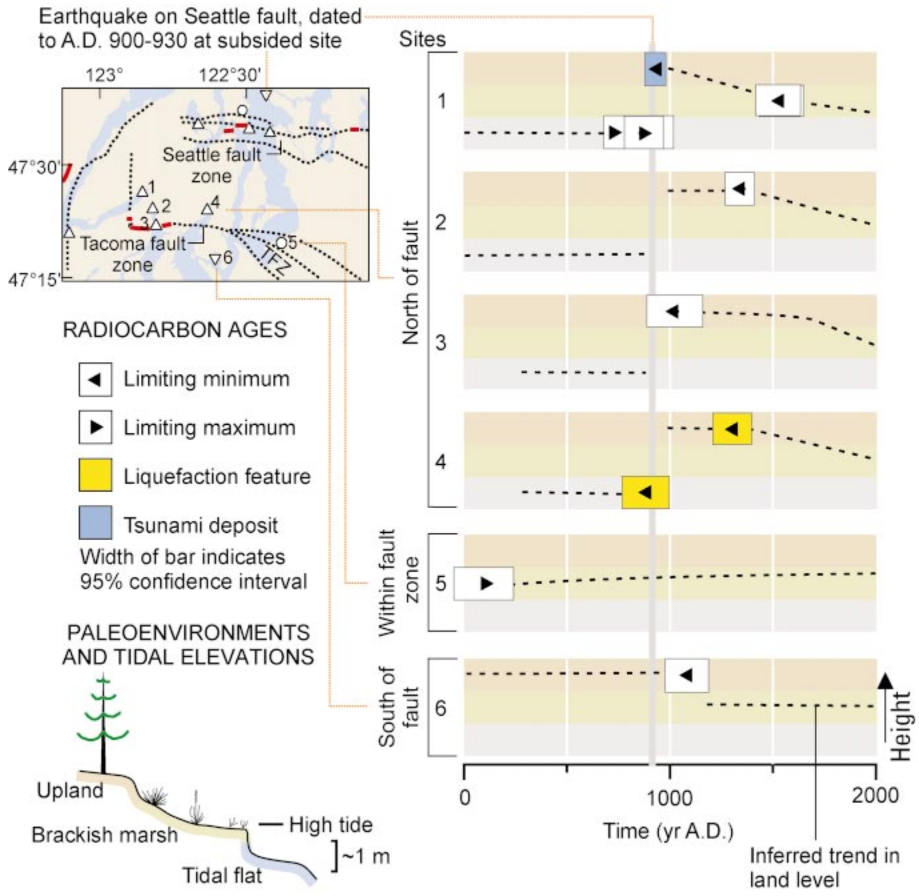

Figure 4. Summary of coastal evidence for late Holocene offset on Tacoma fault. Coastal sites along Tacoma fault zone with evidence for Holocene land-level change: 1—Lynch Cove; 2—North Bay; 3—Catfish Lake; 4—Burley; 5—Wollochet Bay; 6—Dumas Bay. Black dashed lines on index map show locations of faults in Tacoma and Seattle fault zones. Red areas along faults are known surface ruptures. On right side of figure, qualitative elevation curves (dashed black lines) show abrupt land-level changes between A.D. 800 and 1200. Horizontal color bands behind each curve represent paleoenvironments and are keyed to modern tidal elevations (key at bottom left).

Geological Society of America Bulletin, v. 114, p. 169–177.

Booth, D., 1994, Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation: Geology, v. 22, p. 695–698.

Brocher, T.M., Parsons, T., Blakely, R.A., Christensen, N.I., Fisher, M.A., and Wells, R.E., 2001, Upper crustal structure in Puget Lowland, Washington: Results from 1998 seismic hazards investigation in Puget Sound: Journal of Geophysical Research, v. 106, p. 13,541–13,564.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, Abrupt uplift within the past 1700 yr at southern Puget Sound, Washington: Science, v. 258, p. 1611–1614.

Danes, Z.F., Bonno, M.M., Brau, E., Gilham, W.D., Hoffman, T.F., Johansen, D., Jones, M.H., Malfait, B., Masten, J., and Teague, G.O., 1965, Geophysical investigations of the southern Puget Sound area, Washington: Journal of Geophysical Research, v. 70, p. 5573–5580.

Finlayson, D.P., Haugerud, R.A., and Greenberg, H.R., 2001, Building a seamless digital elevation model of the Puget Sound basin, Puget Sound regional research 2001: Olympia, Washington, Proceedings of the 2001 Puget Sound Research Conference: Olympia, Washington, Puget Sound Action Team.

Haugerud, R.A., and Harding, D.J., 2001, Some algorithms for virtual deforestation (vdf) of LIDAR topographic survey data: International Archives of Photogrammetry and Remote Sensing, v. 34, part 3/W4, Commission III, p. 211–217.

Haugerud, R.A., Harding, D.J., Johnson, S.Y., Harless, J., Weaver, C.S., and Sherrod, B.L., 2003, High-resolution lidar topography of the Puget Lowland, Washington—A bonanza for earth science: GSA Today, v. 13, no. 6, p. 4–10.

Johnson, S.Y., Dadisman, S.V., Childs, J.R., and Stanley, W.D., 1999, Active tectonics of the Seattle fault and central Puget Sound, Washington: Implications for earthquake hazards: Geological Society of America Bulletin, v. 111, p. 1042–1053.

Nelson, A.R., Johnson, S.Y., Wells, R.E., Pezzopane, S.K., Kelsey, H.M., Sherrod, B.L., Bradley, L.-A., Koehler, R.D.I., Bucknam, R.C., Haugerud, R., and Laprade, W.T., 2002, Field and laboratory data from an earthquake history study of the Toe Jam Hill fault, Bainbridge Island, Washington: U.S. Geological Survey Open-File Report 02-0060, 37 p.

Porter, S.C., and Swanson, T.W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, p. 205–213.

Pratt, T.L., Johnson, S.Y., Potter, C., Stephenson, W., and Finn, C., 1997, Seismic reflections beneath Puget Sound, western Washington State: The Puget Lowland thrust sheet hypothesis: Journal of Geophysical Research, v. 102, p. 27,469–27,489.

Sherrod, B.L., 1999, Gradient analysis of diatom assemblages in a Puget Sound salt marsh—Can such assemblages be used for quantitative paleoecological reconstructions?: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 149, p. 213–226.

Sherrod, B.L., 2000, Holocene relative sea level changes along the Seattle fault at Restoration Point, Washington: Quaternary Research, v. 54, p. 384–393.

Sherrod, B.L., 2001, Evidence for earthquake-induced subsidence ~1100 yr ago in coastal marshes of southern Puget Sound, Washington: Geological Society of America Bulletin, v. 113, p. 1299–1311.

Sherrod, B.L., 2002, Late Quaternary surface rupture along the Seattle fault zone near Bellevue, Washington [abs. S21C-12]: Eos (Transactions, American Geophysical Union), v. 83, p. F1074.

Wang, K., Wells, R., Mazzotti, S., Hyndman, R.D., and Sagaya, T., 2003, A revised dislocation model of interseismic deformation of the Cascadia subduction zone: Journal of Geophysical Research, v. 108, ser. B1, 2009, DOI 10.1029/2001JB001227.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Seismological Society of America Bulletin, v. 84, p. 974–1002.

Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Forearc migration in Cascadia and its neotectonic significance: Geology, v. 26, p. 759–762.

Wilson, J.R., Bartholomew, M.J., and Carson, R.J., 1979, Late Quaternary faults and their relationship to tectonism in the Olympic Peninsula, Washington: Geology, v. 7, p. 235–239.

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