The western extension of the Seattle fault: new insights from seismic reflection data

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Abstract

Seismic reflection profiling across the Seattle fault west of Puget Sound, western Washington State, reveals near-surface deformation as far west as Hood Canal. North of Green Mountain and in line with the trend of the Seattle fault, folding within late Pleistocene sediments and a deflected stream channel indicate active deformation. Here, I observe folding and faulting in late Pleistocene deposits overlying north-dipping Tertiary strata previously inferred to be part of the Seattle monocline. The greater than 70 km long dominantly east- west striking Seattle fault follows the contours of the northwest edge of Green Mountain and locally strikes south-southwest, or a ~25 degree rotation in local fault trend. Exposures of Eocene bedrock (Crescent Fm) south of the fault indicate deeper exposures than along the eastern portions of the Seattle fault. This deeper exposure, accompanied with greater degrees of deformation than observed to the east may suggest higher uplift rates above the Seattle fault west of Puget Sound. Seismic profiles west of Green Mountain, along strike with the Seattle fault west near the west end of the Seattle Basin, show a complex pattern of late Quaternary and older deformation. However, these profiles extend beyond the inferred limits of the Seattle Basin and Seattle uplift and do not show the characteristic monocline that defines the Seattle fault to the east. Steeply dipping Tertiary strata, southwest-striking structures, and unknown stratigraphy beneath late Quaternary fill suggest a complex and possibly distributed pattern of deformation along the west part of the fault. The Seattle fault continues west beyond its mapped extent north of Green Mountain; it may merge with structures that control the Dewatto Basin along the south edge of the Seattle uplift, including the Frigid Creek or Saddle Mountain faults west of Hood Canal.

Introduction

The Seattle fault is the most hazardous crustal fault in the U.S. Pacific Northwest because it is located beneath the largest cities in the region and has hosted a large Holocene earthquake (Fig. 1). Uplifted terraces, tsunami deposits, and landslides show that the >70 km long thrust or reverse fault hosted a M7 or greater earthquake about 900-930 A.D. (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992). The Seattle Fault Zone (SFZ) manifests itself as a 5-7 km wide zone in which geologic, topographic and geophysical data show deformed shallow strata and several fault strands (Yount and Gower, 1991; Johnson et al., 1994 and 1999; Pratt et al., 1997; Blakely et al., 2002; Sherrod, 2002; Nelson et al., 2002, 2003; ten Brink et al., 2002; Brocher et al., 2004; ten Brink et al., 2006; Liberty and Pratt, 2008).

Seismic reflection imaging for neotectonic studies across the Seattle fault has been conducted on the waterways that cross the region (e.g., Pratt et al., 1997; Johnson et al., 1999) and land-based seismic profiles east of Puget Sound (Liberty and Pratt, 2008). These studies have characterized the Seattle fault as an active south-dipping blind thrust fault system with multiple splays extending to the surface. The active Seattle fault is located along the southern boundary of the Seattle Basin and extends for more than 70 km east to the Snoqualmie River Valley and west to possibly as far as Hood Canal (Figure 1; Johnson et al, 1999; Blakely et al., 2002; Liberty and Pratt; 2008).

The subsurface structure and length of the SFZ remain elusive despite extensive study. Subsurface features are known from seismic profiles (Johnson et al., 1999; ten Brink et al., 2002; Calvert et al., 2001 and 2003; Fisher et al., 2006; Liberty and Pratt; 2008). These profiles have imaged a synclinal axial surface (deformation front) that forms the south edge of the Seattle basin north of several fault strands (Pratt et al., 1997; Johnson et al., 1999; Nelson et al., 2002, 2003; Sherrod, 2002). Individual fault strands have not been well located from seismic profiles because they are steeply dipping and are interpreted to lie within zones of little or no reflectivity. Correlating seismic reflection discontinuities with surface exposures (Sherrod et al., 2000; Nelson et al., 2003), paleoseismic trenches (Sherrod, 2002), and light distance and ranging (lidar) topographic data (Haugerud et al., 2003) also has been difficult because the marine profiles were acquired in deep troughs where the late Quaternary strata have been scoured during the most recent Quaternary glaciation (Booth, 1994).

Geologic and Tectonic Setting

The Puget Lowland of Washington State is a broad valley between the Olympic Mountains Coast Range and the Cascade Range volcanic arc (Fig. 1). The valley is home to more than 3 million people, including the populations of Seattle, Bellevue, Tacoma, Everett and Olympia. The Lowland lies above the Eocene suture zone between Crescent Terrane volcanic rocks and Tertiary North American crust (Johnson, 1984 and Johnson et al., 1996). Today, oblique convergence along the continental margin is accommodated in part by north-south shortening within the Lowland (Pratt et al., 1997; Wells et al., 1998; Miller et al., 2001; Mazzotti et al., 2002; Van Wagoner et al., 2002). This shortening expresses itself as a series of basins and uplifts separated by the Southern Whidbey Island, Seattle, Tacoma, and Olympia faults (Fig. 1).

Of the faults beneath the Puget Lowland, the Seattle fault has the greatest vertical relief on bedrock. The fault is a north-verging thrust or reverse fault separating the approximately 8 km thick Seattle basin on the north from uplifted basement rocks in the Seattle uplift to its south (Johnson et al., 1994; Pratt et al., 1997). Two recent models have been proposed for the Seattle fault: a simple thrust fault dipping to the south at ~40° with multiple strands and backthrusts at its tip (Pratt et al., 1997; ten Brink et al., 2002; Fisher et al. 2006; Liberty and Pratt; 2008), and a passive roof duplex in which a shallow detachment separates the deeper thrust fault from the shallow fault strands (Brocher et al., 2004).

Multiple late Quaternary earthquakes have been documented on the Seattle fault, including a M>7 earthquake at about 900-930 A.D. (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992). This earthquake history has been discerned west of Puget Sound by trenching of fault scarps discovered from recent lidar imagery (Sherrod et al, 2000; Haugerud et al., 2003; Nelson et al., 2003). Interpretations of the shallow structure in the SFZ from seismic reflection profiles are presented by Johnson et al. (1999) for both west and east of Puget Sound, ten Brink et al. (2002, 2006) for beneath Puget Sound, and Liberty and Pratt (2008) east of Puget Sound. Johnson et al. (1999) and Liberty and Pratt (2008) identify a prominent reflector within the Seattle basin as an unconformity between the Tertiary and Quaternary sediments. They place the top of undeformed Tertiary strata within the Seattle Basin at approximately 500 m depth below and east of Lake Washington. Quaternary and Tertiary reflectors are synclinally folded at the SFZ along the south edge of the Seattle Basin, so that strata south of this "deformation front" dip to the north in a structure termed the Seattle monocline (Johnson et al., 1999). Deformation to the south and on the Seattle uplift is characterized by short wavelength folding that separate a series of thrusts and backthrusts of the SFZ system (Liberty and Pratt, 2008).

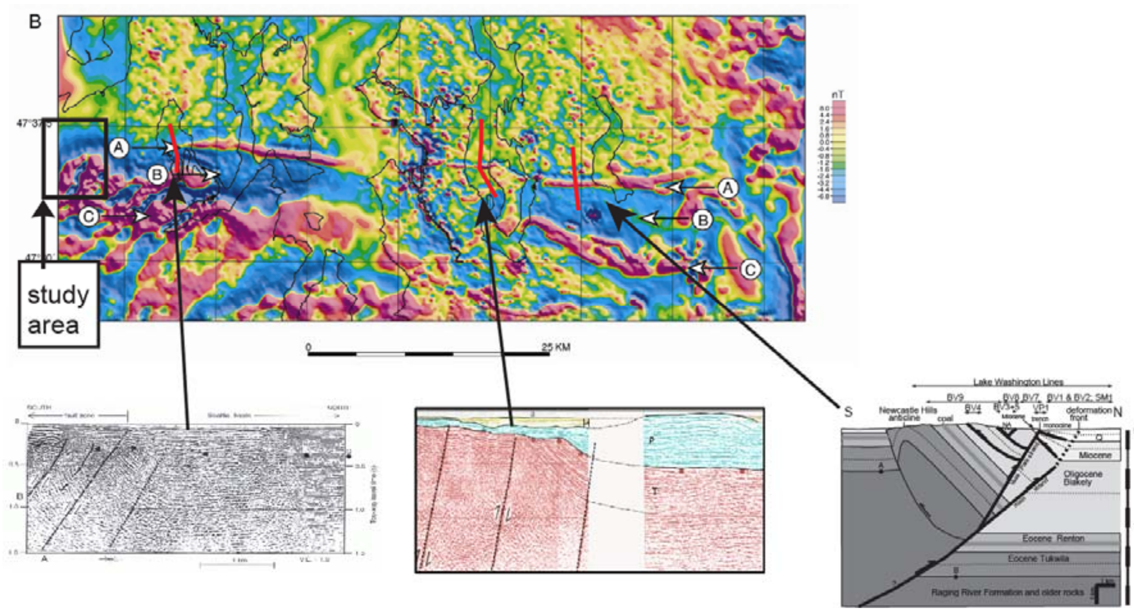

Figure 2. Filtered aeromagnetic anomaly map from the Seattle fault zone emphasizing shallow magnetic sources. Lineament A is related to steeply dipping Tertiary strata within the Seattle monocline that separates the Seattle Basin from the Seattle Uplift. Figure from Blakely et al. (2002). Images of the upper one km across the Seattle fault zone. (left) Dyes Inlet and (middle) Lake Washington seismic profiles showing Seattle fault zone, monocline and Seattle Basin (from Johnson et al., 1999) and (right) schematic of Seattle fault and related structures near Bellevue, Wa (from Liberty and Pratt, 2008). Note the similar deformation style across the length of the Seattle fault.

The Puget Lowland contains a cover of young glacial deposits and vegetation that makes it difficult to map fault from the surface (Schuster, 2005). High-resolution aeromagnetic data show lineaments that correlate with the mapped locations of Tertiary-age volcanic rocks and volcanic sediments (Figure 2; Blakely et al. 2002; Johnson et al., 2004). The well documented M>7 earthquake ca. A.D. 900 (e.g., Atwater et al. 1992; Bucknam et al. 1992; Jacoby et al. 1992) and LIDAR imagery and trenching of fault scarps (Sherrod, 2003; Haugerud et al. 2003) confirm that multiple late Quaternary earthquakes have occurred on the Seattle and Tacoma faults. Yet the geometry, connectivity, and location of these faults are unknown. Numerous tectonic models have been proposed (Pratt et al., 1997; ten Brink et al. 2002; Brocher et al., 2004). The models range from faulting along a single blind fault zone (Pratt et al. 1997) a broadly distributed passive roof duplex model that deforms the crust between the Seattle and Tacoma fault zones (Brocher et al., 2004). The complexity, length, and potential connectivity of the upper crust faults suggest that additional structural and paleoseismic studies are required to properly assess the earthquake hazards posed by faults within the Seattle fault zone.

The new seismic profiles collected during the summer of 2008 were all located west of Puget Sound, west of the city of Bremerton, and along the projected location of the Seattle fault, (Figures 1 and 3). Surface exposures in the region consist of Tertiary volcanic and sedimentary rocks near Green Mountain (Haeussler and Clark, 2000) and Pleistocene glacial and interglacial deposits throughout the remainder of the region.

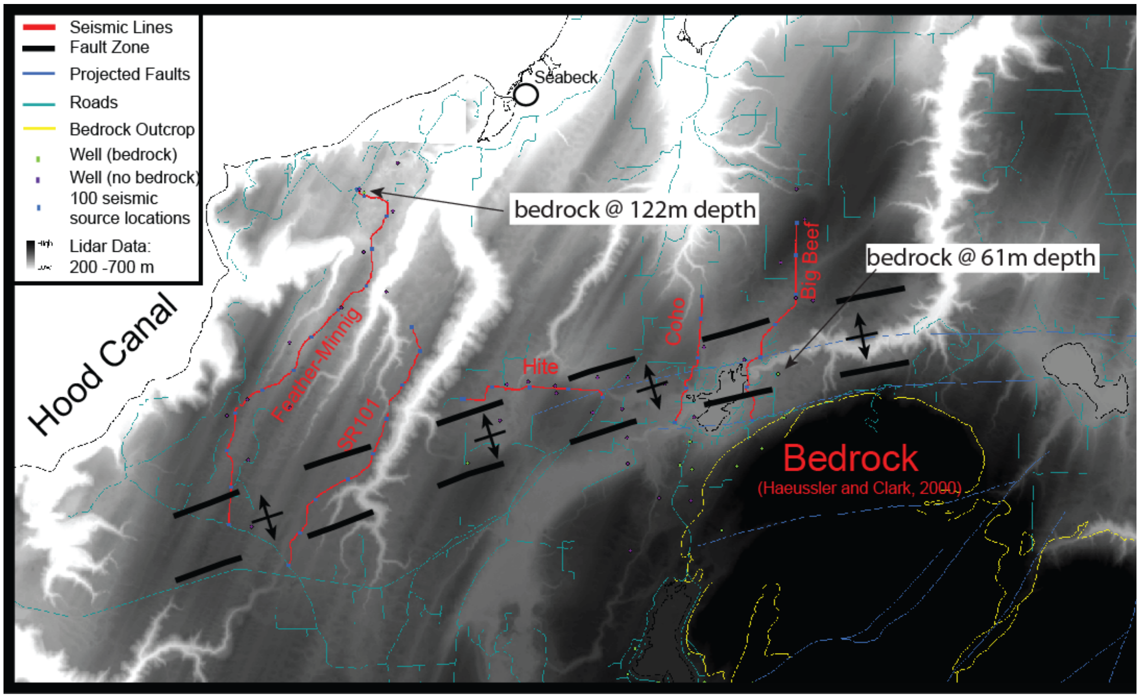

Figure 3. Lidar-derived elevation map showing seismic line locations for the summer 2008 field campaign, bedrock outcrops of Green Mountain (Haeussler and Clark, 2000), water well locations, and simplified interpretations from seismic data presented in this report.

Seismic Reflection Studies

We collected a series of land seismic reflection profiles to characterize the shallow (<1 km) portions of the western SFZ as part of a multi-year seismic study of active faults in the Puget Lowland. Profiles were collected west of Bremerton and east of Hood Canal on the Kitsap Peninsula. This collection of seismic profiles shows deformation related to the SFZ and further documents the SFZ's extent west of Bremerton to possibly interact with active faults and deformation west and south of Hood Canal.

I acquired approximately 25 km of hammer seismic reflection data along a series of mostly north-south profiles (Figure 3). I acquired 120 channel seismic reflection data in an off-end spread configuration to acquire offsets up to 600 m. Source and receiver spacing was 5 m with nominal 60-fold data. I used a Boise State trailer-mounted seismic source along city streets and forest roads. This 200 kg hammer is accelerated with a rubber band with has imaging capabilities (depth and frequency content) equivalent to the IVI Minivib II (e.g., Liberty and Pratt, 2008). I processed the seismic reflection data using ProMAX, a Landmark Graphics software package. Processing included bandpass and notch filters, velocity analyses/dip moveout iterations, common mid-point sort, ground roll and refraction mutes, automatic gain control, and stack. Signal penetration was restricted to the upper one km. Here, I present unmigrated traveltime and migrated depth images with generalized interpretations.

Past seismic reflection studies across the Seattle fault zone as well as the regional compilation of sonic and density logs (Brocher et al. 1998; Rau and Johnson, 1999), geologic mapping information, and aeromagnetic data (Blakely et al., 2002; Johnson et al., 2004) provide the basis for geologic and tectonic interpretations of the newly acquired seismic data. P-wave seismic velocities for latest Pleistocene and Holocene strata average 1,600 m/s when saturated and 1,200 m/s when unsaturated. Tertiary strata within the Seattle uplift and below the Quaternary fill of the Tacoma and Seattle Basins measure more than 2,800 m/s.

Lake Symington Area

I acquired 3 seismic profiles in the Lake Symington area on the Kitsap Peninsula between Hood Canal and Dyes Inlet and south of Seabeck, Washington (Figure 3). This area was mapped by Haeussler and Clark (2000) and shows east-striking faults affiliated with the Seattle fault zone offsetting Tertiary bedrock to the south from late Quaternary glacial deposits to the north (Figure 4). Evidence for active faulting in the Lake Symington area is derived from offset streams and projection of trenching and geophysical studies to the east (e.g., Johnson et al., 1999; Nelson et al., 2003; Liberty and Pratt, 2008). Although faults were mapped, the distinctive aeromagnetic lineament that defines the Seattle fault to the east changes character in the Lake Symington area and does not appear west of Green Mountain (Blakely et al., 2002). We acquired 2 north-south profiles and one west-east profile to determine if the Seattle fault and monocline appears in this area, and if so, define the fault and deformation character.

Big Beef seismic profile

The 2.9 km long Big Beef seismic profile was acquired from NW Holly Road north along Redwing Trail NW, Big Beef Crossing NW, to the northern termination of Bridletree Drive NW (Figure 4). The elevation along the profile increases approximately 60 m from south to north. Although the profile generally progresses from south to north, the middle portion of the profile is subparallel to geologic strike. Immediately south of NW Holly Road, outcrops of Eocene volcanic rocks appear as part of the Seattle uplift, while Pleistocene glacial and fluvial deposits are mapped along the length of the profile (Haeussler and Clark, 2000). A borehole at the Kitsap elementary school approximately 250 m east of position 1,100 identifies bedrock at 60 m depth, suggesting >10 degree dip on the Tertiary bedrock surface from outcrop exposures to the south (Figure 4; Haeussler and Clark, 2000). Haeussler and Clark (2000) project strands of the Seattle fault at positions 1,010 and 1,200.

The seismic profile shows a complex set of reflections in the upper 0.5 s along the profile length (Figure 5). Signal penetration is likely controlled by a combination of seismic source and geology. The southern portions of the profile show ~20 degree dipping strata overlain by broadly folded strata that extend to Location 1,400. Farther north, these folded strata terminate, but a deeper set of reflections appear to the northern portions of the profile.

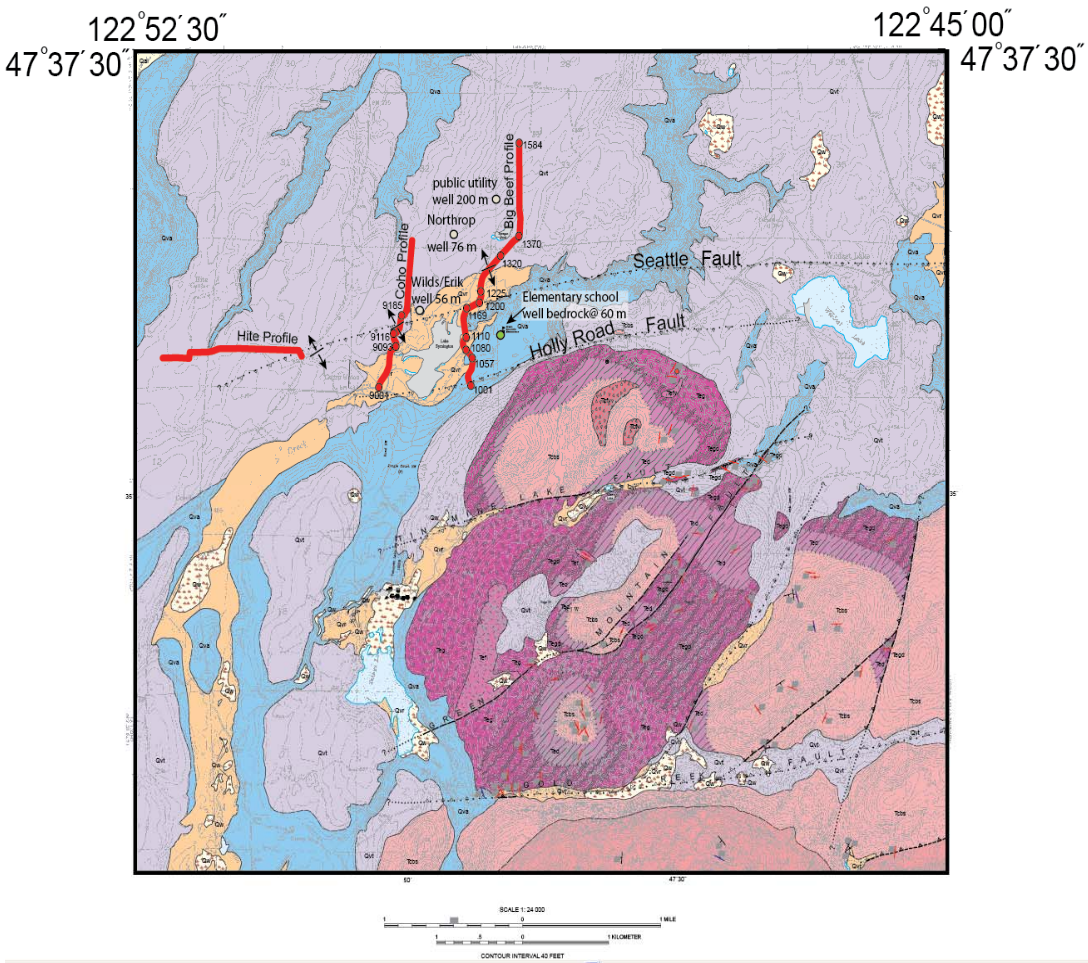

Figure 4. Geologic map for the Lake Symington area from Haeussler and Clark (2000) with seismic profile locations. Note the projected location of the Seattle fault and other related faults.

I interpret the dipping strata along the southern portions of the Big Beef profile as north-dipping Tertiary strata related to the Seattle monocline and Green Mountain within the hanging wall of the Seattle fault (Figure 5). The termination of the north dipping strata and offset reflectors suggests a fault may project to the surface near Location 1,200, consistent with a fault mapped by Haeussler and Clark (2000). The dips on Tertiary strata are consistent with the northernmost strata within the monocline to the east (e.g., Johnson et al., 1999; Liberty and Pratt; 2008) and the age of uplifted strata is likely older than east of Puget Sound. Shallower bedrock exposures at the elementary school suggest that bedrock strike may not be east-west. North of the monocline, a fold, centered at position 1,280, likely relates to deformed late Quaternary sedimentary rocks. These reflectors terminate near Location 1,400. I interpret a second north-directed thrust that offsets late-Quaternary strata at this location, likely a second strand of the Seattle fault. North of position 1,400, gently folded strata comprise strata within the deformation front of the Seattle Basin. Although faults are generally not imaged north of the monocline along the eastern and central portions of the Seattle fault, clear offset of strata along the Big Beef profile may suggest the blind Seattle fault may be closer to the surface near Green Mountain.

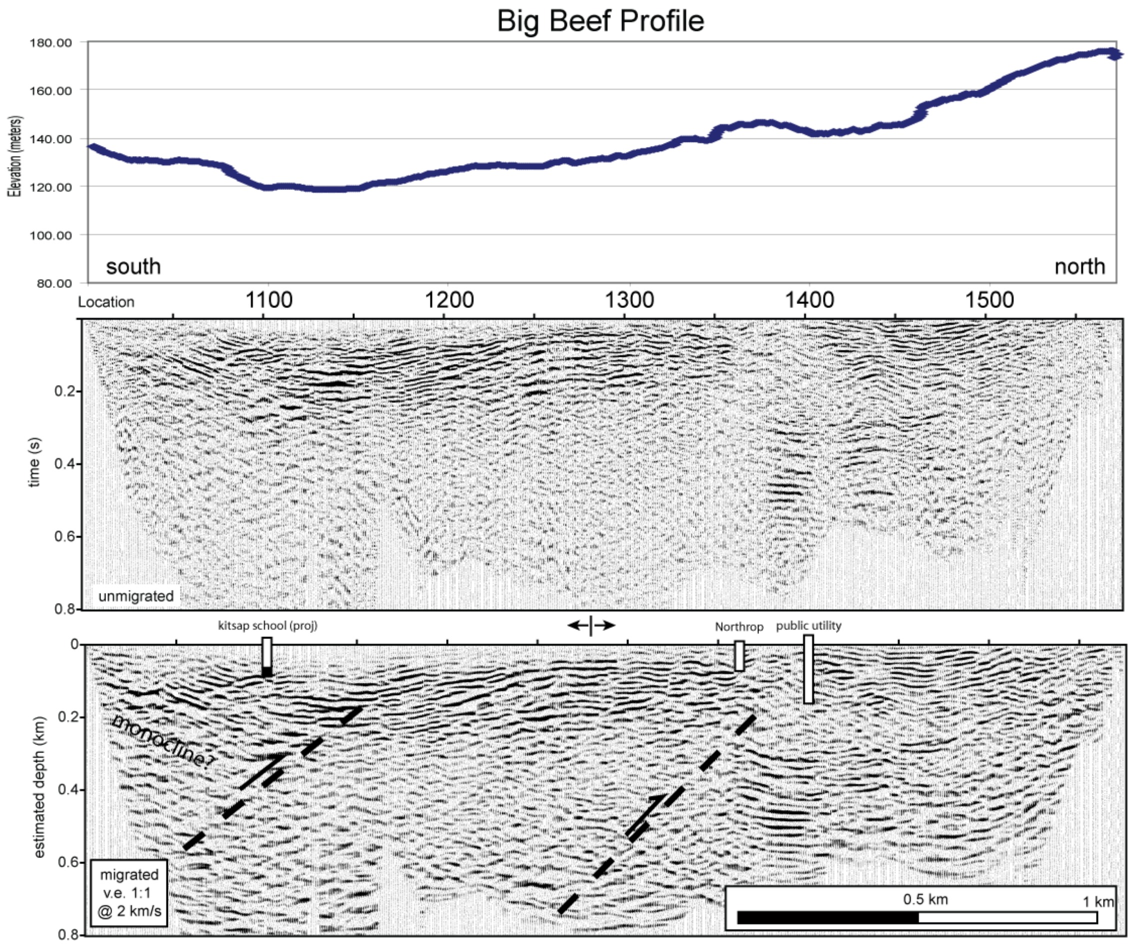

Figure 5. Big Beef unmigrated and migrated seismic profile east of Lake Symington showing late Pleistocene deformation related to the Seattle fault with the axis of an anticline located at Location 1,280. Profile location is shown on Figure 4.

Coho seismic profile

I acquired a 1.5 km long seismic profile approximately one km west of the Big Beef seismic profile, here termed the Coho seismic profile (Figure 4). This south-north profile begins at the intersection of NW Holly Road and NW Coho Run, extends north along Chum Lane NW to Dolly Varden Lane. The profile extends through private property north to Frender Lane NW where it terminates at a private residential road. The profile shows a similar reflection section to the Big Beef profile, however the ~20 m elevation change and the straighter profile provides a clearer image of structures and stratigraphy of the Lake Symington area (Figures 4 and 6).

I identify a near identical set of reflectors on the Coho seismic profile compared to the Big Beef profile (Figures 5 and 6). North-dipping strata along the southern portion of the Coho profile likely relate to the Tertiary strata of the Seattle monocline. The depth to the top of north dipping strata near the southern portions of the profile suggests an increased depth to bedrock, consistent with mapped geology (Haeussler and Clark, 2000). Reflectors are offset near Location 9,100 where I interpret a strand of the Seattle fault offsetting the north-dipping Tertiary strata from the deformed late Quaternary strata to the north. A broad fold is identified on this profile is centered at position 9,170, and offset reflectors suggest a second fault projected to the surface near the northern portion of the profile (Location 9,250). Assuming the two mapped faults identified on both Coho and Big Beef profiles represent the same structures, the Seattle fault strikes southwest in the Lake Symington area.

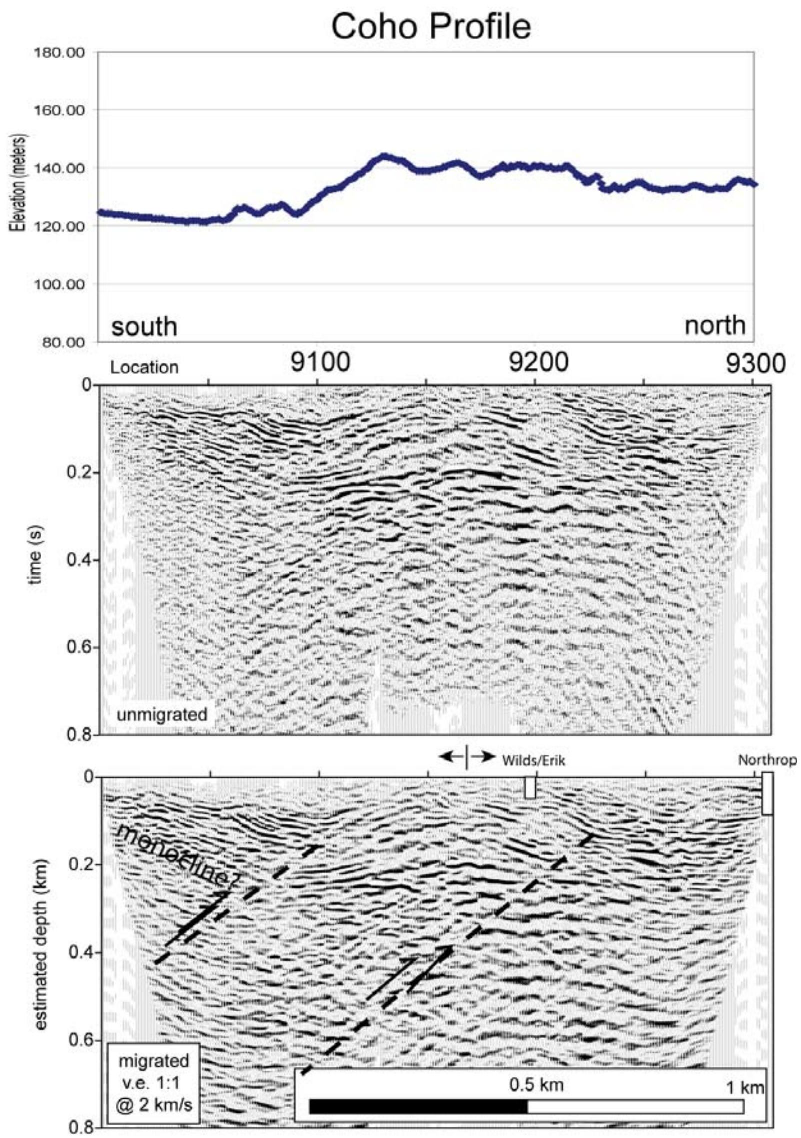

Figure 6. Coho unmigrated time and migrated depth seismic profile west of Lake Symington showing deformation related to the Seattle fault. The anticline centered at 9,170 deforms late Pleistocene sediments with 2 mapped reverse associated with the Seattle fault. Profile location is shown on Figure 4.

Hite seismic profile

The east-west 1.5 km long Hite seismic profile was acquired along NW Hite Center Road west from NW Seabeck Holly Road to the termination of NW Lusby Lane (Figure 4). An elevation change of approximately 10 m across the section along a relatively straight, quiet road provided an ideal environment for seismic acquisition (Figure 7). However, data quality was significantly poorer than either the Coho or Big

Beef profiles. I attribute this change in data quality to subsurface geologic conditions where the profile was acquired oblique to geologic strike with near identical surface conditions compared to the profiles to the east.

I interpret the mostly west-dipping reflectors along the eastern portion of the Hite Road seismic profile to be associated with the interpreted anticline identified on Coho and Big Beef profiles. Projecting the N60E strike of the Seattle fault along the 2 profiles to the east would place the eastern portions of the Hite Road profile along the northwestern limb of this fold. Where data quality diminishes farther west, I interpret the northern strand of the Seattle fault, as identified to the east. The poor data quality and lack of continuous reflectors may indicate that the profile was acquired within the deformation front of the Seattle fault, 60 degrees oblique to the interpreted geologic strike.

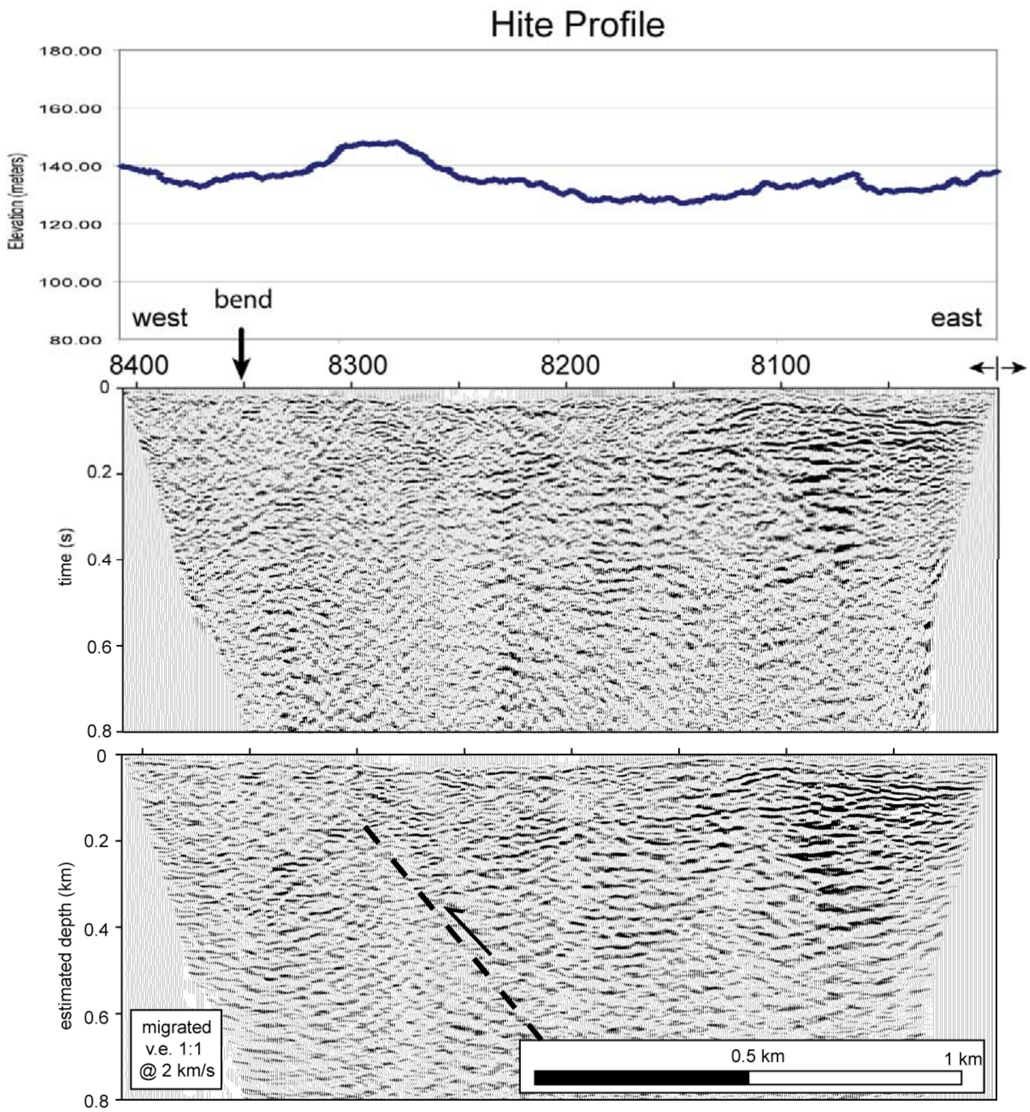

Figure 7. Hite Road unmigrated and migrated seismic profile west of Lake Symington showing deformation related to the Seattle fault. Profile location is shown on Figure 4.

Hood Canal East

The Hood Canal East profiles consist of two parallel south-north profiles immediately west of the Lake Symington profiles (Figure 3). I acquired these profiles to determine whether deformation is observed along strike of the Seattle fault, as interpreted to the east. The SR101 profile is located less than one km west of the western termination of the Hite profile while the Feather-Minnig profile was located approximately 0.5 km west of the SR101 profile. These profiles are located west of the interpreted western boundary of the Seattle Basin (Finn, 1990).

SR101 Profile

The 3.8 km SR101 profile was acquired along gated state forest road 101 east of the Feather-Minnig profile and west of NW Seabeck Holly Road starting south from Nellita Road NW (Figure 3). The profile was acquired on a gravel road with little elevation change (Figure 8). Data quality along the profile was variable, with the southern portions of the profile producing reflections to approximately ½ the depth as observed to the north.

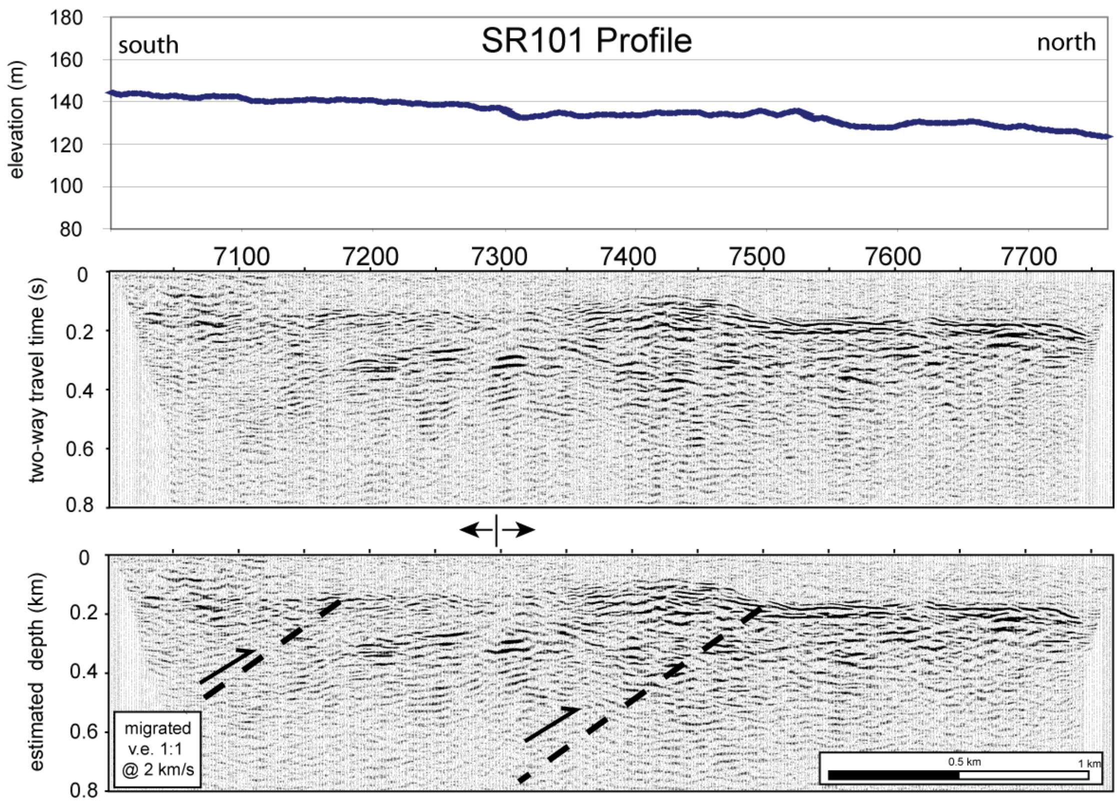

Figure 8. SR101 unmigrated and migrated seismic profile west of Lake Symington and east of Hood Canal showing deformation related to the Seattle fault west of Lake Symington. Seismic line locations are shown on Figure 3.

I identify an anticline centered at position 7,300 along the SR101 profile that matches the character of the fold observed on the Lake Symington profiles (Figure 8). Flat-lying strata to the north and north-dipping strata to the south are also similar to the character observed on Big Beef and Coho profiles. Therefore, I interpret the Seattle fault extending west of Green Mountain along the central portions of the SR101 profile. The poor reflector quality along the southern portions of the profile where the Seattle monocline should appear may be a result of increased depths to Tertiary strata and discontinuous glacial stratigraphy in the upper few hundred meters depth. This reflector character is similar to the Hite seismic profile to the east.

Feather-Minnig Seismic profile

The 5.5 km Feather-Minnig seismic profile was acquired along Feather Lane NW south from Nellita Road NW to the northern road termination (Figure 3). The road then extends through private property north to Minnig Lane NW north to Stavis Bay Road NW (Figure 9). The gravel roads are located approximately 1-2 km east of Hood Canal along strike of the Seattle fault as mapped to the east with an elevation decrease of approximately 50 m from south to north (Figure 9). Water well data indicate that bedrock was reached at 122 m depth along the northernmost portion of the profile.

The reflection character in the upper 0.6 s of the Feather-Minnig profile suggest the Seattle fault, as defined to the east, does not continue along the observed strike to Hood Canal, but may continue along strike of the structures observed on the profiles to the east (Figures 5-8). The southern portion of the profile shows north-dipping strata, and flat-lying and gently folded strata appear along the central and northern portions of the profile (Figure 9). Bedrock is identified at 120 m depth in a well along the northern portion of the profile.

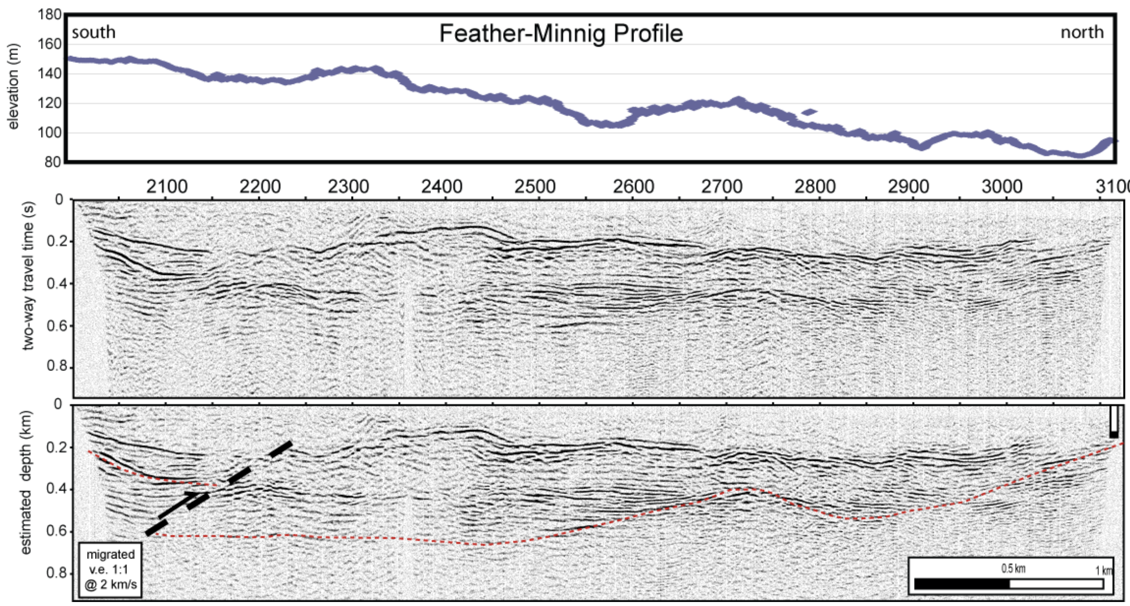

Figure 9. Feather-Minnig unmigrated and migrated seismic profile east of Hood Canal showing deformation related to the Seattle fault. Profile location is shown on Figure 3.

I interpret the north dipping strata along the southern portion of the Feather-Minnig profile as the north limb of the fold observed on the profiles to the east. The structure is along strike of the observed northernmost strand of the Seattle fault at Lake Symington and SR101 profiles. Farther north, a prominent fold appears at approximately 0.2 km depth. Although this fold may be related deformation within the to the Seattle fault zone, deeper strata do not appear to show similar deformation and may be related to glacial deposition. I interpret an unconformity near position 2,700 at ~0.4 km depth as a bedrock (dashed line) high sitting upon flat-lying late Quaternary strata. The bedrock high shallows to the north to tie to bedrock observed in a borehole near position 3,100.

Discussion and Conclusions

Seismic reflection data on the Kitsap Peninsula show deformation related to the Seattle fault as far west as Hood Canal with the Seattle fault appearing north of Green Mountain on the Lake Symington profiles, then striking southwest across the western portions of the Kitsap Peninsula. Each of the seismic profiles is consistent with fold that defines the northern extent of the Seattle fault system. My interpretation suggests the Seattle fault may extend across Hood Canal and possibly interact with the Saddle Mountain fault system and Dewatto Basin structures (Figure 10; Johnson et al., 2004; Blakely et al., 2009). Additionally, east-west oriented magnetic lineaments identified within Hood Canal suggest fault strands related to the SFZ may also continue west of Hood Canal. The interaction of the western extension of the SFZ with the termination of the Seattle Basin and structures mapped west of Hood Canal all suggest a complex interplay of tectonic structures in the area with a need for additional studies to further characterize the geologic and tectonic setting for the area.

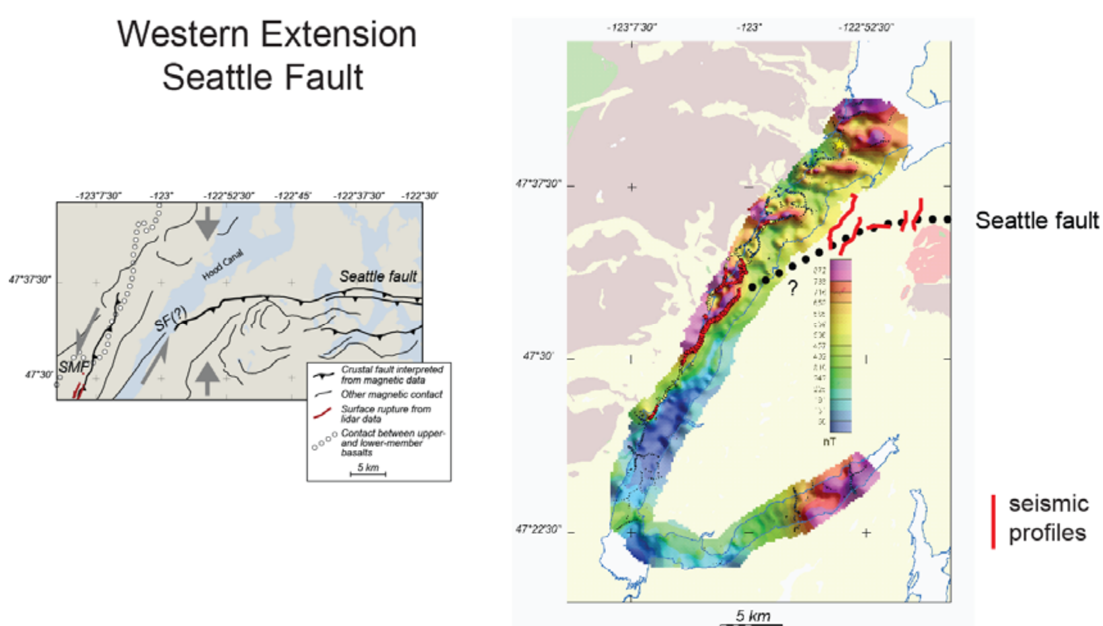

Figure 10. (left) Tectonic interpretation of the western extension of the Seattle fault (revised from Blakely et al. 2009) incorporating structures presented in this report. (right) Newly acquired aeromagnetic data from Hood Canal (R. Blakely, personal comm.) with the interpreted trace of the Seattle fault. The Seattle fault may link to other mapped faults near Hood Canal including the Saddle Mountain fault (SMF).

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References

Atwater, B. F. and A. L. Moore (1992). "A tsunami about 1000 years ago in Puget Sound, Washington." Science **258**(5088): 1614-1617.

Blakely, R.J., Sherrod, B.L., Hughes, J.F., Anderson, M.L., Wells, R.E., and Weaver, C.S. (2009). Saddle Mountain fault deformation zone, Olympic Peninsula, Washington: Western boundary of the Seattle uplift, *Geosphere*; v. 5; no. 2; p. 105–125; doi: 10.1130/GES00196.

Blakely, R. J., R. E. Wells, C. S. Weaver, and S. Y. Johnson (2002). Location, structure, and seismicity of the Seattle fault, Washington, Geol. Soc. Am. Bull. 114, 169–177.

Booth, D.B., Troost, K.G., and Hagstrum, J.T., (2004). Deformation of Quaternary strata and its relationship to crustal folds and faults, south-central Puget Lowland, Washington State, Geological Society of America Bulletin, v. 32, no. 6, p. 505-508.

Brocher, T.M., R.J. Blakely, and R.E. Wells (2004). Interpretation of the Seattle Uplift, Washington, as a passive-roof duplex, Bull. Seism. Soc. Am., 94, 1379-1401.

Brocher, T. M., T. Parsons, R. J. Blakely, N. I. Christensen, M. A. Fisher, R. E. Wells, and SHIPS Working Group (2001), Upper crustal structure in Puget Lowland, Washington: Results from 1998 Seismic Hazards Investigation in Puget Sound, J. Geophys. Res., 106, 13,541–13,564, doi:10.1029/2001JB000154.

Brocher, T. M. and A. L. Ruebel (1998). Compilation of 29 sonic and density logs from 23 oil test wells in western Washington state, U.S. Geological Survey Open file report 98-249.

Bucknam, R. C., E. Hemphill-Haley, et al. (1992). "Abrupt uplift within the past 1700 years at southern Puget Sound, Washington." Science **258**(5088): 1611-1614.

Calvert, A. J., M. A. Fisher, and the SHIPS Working Group (2001). Imaging the SFZ with high-resolution seismic tomography, *Geophys. Res. Lett*. **28**, 2337–2340.

Calvert, A. J., M. A. Fisher, S. Y. Johnson, and the SHIPS Working Group (2003). Along-strike variations in the shallow seismic velocity structure of the SFZ: Evidence for fault segmentation beneath Puget Sound, *J. Geophys. Res.* **108 (B1)**, doi:10.1029/2001JB001703.

Finn, C., (1990). Geophysicacal constraints on Washington Convergen Margin Structure, *Journal of Geophysical Research*, v. 95, no. B 12,19,533-19,546.

Fisher, M.A., Hyndman, R.D., Johnson, S.Y., Brocher,T.M., Crosson, R.S., Wells, R.E., Calvert, A.J., and ten Brink, U.S. (2006). Crustal Structure and Earthquake Hazards of the Subduction Zone in Southwestern British Columbia and Western Washington, in Kayen, R., editor, Earthquake Hazards of the Pacific Northwest Costal and Marine Regions, USGS Professional Paper 1661-C, 28 p.

Haeussler, P. J., and Clark, K. M., 2000, Geologic map of the Wildcat Lake 7.5' quadrangle, Kitsap county, Washington: U. S. Geological Survey Open File

Report 00-356, scale 1:24,000, 1 sheet: http://geopubs.wr.usgs.gov/openfile/of00-356/.

Haugerud, R.A., harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S. (2003). High-Resolution Lidar Topography of the Puget Lowland, Washington, GSA Today.

Jacoby, G. C., P. L. Williams, et al. (1992). "Tree ring correlation between prehistoric landslides and abrupt tectonic events in Seattle, Washington." Science **258**(5088): 1621-1623.

Johnson, S. Y. (1984). Evidence for a margin-truncating transcurrent fault (pre–late Eocene) in western Washington, *Geology*, **12**, 538–541.

Johnson, S. Y., S. V. Dadisman, J. R. Childs, and W. D. Stanley (1999). Active tectonics of the Seattle fault and central Puget Lowland: Implications for earthquake hazards, *Geol. Soc. Am. Bull.* **111**, 1042–1053.

Johnson, S. Y., C. J. Potter, and J. M. Armentrout (1994). Origin and evolution of the Seattle basin and Seattle fault, *Geology* **22**, 71–74.

Johnson, S. Y., C. J. Potter, J. M. Armentrout, J. J. Miller, C. Finn, and C. S. Weaver (1996). The southern Whidbey Island fault, an active structure in the Puget Lowland, Washington, *Geol. Soc. Am. Bull.* **108**, 334–354.

Liberty, L.M. and Pratt, T.L. (2008). Structure of the Eastern Seattle Fault Zone, Washington State: New Insights from Seismic Reflection Data: Bull. Seis. Soc. Am., Vol. 98, No. 4, pp. 1681–1695, doi: 10.1785/0120070145.

Mazotti, S., H. Dragert, and R. D. Hyndman (2002). N-S shortening across the Olympic Mountains and Puget Sound evidenced by GPS, *Geol. Soc. Am. Abstr. Programs* **34**, A90.

Miller, M. M., D. J. Johnson, et al. (2001). "GPS-determination of along-strike variation in Cascadia margin kinematics; implications for relative plate motion, subduction zone coupling, and permanent deformation." Tectonics **20**(2): 161-176.

Nelson, A. R., S. Y. Johnson, H. M. Kelsey, R. E. Wells, B. L. Sherrod, S. K. Pezzopane, L. Bradley, and R. D. Koehler III (2003). Late Holocene earthquakes on the Toe Jam Hill fault, SFZ, Bainbridge Island, Washington, Geol. Soc. Am. Bull. 115, 1388–1403.

Nelson, A. R., S. Y. Johnson, R. E. Wells, S. K. Pezzopane, H. M. Kelsey, B. L. Sherrod, L. A. Bradley, R. D. Koehler III, R. C. Bucknam, R. A. Haugerud, and W. T. LaPrade (2002). Field and laboratory data from an earthquake history study of the Toe Jam Hill fault, Bainbridge Island, Washington, *U.S. Geol. Surv. Open-File Rept.* 02-60, 37 pp., 2 plates.

Pratt, T. L., S. Y. Johnson, et al. (1997). "Seismic reflection images beneath Puget Sound, western Washington State; the Puget Lowland thrust sheet hypothesis." *Journal of Geophysical Research, B, Solid Earth and Planets* **102**(12): 27,469-27,489.

Sherrod, B.L. (2002). Late Quaternary surface rupture along the Seattle fault zone near Bellevue, Washington: *Eos, Transactions, American Geophysical Union* **83,** Fall Meeting Supplement S21C-12.

Sherrod, B. L., R. C. Bucknam, and E. B. Leopold (2000). Holocene relative sea level changes along the Seattle fault at Restoration Point, Washington, *Quat. Res.* **54**, 384–393.

ten Brink, U. S., P. C. Molzer, et al. (2002). "Subsurface geometry and evolution of the Seattle fault zone and the Seattle Basin, Washington." Bulletin of the Seismological Society of America **92**(5): 1737-1753.

Van Wagoner, T. M., R. S. Crosson, K. C. Creager, G. F. Medema, L. A. Preston, N. P. Symons, and T. M. Brocher (2002). Crustal structure and relocated earthquakes in the Puget Lowland, Washington from high resolution seismic tomography, *J. Geophys. Res.* **107 (**B12), 2381, doi 10.1029/2001JB000710.

Wells, R. E., C. S. Weaver, and R. J. Blakely (1998), Forearc migration in Cascadia and its neotectonic significance, Geology, 26, 759 – 762, doi:10.1130/0091-7613

Yount, J. C., and H. D. Gower (1991). Bedrock geologic map of the Seattle 300 by 600 quadrangle, Washington, scale 1:100,000, *U.S. Geol. Surv. Open File Rep.* **91 – 147**, 37 pp., 4 plates.