Seismic Characterization of the Seattle and Southern Whidbey Island Fault Zones in the Snoqualmie River Valley, Washington

Project Award Number: 06HQGR0111

Lee M. Liberty and Kristin M. Pape

Center for Geophysical Investigation of the Shallow Subsurface (CGISS)

Boise State University

Boise, Idaho 83725-1536

Phone: 208-426-1166

Fax: 208-426-3888

lml@cgiss.boisestate.edu

http://cgiss.boisestate.edu/~lml

Program Element: II

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 06HQGR0111. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Abstract

This report summarizes the results from seismic reflection profiling across the South Whidbey Island fault (SWIF) during the summer 2006 field season. The team from Boise State University collected seven seismic transects totaling more than 30 km to locate and characterize faults associated with the SWIF. Each transect crosses the projected location of the SWIF or related fault system. Data quality from each section provides clear images to upwards of one km depth. The base of the Quaternary strata and top of the Eocene volcanic rock surface are imaged, as are fault related structures. Our results confirm active faulting near Woodinville, consistent with trench, LiDAR, and aeromagnetic anomalies. Along the Ames Lake profile, a kink-band showing north-side up faulting is in line with the projected SWIF. Farther south, deformation related to the Seattle fault and Rattlesnake Mountain fault system suggests these three fault systems interact and/or merge near Snoqualmie, Washington. Our observations suggest the Seattle fault extends east to the Snoqualmie River and the faulting along the projected SWIF continues along trend along the mapped Rattlesnake Mountain fault. It is unclear the tectonic history of each fault segment due to the presence of young fluvial sediments in the Snoqualmie River Valley, but our results are consistent with a >150 km long active SWIF.

Introduction

Seismic reflection imaging for neotectonic studies across the South Whidbey Island fault (SWIF) has thus far been conducted on the waterways of Puget Sound (e.g., Pratt et al., 1997; Johnson et al., 1996). However, the SWIF is projected to extend outside the reach of Puget Sound and may extend more than 150 km (Johnson et al., 1996; Sherrod et al., 2008). We acquired seismic reflection profiles at six different locations totaling approximately 30 km with a 200 kg trailer-mounted accelerated weight drop truck. The goal was to image Neogene and younger sediments across the projected location of the SWIF southeast of Puget Sound and along the northern margins of the Seattle Basin along the projected location of the Seattle fault. Here, we describe each profile, summarize the results for each transect and describe the implications of this study.

Geologic and Tectonic Setting

The broad valley west of the Cascade Range and east of the Olympic Mountains in the vicinity of Seattle, Washington is termed the Puget Lowland. This forearc basin lies above terranes accreted to North America along the Cascadia subduction zone (Figure 1). Oblique convergence along the continental margin is accommodated by north-directed shortening in the Puget Lowland (Wells et al. 1998; Miller et al. 2001). The region contains a cover of young glacial deposits and vegetation that makes it difficult to map faults from the surface. 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 recent LIDAR imagery, trenching and geologic mapping of fault scarps (e.g., Nelson et al. 2003; Sherrod et al, 2008) confirm that multiple late Quaternary earthquakes have occurred on the Seattle fault and SWIF. Yet the geometry, connectivity, and location of all the faults in the Puget Lowland are unknown. Tectonic models to connect many of the faults of the region range from faulting along a single blind fault zone (Pratt et al. 1997) and a broadly distributed passive roof duplex model that deforms the crust (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 the Seattle fault.

Based on the potential field anomalies, Gower et al. (1985) originally mapped the SWIF as a single, steeply dipping, down-to-the-north 80 km long fault extending northwestward from Whidbey Island to Vancouver Island (Figure 1). Johnson et al. (1996) used seismic-reflection profiles in Puget Sound near Whidbey Island, sea-cliff exposures on Whidbey Island, and sparse borehole data to map and interpret the SWIF as a broad fault zone (6 to 11 km wide) dipping steeply to the northeast. Both studies suggested that the SWIF developed in the early Eocene as an arc-parallel strike-slip fault, and, responding to oblique convergence of the subducting plate and clockwise rotation of the forearc, has evolved into a complex transpressional structure exhibiting dextral strike-slip, reverse, and thrust components of displacement. Kelsey et al. (2004) showed evidence from two marshes on opposite sides of the northern strand on Whidbey Island for north-side-up displacement about 3000 years ago, probably associated with a M7 earthquake.

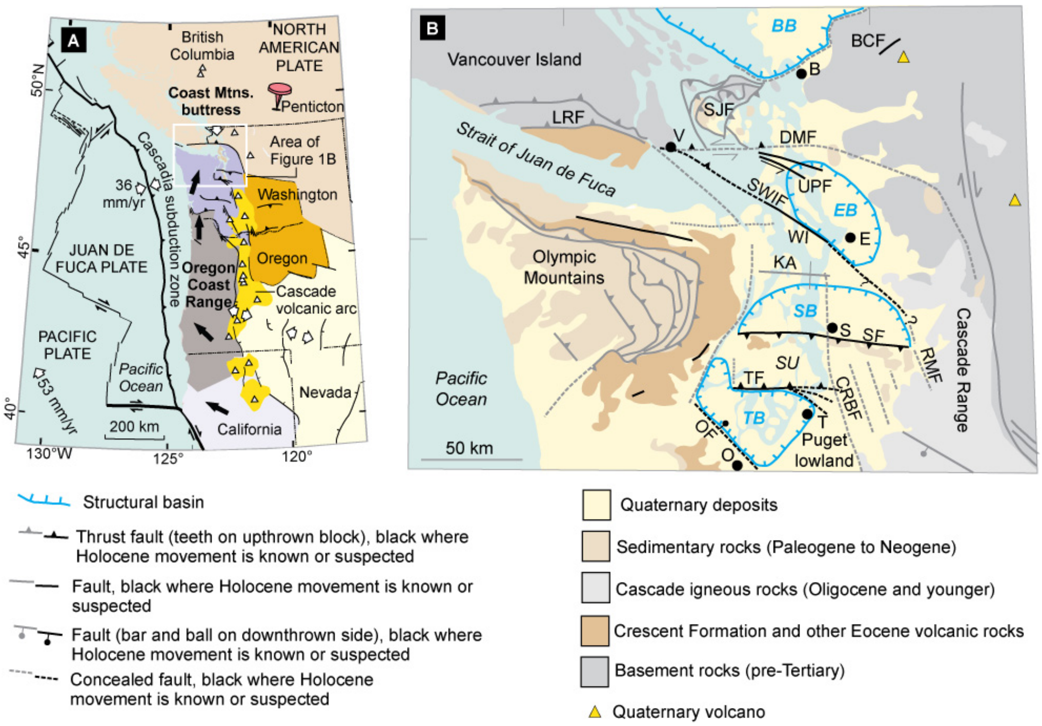

Figure 1. (a) Kinematic model of Cascadia forearc, simplified from Wells and others (1998) and Wells and Simpson (2001). Northward migration of the Oregon Coast Range squeezes western Washington against North America, producing faults and earthquakes in the Puget Lowland. (b) Generalized map of the Puget Lowland. BB, Bellingham basin; EB, Everett basin; SB, Seattle basin; TB, Tacoma basin; LRF, Leech River fault; BCF, Boulder Creek fault; SJF, San Juan fault; DMF, Devils Mountain fault; UPF, Utsalady Point fault; SWIF, southern Whidbey Island fault; SF, Seattle fault; TF, Tacoma fault; OF, Olympia fault; CRBF, Coast Range boundary fault; RMF, Rattlesnake Mountain fault; V, Vancouver; B, Bellingham; E, Everett; S, Seattle; T, Tacoma; O, Olympia; WI, Whidbey Island; KA, Kingston arch; SU, Seattle uplift.

The SWIF lies adjacent to the 8.5 km deep Everett basin that is filled with Tertiary and younger sedimentary rocks (Figure 1; Johnson et al., 1996). To the northwest, the SWIF passes along the northeastern margin of the Port Townsend basin, identified with seismic tomography (Brocher et al., 2004; Ramachandran et al., 2005), and merges with the Leech River and Devils Mountain (Figure 1). The southeastward extension of the SWIF may cross or control the northeastern margin of the Seattle basin and merge with the Seattle fault and Rattlesnake Mountain fault. If this is the case, the SWIF extends 150 km, from near Victoria, British Columbia to Snoqualmie, Washington (Figures 1 and 2).

The Seattle fault is a north-directed blind thrust fault that controls many of the structures associated with the Seattle basin, Seattle uplift, and Tacoma Basin (e.g., Pratt et al. 1997; Johnson et al. 1999; Brocher et al. 2004; Liberty and Pratt, 2008). The Seattle fault is a 5-7 km wide > 70 km long fault zone that separates the Seattle Basin to the north from the Seattle uplift to the south (Figures 1 and 2). A faulted and folded monocline represents the southern boundary of the Seattle fault (e.g., Johnson et al., 1999; Blakely et al., 2002; Liberty and Pratt, 2008). Faulting and folding related to the Seattle fault extends at least

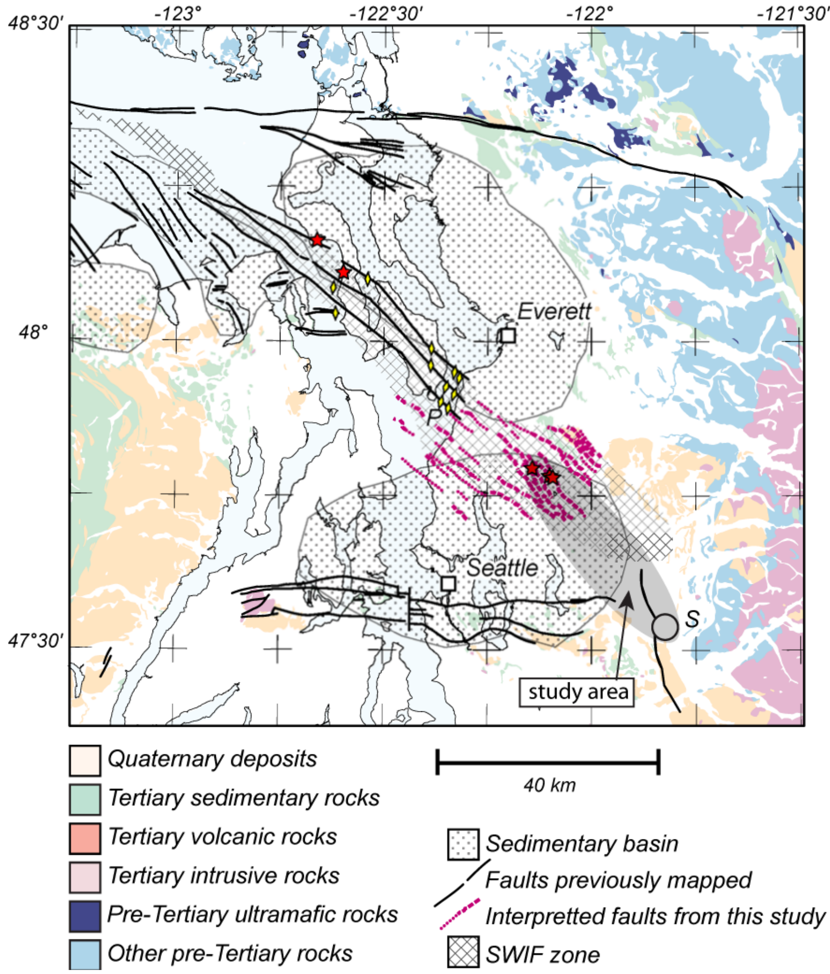

Figure 2. The SWIF and Seattle fault in relation to Tertiary and older bedrock structures. Solid black lines are faults from the USGS Quaternary fault database. Red dashed and dotted lines are aeromagnetic lineaments and red stars are observations of Holocene deformation (Sherrod et al., 2008). Stippled areas are sedimentary basins. Red crosshatch pattern indicates the width of the SWIF. Geoloigic units are generalized from Dragovich et al. (2002). The gray oval represents the study area presented in this report. S=Snoqualmie.

as far east as Lake Sammamish, perhaps to the eastern extent of the Seattle Basin (Liberty and Pratt, 2008).

Seismic Reflection Studies

The only past seismic reflection studies across the SWIF were acquired in Puget Sound (Johnson et al., 1996). These seismic profiles, as well as the (Brocher et al. 1998) regional compilation of sonic and density logs, geologic mapping information, and aeromagnetic data (Blakely et al., 2004; Sherrod et al., 2008) 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 1600 m/s when saturated and 1200 m/s when unsaturated. Pleistocene strata appear within the Seattle Basin and average 2000 m/s. Miocene and older strata within the Seattle uplift and below the Quaternary fill of the Seattle Basin measure upwards of 2800 m/s. Glacial till that appears in outcrop throughout the region and is likely contained within the upper few hundred meters, contains measured seismic velocities up to 2500 m/s. These seismic velocity values are important to note when converting seismic travel time measurements to depth, especially in regions where large lateral velocity variations appear (e.g., where glacial till juxtaposes fine-grained Pleistocene and Holocene strata).

The seismic surveys employed a 120-channel seismograph with 5 m source and receiver spacing. The seismic source was a 200 kg trailer-mounted hammer-drop capable of imaging down to depths of 1 km. Data processing included elevation and residual statics, bandpass filter, multiple iterations of velocity analysis and dip move-out, and post-stack Kirchoff migration (Yilmaz, 2001).

Woodinville Area Profiles

Two high-resolution seismic-reflection profiles acquired from the Woodinville area show evidence for active faulting. These results are published in Sherrod et al. (2008). The 2.8 km long east-west oriented 195th Street profile was acquired through a residential area adjacent to a paleoseismic excavation (Figure 3). The 2.0 km long north-south oriented Crystal Lake profile was acquired on a private road along the lake's western shore. The most recognizable contact in the seismic sections (noted by the black triangles in Figure 3) is located in the upper 100-300 m (0.15-0.4 s two-way travel time) and is characterized by an abrupt change from thin, evenly bedded reflectors over discontinuous, wavy reflectors. We interpret this change in seismic character to represent an unconformity separating Tertiary rocks from overlying Quaternary deposits, consistent in depth to nearby boreholes (Rau and Johnson, 1999). In the 195th Street section, reflections along the eastern portion of the profile dip westward while reflections along the western portion of the profile dip to the east.

The 195th Street profile crosses, from west to east, the Leota aeromagnetic lineament, the Grace topographic lineament, the Little Bear Creek aeromagnetic lineament, and an unnamed LiDAR scarp (Figure 3; Sherrod et al., 2008). Deformed strata were observed near each of these lineaments with the greatest vertical motion correlating with the location of two aeromagnetic lineaments. The most prominent deformation occurs near the center of the seismic section (Figure 3, immediately west of GL/LBCL), where the reflectors are laterally truncated near the synclinal axis of a broad fold. We infer that movement on the Grace lineament resulted in deformation of Tertiary and overlying Quaternary deposits. Approximately 0.4 km east of this fault, we identify a second fault that offsets Tertiary strata, but overlying Quaternary strata are undeformed. The fault observed near the Leota aeromagnetic lineament offsets Tertiary strata, but shallow Quaternary deposits were not clearly imaged on this profile (Figure 3, label LL).

The Crystal Lake profile, in contrast to the 195th Street profile, shows relatively undisturbed reflectors along its entire length (Figure 3). A feature observed on the LiDAR maps crosses near the middle of the Crystal Lake profile. This feature, labeled

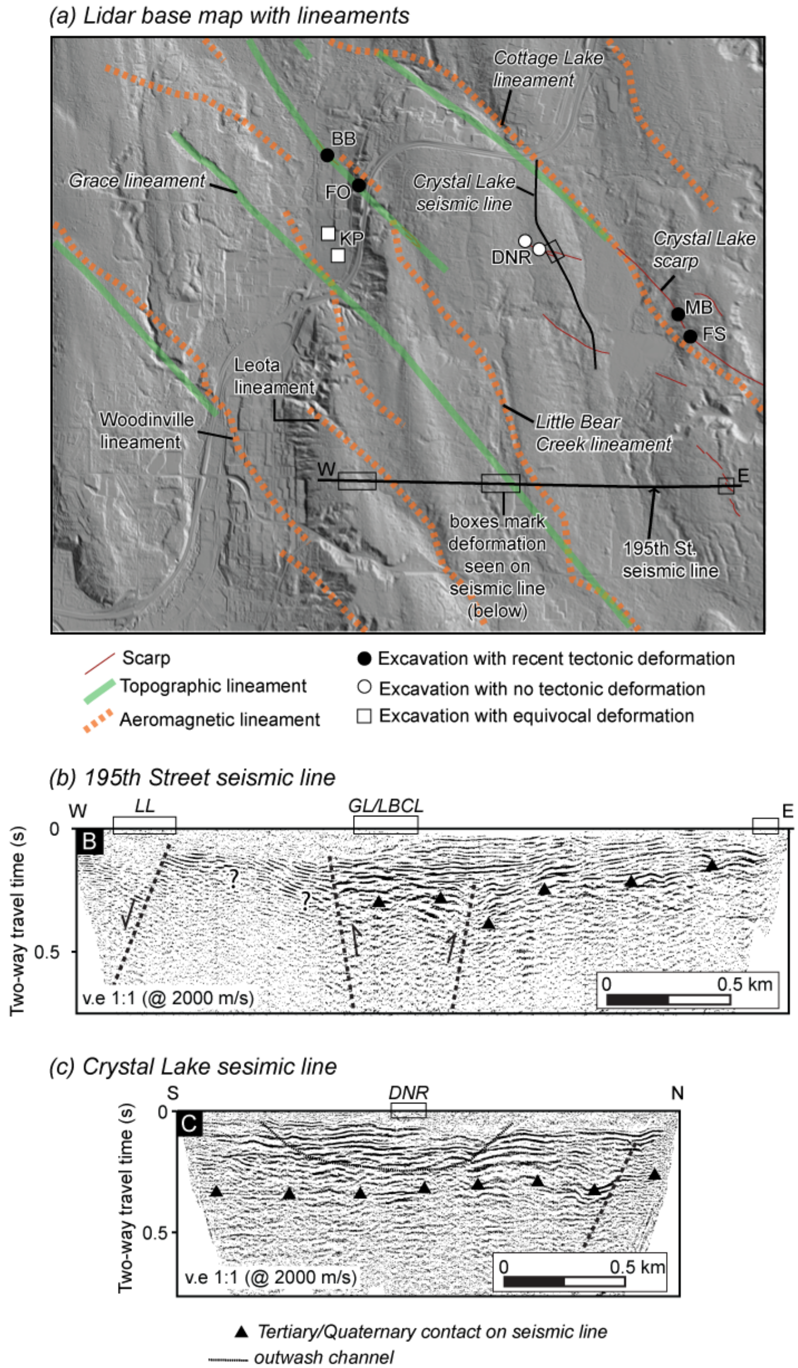

Figure 3. (a) Interpreted LiDAR image of the Woodinville area showing paleoseismic trench excavation locations (Sherrod et al., 2008). Thick lines are magnetic and topographic lineaments. This image graphically shows the relationship of excavations with tectonic features to mapped lineaments, and the lack of deformation in areas between the lineaments. (b) Seismic reflection profile along 195th St. showing a zone of deformation where the Grace lineament and the Leota lineament cross the profile. (c) Seismic reflection profile along Crystal Lake Road showing flat lying strata and a paleochannel in the center of the profile.

DNR, was initially interpreted as a possible fault scarp. However, excavations across this feature did not show any deformation (Sherrod et al., 2008). We interpret an outwash channel centered at DNR and a fault along the northern portion of this profile. This normal fault matches the location of the Cottage Lake lineament where Quaternary strata are dragged down to the south.

Seismic data collected across the Cottage Lake and Woodinville aeromagnetic lineaments, interpreted as seismically active from analysis of magnetic and lidar data and from trench excavations, provide confirmation of the location of these lineaments and suggest that they are tectonically active (Figure 3). In particular, the 195th Street seismic profile across the Grace lineament shows clear offset of near-surface layers, consistent with tectonic faulting. In summary, seismic data, in concert with magnetic data, lidar images, and trench excavations show that three aeromagnetic lineaments—Cottage Lake, Little Bear Creek, and Grace—are active strands of the SWIF.

Ames Lake Profile

The 7.5 km long north-south Ames Lake seismic profile was acquired along 284th Ave and Ames Lake Road west of Carnation, Washington and immediately south and west of Snoqualmie River (Figures 4 and 5). The quiet farm road and low elevation with respect to the water table along the northern portions of the profile resulted in good data quality. Farther south, Ames Lake Road is a busier, curved road that increases in elevation and water table depths. We retained a flag crew to control traffic, and increased the number of shots to address increased cultural noise and ground roll. Reflections in field records appear to more than 0.7 s two way travel time at offsets up to 600 meters. We break the Ames Lake seismic profile into two sections to retain an approximate 1:1 aspect ratio.

Northern Ames Lake Profile

Along the northern portion of the profile, from north to south, the elevation rises from approximately 10 m to 70 m (Figure 4). Reflections along this segment are characterized by a high amplitude arrival at ~0.4 s twtt along the northern portion of the profile and flat-lying reflectors along the southern portions of this segment. Quaternary glacial and fluvial deposits dominate the surface exposures surrounding the Ames Lake profile and outcrops of Tertiary volcanic rocks appear approximately 6 km northeast of the Ames Lake profile (Tabor et al, 1993; Dragovich et al., 2007). We interpret a reflection that extends to approximately 0.3 km depth within one km of the Snoqualmie River to represent the base of sediments affiliated with the modern river channel. A similar, but broad reflection package extends to the south an additional 2 km and likely represents an older paleochannel associated with the Snoqualmie River that has scoured and replaced older strata. Between CDP 6900 to 7100, the reflector associated with the base of the river channel shallows to near-surface depths and is replaced with flat-lying reflectors south of CDP 7200. These flat-lying reflectors are likely from Tertiary and younger marine strata that comprise the Seattle Basin and that appear in nearby boreholes and interpreted from crustal refraction profiles (e.g., Tabor et al., 1993; Jones, 1996; Snelson et al., 2007; Liberty and Pratt, 2008). Near position 7200, an approximately 0.5 km wide zone, reflectors dip to the south approximately 15 degrees and may represent a fault-related kink-band that is in-line with the projected SWIF. It is unclear whether this reflector kink extends into the overlying Quaternary fill that is very thin at this location. Reflectors beneath the Snoqualmie River paleochannel and farther south dip to the south approximately 2 degrees or less. This shallow dip on Tertiary? strata likely represents shallowing towards the eastern margins of the Seattle Basin (e.g., Dragovich et al., 2007). The lack of basal reflector associated with bottom of the Seattle suggests the basin is likely more than one km deep along Ames Lake Road, consistent with regional tomographic data (Snelson et al., 2007).

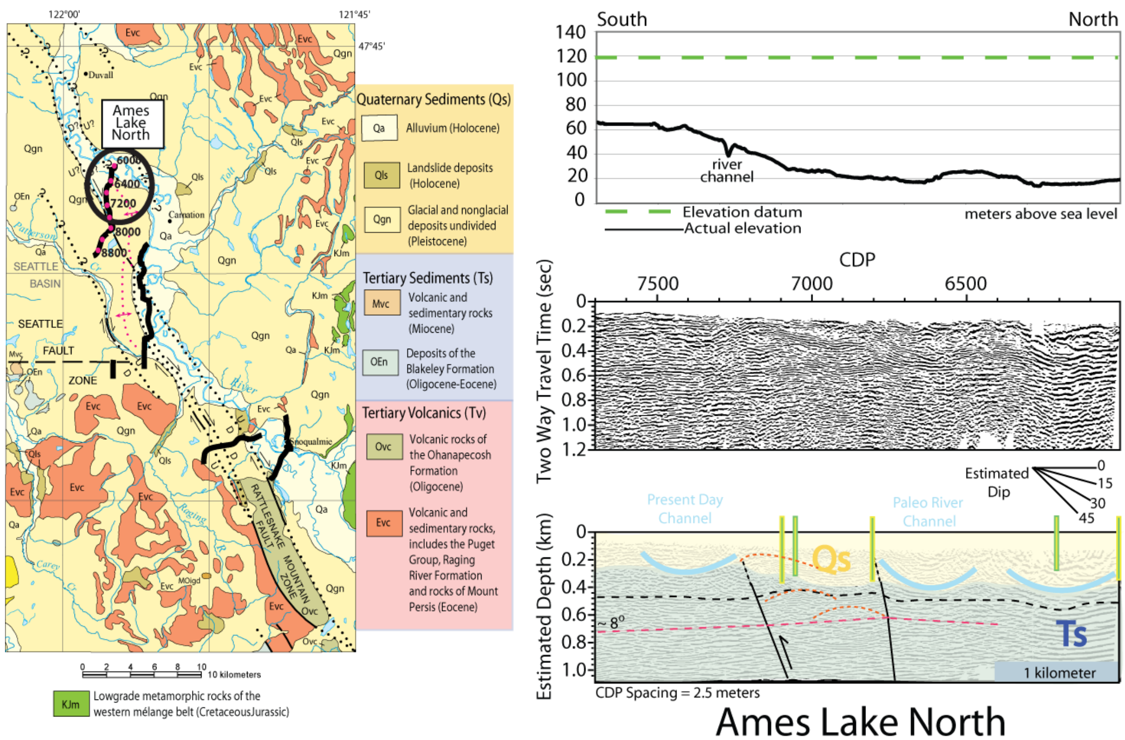

Figure 4. Ames Lake North profile. (left) Geologic map (modified from Dragovich et al., 2007) showing line location, outcrop location of Tertiary strata (purple), and the projected location of the SWIF. Below is the elevation profile, unmigrated travel time seismic image, and depth converted migrated seismic image.

Southern Ames Lake Profile

The southern 3 km of the Ames Lake profile is shown on Figure 5. Here, the surface elevation rises more than 80 m from north to south along Ames Lake Road. Along this portion of the seismic profile, flat-lying strata described along the northern Ames Lake segment appear from position 7500 to position 8000. South of position 8000, a change in the profile trend to southwest coincides with a change in seismic character. This change in reflector character and poorer data quality may be related to the oblique nature of the profile with respect to the geologic dip, or it may be related to the increased elevation of the profile, deepening water table, and heavier road traffic. As a result, signal quality below 0.5 s twtt is diminished. Near position 8300, a prominent reflector at 0.2 km depth is offset approximately 100 m. We interpret this offset as a south-directed thrust, in line with, and potentially related to, the SWIF.

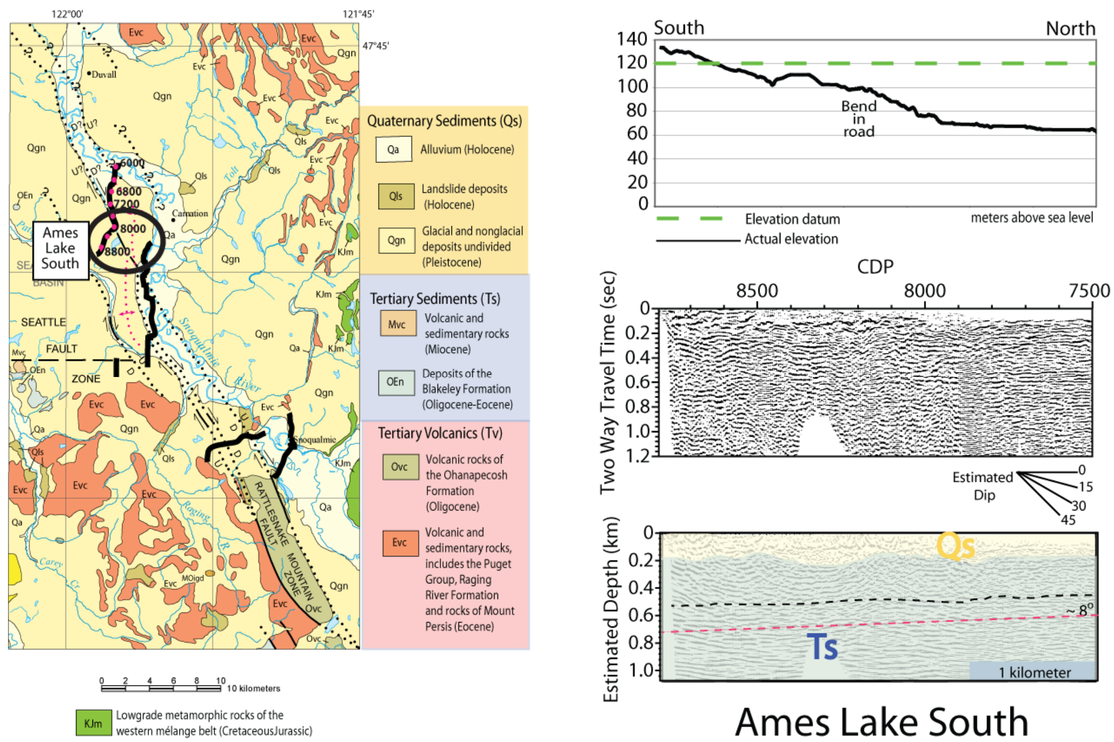

Figure 5. Ames Lake South. (left) Geologic map (modified from Dragovich et al., 2007) showing line location, outcrop location of Tertiary strata (purple), and the projected location of the SWIF. Below is the elevation profile, unmigrated travel time seismic image, and depth converted migrated seismic image.

River Road Profile

The River Valley Road profile is approximately 8.5 km long and was collected along a rural road west of the Snoqualmie River (Figures 6 and 7). The profile is located south of the Ames Lake Road profile between the cities of Issaquah and Fall City Washington, and crosses the projected SWIF near the center of the profile. The majority of the road offered very little shoulder so shots were collected on the road surface. Receivers were planted along the side of the road with up to a half meter change in elevation between source and receiver locations. Fluvial deposits related to the Snoqualmie River are mapped along the majority of the River Road profile (Tabor et al, 1993; Dragovich et al., 2007). Tertiary strata appear on Mitchell Hill approximately 2 km south of the southern portion of the profile.

River Road North

The River Road North profile contains generally flat-lying reflectors beneath a zone containing a hummocky reflector pattern. Offsets along the deeper strata are observed at one location and possibly others. Reflections in the upper 200 m are associated with fluvial strata within the Snoqualmie River Valley. Below, mostly flat-lying Tertiary strata of the eastern margins of the Seattle Basin suggest faulting with a major dip-slip component is absent. We identify the contact between Quaternary fluvial deposits and underlying Tertiary strata using both nearby borehole information (e.g., Jones, 1997; Dragovich et al., 2007) and the change in reflector character. We identify one location where reflectors are offset, possibly related to a fault, near position 2800. Here, north-side up strata appear, consistent with the SWIF mapped farther north (Johnson et al., 1996; Sherrod et al., 2008). No clear evidence that this fault extends to within the Quaternary strata suggests we cannot confirm Holocene fault activity along this profile.

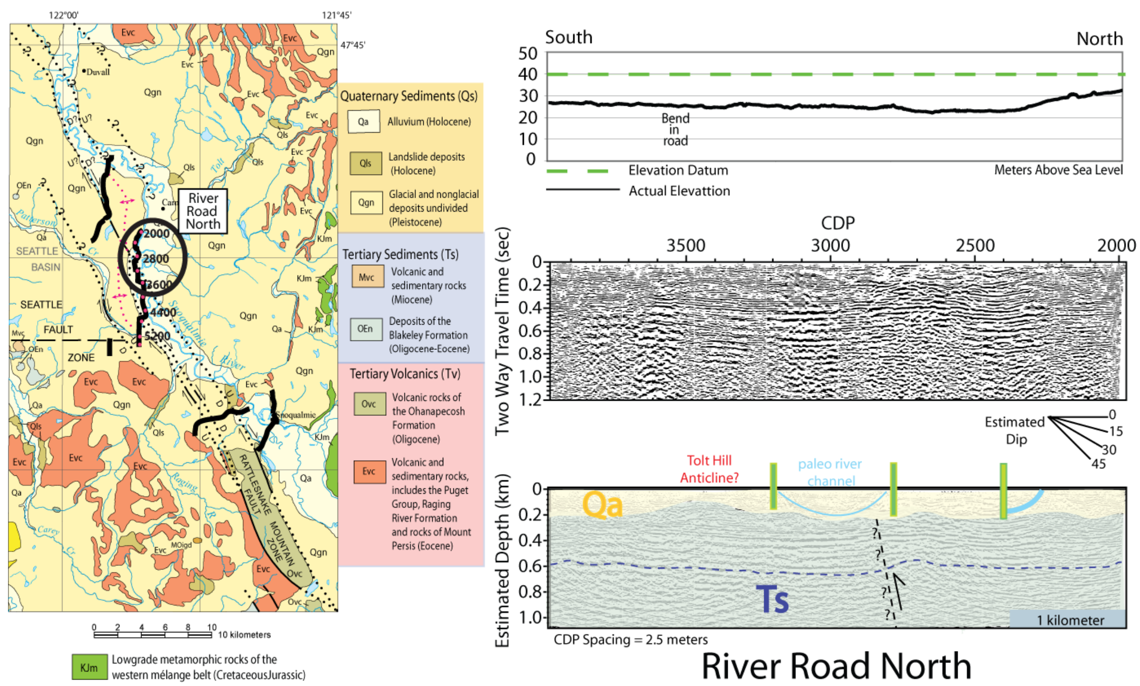

Figure 6. River Road North. (left) Geologic map (modified from Dragovich et al., 2007) showing line location, outcrop location of Tertiary strata (purple), and the projected location of the SWIF. Below is the elevation profile, unmigrated travel time seismic image, and depth converted migrated seismic image.

River Road South

The southward continuation of the River Road profile shows mostly flat-lying reflectors along the northern portions of the profile and north-dipping reflectors along the southern portions of the profile. These ~20 degree dipping strata along the southern reaches of the profile are consistent with reflection profiles farther west that show deformation related to the Seattle fault within the Seattle monocline. This reflection pattern is best explained by the Seattle fault extending east to Fall City, an addition of ~3km in fault length that reported by Liberty and Pratt (2008). The flat-lying strata to the north suggest little dip-slip motion appears along mapped strands of the Rattlesnake Mountain fault north of the Seattle fault.

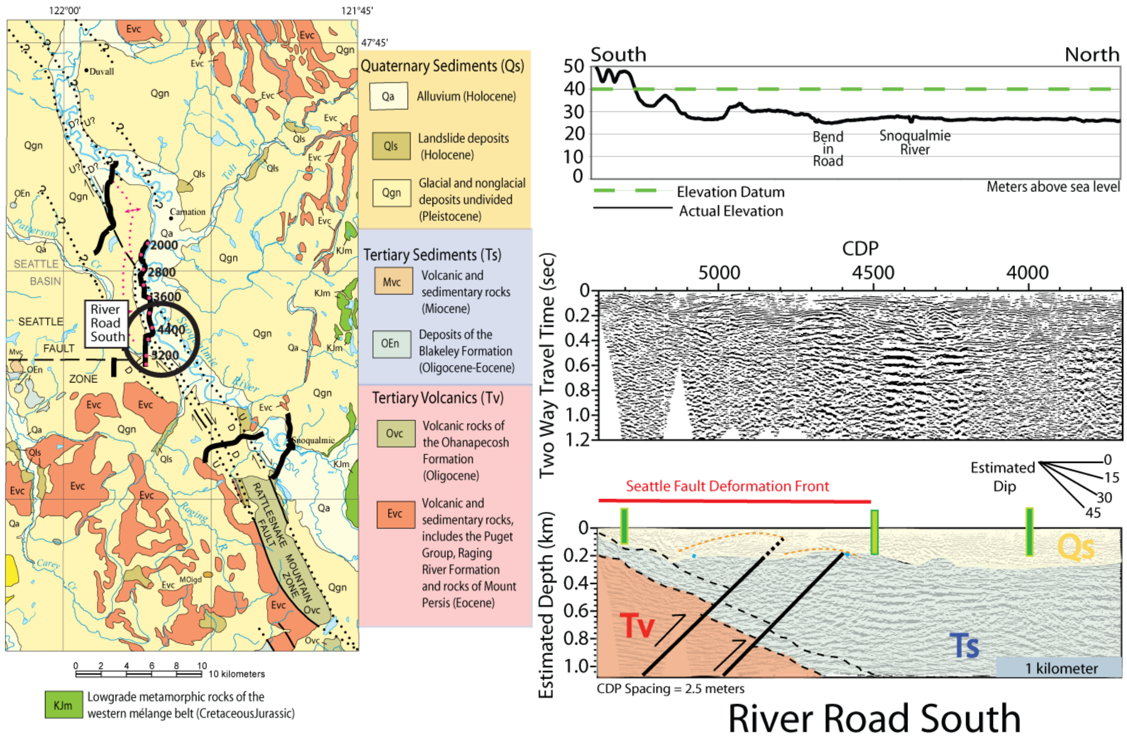

Figure 7. River Road South. (left) Geologic map (modified from Dragovich et al., 2007) showing line location, outcrop location of Tertiary strata (purple), and the projected location of the SWIF. Below is the elevation profile, unmigrated travel time seismic image, and depth converted migrated seismic image.

187th Street Profile

The 187th street profile is 1.3 kilometer long that is located approximately 0.5 km west of the southern end of the River Valley Road profile (Figure 8). We acquired this short profile to connect the reflection profiles to the north with outcrop exposures of Tertiary strata on Mitchell Hill. This profile is described in Liberty and Pratt (2008) as imaging the Seattle monocline at dips similar to that observed farther west. This profile provides evidence that the Seattle fault extends east of Lake Sammamish to the intersection of the SWIF and Rattlesnake Mountain faults.

Meadowbrook/Tokul Road Profile

The 5 km Meadowbrook/Tokul Road profile is trends north-south through the city of Snoqualmie and across the Snoqualmie River into the foothills of the Cascades. This profile crosses the northern margin of the interpreted SWIF and Rattlesnake Mountain faults (Figure 9). Tertiary volcanic rock exposures are mapped along both the south and north ends of this profile. An elevation change of approximately 50 m is observed along the profile from south to north.

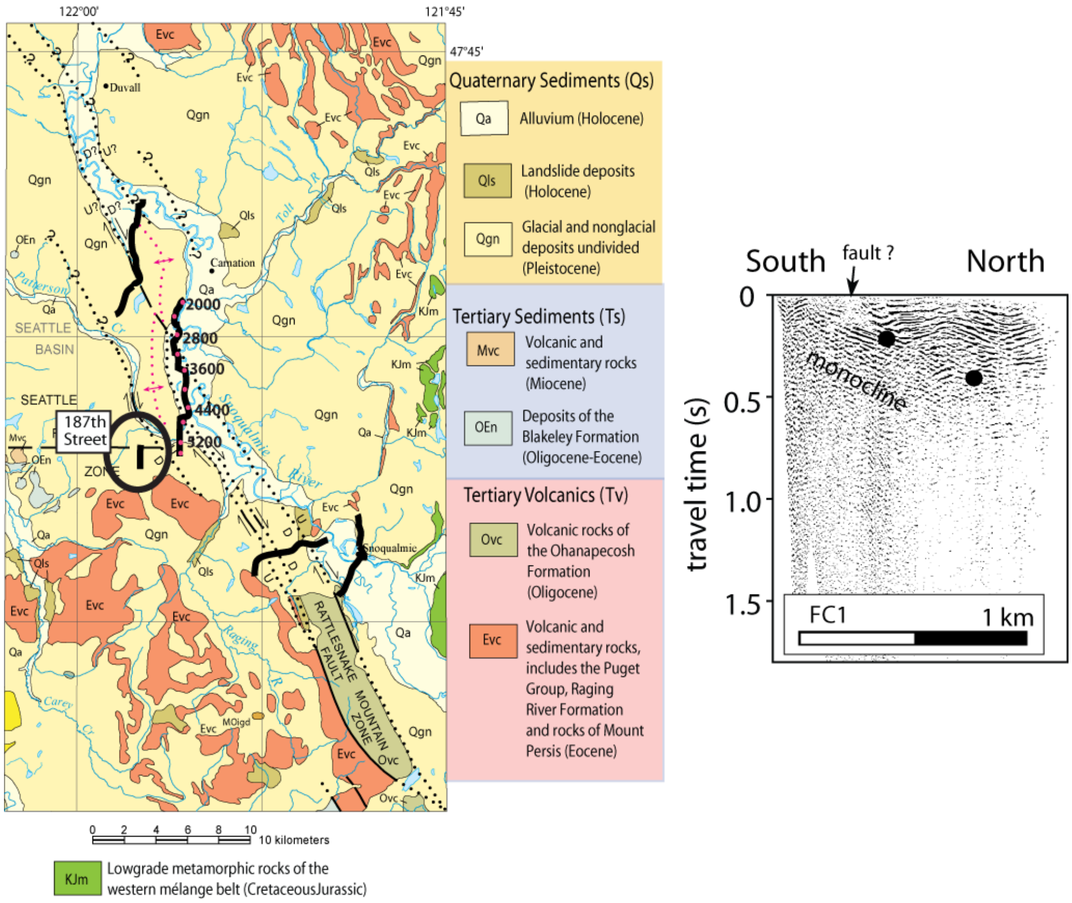

Figure 8. 187th Street Profile. (left) Geologic map (modified from Dragovich et al., 2007) showing line location, outcrop location of Tertiary strata (purple), and the projected location of the Seattle fault and SWIF. This profile is located immediately west of the SWIF intersection and shows clear evidence of the Seattle monocline and Seattle fault. Results from this profile are summarized in Liberty and Pratt (2008).

Data collected along the Meadowbrook profile shows reflectors down to about 0.5 two way travel time along the southern portions of the profile while reflections were limited to the upper 0.3 s along the northern portion of the profile. A strong amplitude reflection package shallows where interpreted Tertiary sedimentary and volcanic rocks outcrop. We interpret reflections along the southern half of the profile as part of the Snoqualmie River channel that has scoured and replaced older rocks. This ~300 m deep channel shows few coherent reflections within the channel fill deposits, typical of a high energy stream environment. The top of Tertiary rocks (Tv) shallows near position 9000 and is exposed in outcrop near position 9500. No clear evidence for offset Tertiary or younger strata appear along the section, but arcuate reflections are consistent with folding within the Tertiary strata.

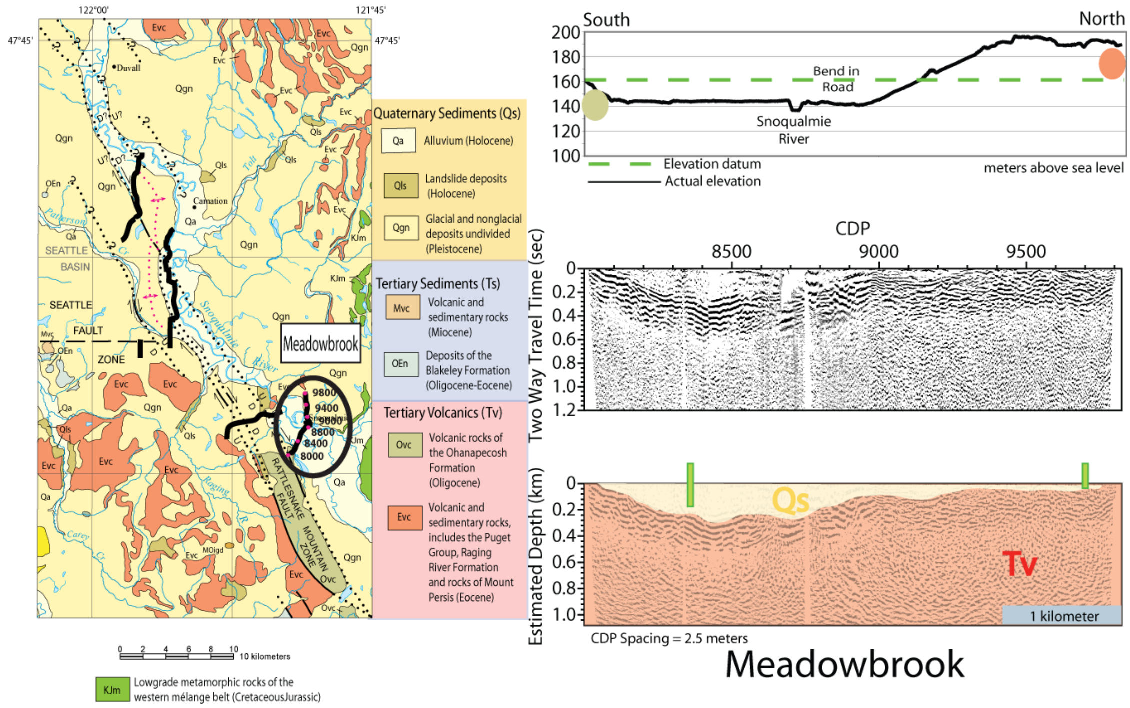

Figure 9. Meadowbrook seismic profile, located south and east of the Seattle and south Whidbey Island faults. The prominent feature on the seismic section is the Snoqualmie River channel that extends ~0.3 km depth near position 8500. Folded Tertiary strata appear within the upper 100 m depth north of the river channel, but no apparent offset of post Tertiary strata suggest active faulting may not cross the Meadowbrook profile.

Snoqualmie Parkway Profile

The Snoqualmie Parkway profile was acquired along the very busy 4-lane Snoqualmie Parkway (Figure 10). Heavy traffic noise, buried utilities, and poor source and receiver coupling provided poor data quality. Exposures of Tertiary sedimentary and volcanic rocks appear both along the southern and northern limits of this profile with the projected location of the Rattlesnake Mountain fault bisecting the profile.

Reflections along the southern portions of the Snoqualmie Parkway profile dip to the north, while reflections along the central and southern portions of the profile dip gently to the south. This reflection pattern is consistent with steeply dipping faults that have uplifted the eastern limits of Mitchell Hill relative to the strata farther east. This uplift pattern is similar to the Seattle monocline, but southwest-dipping footwall strata are not consistent with the style of faulting related to the Seattle fault (e.g., Liberty and Pratt, 2008). Faulting related to the Rattlesnake Mountain fault is likely dominated by strike-slip faulting with a minor dip-slip component (e.g., Dragovich et al., 2007). The seismic profile suggests a complex interplay between the two fault systems, with perhaps a pull-apart basin accommodating north-directed shortening related to the Seattle fault and strike-slip faulting related to the Rattlesnake Mountain fault.

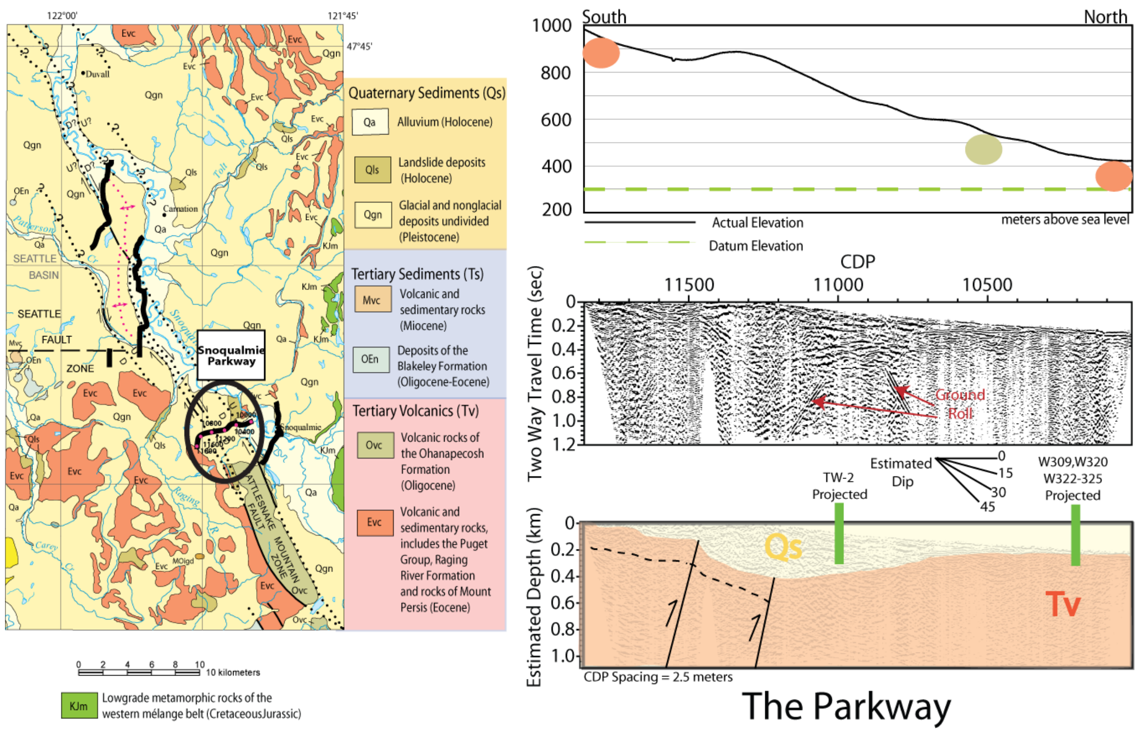

Figure 10. Snoqualmie Parkway profile. (left) Geologic map showing line location, outcrop location of Tertiary strata (purple), and the projected location of the Seattle fault and SWIF. This profile is located immediately west of the SWIF intersection and shows clear evidence of the Seattle monocline and Seattle fault.

Discussion and Conclusions

Seismic reflection profiles along the projected southeastern extension of the SWIF have identified offset and kinked strata that suggest the SWIF fault system extends and perhaps merges with the Rattlesnake Mountain fault system. Deformation related to the Seattle monocline extends east to Fall City and the eastern margin of the Seattle Basin. This report suggests the Seattle fault, SWIF, and Rattlesnake Mountain faults converge at the Snoqualmie River Valley. Here, the three fault systems interact in a complex manner that results in strike slip and dip slip motion on the eastern margin of the Seattle Basin. We do not provide evidence to suggest the Seattle fault zone extends east beyond the Seattle Basin and into the Cascades, but remains a possibility.

Acknowledgements

The author wishes to thank Thomas Pratt from the U.S. Geological Survey for assisting with permitting, data acquisition, and guidance on this project. King and Snohomish Counties, and the city of Woodinville provided key permits. The Boise State University field crew consisted of Kristin Pape, Andy Weigel, Adam Halpert (IRIS intern), Chris Paul. Seattle-based volunteers consisted of more than a dozen high school students, graduate students, and professionals from the community. CGISS contribution 08-04.

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., R. E. Wells, et al. (2002). "Location, structure, and seismicity of the Seattle fault zone, Washington; evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data." Geological Society of America Bulletin **114**(2): 169-177.

Brocher, T. M., R. J. Blakely, et al. (2004). "Interpretation of the Seattle Uplift, Washington, as a passive-roof duplex." Bulletin of the Seismological Society of America **94**(4): 1379-1401.

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.

Dragovich, J.D., Anderson, M.L., Walsh, T.J., Johnson, B.L., and Adams, T.L. (2007). "Geologic map of the Fall City 7.5-minute quadrangle, King County, Washington", Washington Division of Geology and Earth Resources Geologic Map GM-67, scale 1:24,000, with 16 p. text.

Dragovich, J.D., R.L. Logan, H.W. Schasse, T.J. Walsh, W.S. Lingley Jr., D.K. Norman, W.J. Gerstel, T.J. Lapen, J.E. Schuster, and K.D. Meyers (2002), "Geologic map of Washington-Northwest quadrant", Geologic Map GM-50, Washington Division of Geology and Earth Resources, 72 p. pamphlet, 3 sheets, scale 1:250,000, Olympia, Washington.

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

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., Potter, C.J., Armentrout, J.M., Miller, J.J., Finn, C.A., and Weaver, C.S. (1996), "The southern Whidbey Island Fault; an active structure in the Puget Lowland, Washington", Geological Society of America Bulletin, 108, 334-354.

Johnson, S. Y., S. V. C. J. R. Dadisman, et al. (1999). "Active tectonics of the Seattle Fault and central Puget Sound, Washington; implications for earthquake hazards." Geological Society of America Bulletin **111**(7): 1042-1053.

Kelsey, H.M., Sherrod, B., Johnson, S.Y., and Dadisman, S.V. (2004), "Land-level changes from a late Holocene earthquake in the northern Puget Lowland, Washington", Geology, 32, 469-472.

Liberty, L.M. and Pratt, T.L. (2008). "Structure of the Eastern Seattle Fault Zone, Washington State: New Insights from Seismic Reflection Data", Bulletin of the Seismological Society of America, v. 98, no. 4.

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, et al. (2003). "Late Holocene earthquakes on the Toe Jam Hill Fault, Seattle fault zone, Bainbridge Island, Washington." Geological Society of America Bulletin **115**(11): 1388-1403.

Nelson, A. R., S. Y. K. H. M. Johnson, et al. (2003). "Field and laboratory data from an earthquake history study of the Waterman Point Fault, Kitsap County, Washington". Reston, VA, U. S. Geological Survey.

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.

Ramachandran, K., S.E. Dosso, G.D. Spence, R.D. Hyndman, and T.M. Brocher (2005), "Forearc structure beneath southwestern British Columbia; a three-dimensional tomographic velocity model", J. Geophys. Res., 110, B2, DOI 10.1029/2004JB003258.

Sherrod, B. L., R. J. Blakely, C. S. Weaver, H. M. Kelsey, E. Barnett, L. Liberty, K. L. Meagher, and K. Pape (2008), "Finding concealed active faults: Extending the southern Whidbey Island fault across the Puget Lowland, Washington", Journal of Geophysical Research, B, Solid Earth and Planets, 113, B05313, doi:10.1029/2007JB005060.

Tabor, R.W., Frizzell, V.A., Booth, D.B., Waitt, R.B., Whetten, J.T., and Zartman, R.E (1993). "Geologic map of the Skykomish River 30- by 60-minute quadrangle, Washington". U.S. Geological Survey Miscellaneous Investigations Series Map I-1963.

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.

Wells, R. E., C. S. Weaver, et al. (1998). "Fore-arc migration in Cascadia and its neotectonic significance." Geology **26**(8): 759-762.

Yilmaz, O. (2001). "Seismic data analysis: processing, inversion, and interpretation of seismic data", *Society of Exploration Geophysicists*, Tulsa, Oklahoma, 2027 p.