# Western limits of the Seattle fault zone and its interaction with the Olympic Peninsula, Washington

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#### ABSTRACT

We present evidence that the Seattle fault zone of Washington State extends to the west edge of the Puget Lowland and is kinematically linked to active faults that border the Olympic Massif, including the Saddle Mountain deformation zone. Newly acquired highresolution seismic reflection and marine magnetic data suggest that the Seattle fault zone extends west beyond the Seattle Basin to form a >100-km-long active fault zone. We provide evidence for a strain transfer zone, expressed as a broad set of faults and folds connecting the Seattle and Saddle Mountain deformation zones near Hood Canal. This connection provides an explanation for the apparent synchroneity of M7 earthquakes on the two fault systems ~1100 yr ago. We redefine the boundary of the Tacoma Basin to include the previously termed Dewatto basin and show that the Tacoma fault, the southern part of which is a backthrust of the Seattle fault zone, links with a previously unidentified fault along the western margin of the Seattle uplift. We model this northsouth fault, termed the Dewatto fault, along the western margin of the Seattle uplift as a low-angle thrust that initiated with exhumation of the Olympic Massif and today accommodates north-directed motion. The Tacoma and Dewatto faults likely control both the southern and western boundaries of the Seattle uplift. The inferred strain transfer zone linking the Seattle fault zone and Saddle Mountain deformation zone defines the northern margin of the Tacoma Basin, and the Saddle Mountain deformation zone forms the northwestern boundary of the Tacoma Basin. Our observations and model suggest that the western portions of the Seattle fault zone and Tacoma fault are complex, require temporal variations in principal strain directions, and cannot be modeled as a simple thrust and/or backthrust system.

# INTRODUCTION

Oblique subduction of the Juan de Fuca plate beneath the North American continent results in northeast migration of coastal regions of Washington State relative to stable North America. This northeast motion is resisted by Mesozoic and older rocks that form the stable craton of southwest Canada, resulting in shortening of the Puget Lowland region of Washington State (Wells et al., 1998; Mazzotti et al., 2002; McCaffrey et al., 2007). This shortening is expressed, in part, as a series of northwest- and west-trending active faults that separate basins and structural uplifts beneath the Puget Lowland, within which are the Seattle and Tacoma metropolitan areas (Fig. 1; Johnson et al., 1996; Pratt et al., 1997).

The Seattle Basin and Tacoma Basin extend eastward ~70 km from Hood Canal, beneath the Seattle-Tacoma urban corridor, to the foothills of the Cascade Range (Fig. 1). The Seattle uplift, separating the basins, is interpreted as a pop-up block above the south-dipping Seattle thrust fault to the north and the Tacoma backthrust to the south (Pratt et al., 1997; Brocher et al., 2001, 2004). Direct geologic evidence for the Seattle and Tacoma fault systems is sparse, consisting primarily of uplifted bedrock terraces (Bucknam et al., 1992; Kelsey et al., 2008), topographic scarps observed in light detection and ranging (Lidar) surveys that cover a large area of the Puget Lowland (e.g., Haugerud et al., 2003; Sherrod et al., 2004, 2008), and faults and folds found in detailed studies of trench excavations across Lidar scarps (e.g., Nelson et al., 2003; Sherrod et al., 2004). Fault strands and underlying structures are inferred from seismicity, magnetic, gravity, geologic, and seismic reflection data (e.g., Finn, 1990; Pratt et al., 1997; Brocher et al., 2001; Blakely et al., 2002; Johnson et al., 2004; Stephenson et al., 2006; Liberty and Pratt, 2008; Sherrod et al., 2008).

The ~70-km-long Seattle fault zone is composed of south-dipping thrust faults and interpreted north-dipping backthrusts that are in part beneath the Seattle metropolitan area (Fig. 1). The shallow portion of this fault zone is composed of a monocline that bounds the southern margin of the Seattle Basin, and mapped faults and folds in the hanging wall just south of the monocline. The Seattle fault zone may extend to the east beyond the boundaries of the Seattle Basin to merge with the active South Whidbey Island fault (Fig. 1; Johnson et al., 1996; Liberty and Pratt, 2008; Sherrod et al., 2008; Blakely et al., 2009).

The Tacoma fault on the south side of the Seattle uplift is less well defined than the Seattle fault. The Tacoma fault extends ~20 km along the southern margin of the Seattle uplift between Carr Inlet and the southeastern extent of Hood Canal (Fig. 1B). The Tacoma fault is along strike of the White River fault (Fig. 1A), which extends through the Cascade Range, but no direct evidence links these two fault systems (Blakely et al., 2007, 2011). Field studies show that the Seattle and Tacoma faults are capable of causing large earthquakes (Atwater and Moore, 1992; Sherrod et al., 2004), so knowing their overall lengths and their interactions with neighboring faults help us to understand fault kinematics and earthquake hazards in this area. The most recent large rupture occurred on the Seattle fault zone in A.D. 900-930, producing a M7-7.5 earthquake that lifted the hanging wall ~6.5 m and generated a local tsunami and landslides (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992; Atwater and Hemphill-Haley, 1997; Sherrod et al., 2000; ten Brink et al., 2006). Trench studies across Lidar scarps on the Tacoma and Saddle Mountain faults (Fig. 1) suggest earthquakes with timing (within the limits of radiocarbon dating) similar to that of the Seattle fault zone event 1100 yr ago that may be contemporaneous (e.g., Sherrod et al., 2004, 2008; Blakely et al., 2009).

In this paper, we explore the deformation caused by convergence across the Seattle fault zone and eastern portions of the Olympic Massif

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Figure 1. (A) Map modified from Blakely et al. (2009) showing the tectonic setting of the Puget Lowland and Olympic Peninsula. The yellow arrow shows the regional direction of strain relative to North America (McCaffrey et al., 2007). This strain causes north-south compression that is buttressed by the stable Canadian craton and results in  $4.4 \pm 0.3$  mm/yr of permanent shortening being accommodated across the Puget Lowland region. FCF-Frigid Creek fault; HRF—Hurricane Ridge fault; OF-Olympia fault: OU—Olympia uplift: SB—Seattle Basin; SF—Seattle fault; SMF—Saddle Mountain East and Saddle Mountain West faults; SMDZ—Saddle Mountain deformation zone; SU-Seattle uplift; TB-Tacoma Basin; TF—Tacoma fault. Other regional faults not referred to in this research but shown in Figure 1: CRF-Canyon River fault; DMF-Devils Mountain fault; EB-Everett basin; KA-Kingston arch; LRF-Leech River fault: **RMF**—Rattlesnake Mountain fault; SCF—Straight Creek fault; SWIF-southern Whidbey Island fault; WRF-White River fault. (B) Geological map modified from Schuster (2005) and Blakely et al. (2009).



using new high-resolution seismic profiles and magnetic data between Hood Canal and Puget Sound (Fig. 2). These new data cross the northwest and west flanks of the Seattle uplift where structures may define the western limits of the Seattle fault zone. We integrate results from these newly acquired data with previously published geological and geophysical data to test whether there is a link between the Seattle fault zone and structures in the Olympic Massif to the west. Our interpretations suggest a kinematic link between several fault systems in the Puget Sound region, providing a possible explanation for synchronous ruptures of multiple faults during large earthquakes.

## GEOLOGICAL AND GEOPHYSICAL SETTING

The Olympic subduction complex, an exhumed part of the Cascadia accretionary wedge (Brandon et al., 1998), is west of the

Puget Lowland and the Seattle fault zone (Fig. 1A). The complex is cored by severely deformed and metamorphosed Eocene to Miocene marine sedimentary rocks that have been uplifted to form the Olympic Massif (Fig. 1A). The sedimentary strata are thrust beneath peripheral rocks of the Siletz terrane, a largely volcanic terrane of oceanic affinity that forms the crystalline basement beneath most of the Cascadia forearc and reaches thicknesses of as much as 35 km (Finn, 1990; Lees and Crosson, 1990; Trehu



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et al., 1994; Parsons et al., 1998). Exhumation of the Olympic subduction complex began ca. 18 Ma (Brandon et al., 1998). The Olympic subduction complex is bordered to the east by the uplifted portion of the Siletz terrane, marked by the Hurricane Ridge fault (Brandon et al., 1998). The regions of the Siletz terrane bordering Hood Canal host steeply east-dipping thrust faults, including the Saddle Mountain and Hurricane Ridge faults (Blakely et al., 2009; Brandon et al., 1998). These faults, along with the Frigid Creek and Canyon River faults, have been previously defined as elements of the Saddle Mountain deformation zone that accommodates northward shortening of the Puget Lowland crust east of the Olympic Massif (Blakely et al., 2009). These faults also have components of vertical displacement that accommodate exhumation of the Olympic Massif (e.g., Wilson et al., 1979; Brandon et al., 1998; Witter and Givler, 2008; Blakely et al., 2009).

The Crescent Formation is a mafic volcanic component of the Siletz terrane, which is part of the Paleocene to Eocene Coast Range Volcanic Province (Babcock et al., 1992; Hirsch and Babcock, 2009). The Crescent Formation is exposed along the north and east sides of the Olympic Massif (Fig. 1B), where it can be subdivided into a lower member consisting of massive submarine basalt flows and an upper member of subaerial basalt with sparse sedimentary interbeds (Tabor and Cady, 1978a; Babcock et al., 1992; Hirsch and Babcock, 2009). These two members represent an upward progression from an oceanic deep-water origin in the lower member to a coastal marine and terrestrial setting in the upper member. The Crescent Formation dips eastward from the Saddle Mountain deformation zone, and except for exposures in the Green Mountain uplift, is largely covered east of Hood Canal by Tertiary sedimentary rocks and glacial deposits of late Quaternary age beneath the Puget Lowland (Figs. 1 and 2; Johnson et al., 1994, 2004; Haeussler and Clark, 2000; Blakely et al., 2009; Tabor et al., 2011).

The Crescent Formation has been delineated beneath the Puget Lowland using aeromagnetic and gravity anomalies because of its high magnetic susceptibility and density (Finn, 1990; Babcock et al., 1992; Blakely et al., 2009). The upper member is more magnetic than the lower member and therefore is more evident in aeromagnetic data (Blakely et al., 2009). The strong magnetic properties result in well-defined, linear magnetic anomalies where the Crescent Formation is folded or vertically displaced by faults, allowing potential field modeling of structures in the region (e.g., Daneš et al., 1965; Gower et al., 1985; Blakely et al., 1999, 2002, 2009; Brocher et al., 2004; Johnson et al., 2004).

Northward motion of the Puget Lowland at rates of  $4.4 \pm 0.3$  mm/yr (Mazzotti et al., 2002; McCaffrey et al., 2007) and clockwise rotation of the Cascadia Forearc at  $1.5^{\circ} \pm 0.5^{\circ}/\text{m.y.}$ (Wells et al., 1998) have resulted in the formation of the 7-9-km-deep Seattle Basin, the 5-7-km-deep Tacoma Basin, and the ~25-kmwide Seattle uplift that separates the two basins (Fig. 1; Johnson et al., 1994, 2004; Pratt et al., 1997; Brocher et al., 2001; van Wagoner et al., 2002). A number of tectonic models have been proposed for the Seattle fault zone and Tacoma fault that bound the Seattle uplift. The prevailing view is that the Seattle fault zone comprises a blind, south-dipping thrust fault. Some models propose steep dip angles (Brocher et al., 2001), while others propose shallower dip angles with penetration to detachment surfaces at depths of 14-20 km (Pratt et al., 1997; ten Brink et al., 2002; Johnson et al., 2004). Brocher et al. (2001) and Johnson et al. (2004) suggested that the Tacoma fault is a 30°-45° dipping backthrust to the Seattle fault zone, while Brocher et al. (2004) interpreted the Seattle uplift as a passiveroof duplex with greater uplift rates on the west end of the Seattle uplift compared to farther east. An overview of these models was presented in Mace and Keranen (2012), who also interpreted a zone of recent northeast-southwest faulting that crosses the Seattle Basin and Seattle uplift. Mace and Keranen (2012) suggested that this northeast-southwest-aligned faulting may be responsible for cyclic accommodation of eastward transport of the Olympic Massif and northsouth shortening of the Washington block.

#### WESTERN EXTENT OF SEATTLE FAULT ZONE

The first evidence for Holocene displacement on the Seattle fault zone came from uplifted shorelines along Puget Sound and accompanying tsunami deposits (Bucknam et al., 1992; Atwater and Moore, 1992; Sherrod et al., 2000; Nelson et al., 2003). Subsequent trenching of fault scarps has confirmed Holocene earthquakes (Wilson et al., 1979; Sherrod, 2001; Nelson et al., 2003). The Seattle monocline marks the southern boundary of the Seattle Basin and is formed by north-dipping Tertiary sedimentary rocks. The monocline extends westward from near Fall City to the north flank of Green Mountain, and apparently formed by north-south compression along the Seattle fault zone (Fig. 1; Johnson et al., 1999; Blakely et al., 2002; Brocher et al., 2004; Liberty and Pratt, 2008). The extension of deformation related to the Seattle fault zone west of Puget Sound is inferred from geologic mapping near Green Mountain, seismic profiles in Dyes Inlet, and aeromagnetic lineations over the hanging wall (Johnson et al., 1999; Haeussler and Clark, 2000; Blakely et al., 2002; Tabor et al., 2011). Farther west, potential field modeling and geologic mapping were used (Blakely et al., 2009) to suggest that the north-northweststriking Saddle Mountain fault on the Olympic Peninsula extends northward to near the projected western extension of the Seattle fault zone (Fig. 2), and that west-trending magnetic lineations between the Saddle Mountain deformation zone and Seattle fault zone indicate that the two fault systems may be linked by structures extending beneath Hood Canal. Both of these fault systems produced large earthquakes ~1000–1100 yr ago (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992; Karlin and Abella, 1992; Schuster et al., 1992), suggesting that they may form a linked, >150-km-long set of active fault systems (Hughes, 2005).

#### **Geophysical Investigations**

To characterize possible structural ties between the Seattle fault zone and Saddle Mountain deformation zone, we collected five high-resolution seismic reflection profiles across the western portion of the Seattle fault zone (Fig. 3). We acquired all seismic data using a 200-kg accelerated weight drop source, a 120-channel seismic recording system, and a 5-m source and receiver spacing to produce a nominal 60-fold data set with sourcereceiver offsets as great as 600 m. All seismic profiles were acquired on roadways. Standard processing techniques were applied to produce the uninterpreted and interpreted seismic profiles presented in Figures 4-8 (Yilmaz, 2001). The velocity model derived from normal-moveout corrections was used to perform the time to depth conversions. The unmigrated data (Figs. 4, 6A, and 6C) were used to assist with our interpretations of the migrated data (Figs. 5, 6B, and 6D) because there tends to be more signal coherency in the unmigrated data. This greater coherency is likely due to inaccuracies in our near-suface velocity model and out-of-plane reflections that can reduce the effectiveness of the migration process (Figs. 5, 6B, and 6B).

The magnetic data presented here were acquired by the U.S. Geological Survey, using a nominal altitude of 300 m above ground, but the altitude increased to >1 km over the eastern margin of the Olympic Mountains (Blakely et al., 1999). The north-south flight lines were spaced 400 m apart, with east-west tie lines spaced 8 km apart. We corrected the raw magnetic data for the Earth's background field and then reduced to the pole. Reduction to the pole simplifies data interpretation by recalculating the magnetic intensity data as if it were at the north pole. In Figure 2A, we emphasize the magnetic sources in the upper



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Figure 4. (A) Unmigrated and uninterpreted seismic section for the Big Beef Road (BB) seismic line, including the locations and depths of three water wells used to make our interpretations (v.e.-vertical exaggeration). Seismic line locations are shown in Figure 3. (B) Unmigrated and uninterpreted seismic section for the Coho Road (CO) seismic line located ~500 m west of the BB seismic line. (C) Unmigrated and uninterpreted seismic section for the HI (Hite Road) seismic line including the locations and depths of two water wells used to make our interpretations.





Figure 6. (A) Unmigrated and uninterpreted seismic section for the State Route 101 (SR) seismic line (v.e.—vertical exaggeration). Line locations are shown in Figure 3. (B) Time-migrated, time-depth converted, and interpreted seismic section for the SR seismic line. A1— interpreted anticline. See legend for additional explanations. (C) Unmigrated and uninterpreted seismic section for the Feather-Minnig Road (FM) seismic line. (D) Time-migrated, time-depth converted, and interpreted seismic section for the FM seismic line. A1 and A2— interpreted anticlines; S2 and S3—interpreted synclines; F2—interpreted south-dipping thrust fault.

2 km by upward continuing the reduced-to-thepole aeromagnetic data by 4 km and then subtracting the result from the original reduced-tothe-pole grid (Jacobsen, 1987). The gravity data were acquired or compiled by U.S. Geological Survey personnel and had been previously reduced to isostatic residual anomaly values. Isostatic residual anomalies have been gridded using minimum curvature, with a 250-m grid cell size.

The aeromagnetic survey was flown at a nominal altitude of 250 m above ground through most of the region, but the high topography of the Olympic Mountains required significantly higher flight altitudes over Hood Canal. To supplement the aeromagnetic data in this area, we conducted an additional marine magnetic survey of Hood Canal using a 6-m-long fiberglass fishing boat. The magnetometer was positioned 3 m forward of the bow using 3-m-long wooden boom to reduce the magnetic effects of the boat. At the position of the sensor, the magnetic field of the boat had a maximum directional error of ~7 nT, determined by crossing a single point in the four cardinal directions. The marine data were corrected for this heading error, even though it is small in comparison to anomalies of geologic origin. The survey tie lines and magnetic anomaly results are presented in the left and middle panels, respectively, of Figure 2C. A comparison of these results with the aeromagnetic anomalies (right panel of Fig. 2C) demonstrates the additional information provided by the marine magnetic data. To facilitate our analyses, these marine magnetic data are superimposed onto the aeromagnetic anomaly map in Figure 3.

We used legacy marine seismic data acquired in Hood Canal (Dadisman et al., 1997; Fig. 3) to further investigate the hypothesized structural link beneath Hood Canal. These seismic data extend much farther to the north and south than our land-based seismic lines, and should intersect any westward projection of the Seattle fault zone. The narrow, steep walls of Hood Canal can cause out-of-plane reflection interference in the seismic profiles, but depths to interpreted Crescent Formation basement rocks are estimated along the length of the profile and plotted with the corresponding magnetic anomaly data.

Water well log data obtained from the Washington State Department of Ecology (http:// apps.ecy.wa.gov/welllog) were used to assist with our seismic interpretations. The locations and identifications tags of these wells are shown in Figures 3–6.

#### Results

Two seismic profiles collected on Big Beef (BB) and Coho (CO) roads were acquired on glacial till and outwash deposits immediately

north of exposed Crescent Formation rocks at Green Mountain (Haeussler and Clark, 2000; Tabor et al., 2011; Fig. 3). The magnetic field decreases in amplitude northward along both profiles (Fig. 3), suggesting a northward deepening of the Crescent Formation from exposures at Green Mountain. This increasing bedrock depth to the north is supported by well log data that indicate a bedrock depth of ~50 m on the southern end of the BB profile but no bedrock above a depth of ~200 m on the north end of the BB profile (Figs. 4A and 5A). Additional well logs near the BB and CO lines are all consistent with the Crescent Formation dipping to the north. We used these well log and magnetic data along with geologic mapping (Haeussler and Clark, 2000) to interpret the Quaternary-Tertiary boundary on the BB and CO seismic lines. A diverted stream channel (Big Beef Creek), apparent on the Lidar topographic image, overlies a syncline (S1 in Fig. 3) evident on seismic profiles BB and CO (Fig. 5) and may be structurally controlled, offering evidence for synclinal growth that may be related to active faulting. The southwestern extension of syncline S1 underlies a second diverted stream channel (Anderson Creek) also visible on the Lidar data.

The BB and CO profiles show the north-dipping bedrock surface north of Green Mountain, and exhibit north-dipping structures in the upper 0.5 km (Figs. 5A and 5B). These structures include syncline S1 and anticline A1. The distance between S1 and A1 decreases at the CO profile and increases again farther to the west (Fig. 3). Both of these structures become more southward in trend as they wrap around the northwest flank of Green Mountain, following the northern margin of the pronounced magnetic high centered over Green Mountain (Fig. 3). Structures S1 and A1 likely reflect either glacial processes (moraines) or late Quaternary tectonic deformation. We favor the latter interpretation because the BB and CO seismic profiles also exhibit reflector truncations and changes in Quaternary reflector dip that we interpret as marking a southwest-striking reverse fault F1 with southside-up Quaternary displacement of >200 m. We show F1 on the BB and CO seismic profiles with a splay (Figs. 5A and 5B) due to the packet of steeply north dipping reflections above 0.1 km depth that are not present in the hanging wall. The truncation on these shallow reflections may be due to out-of-plane reflections or dextral strikeslip motion causing an along-strike offset. The fault strikes southwest and may, through increasing strike-slip motion, accommodate an element of north-south shortening. This northeast-southwest-aligned dextral strike-slip motion is also supported by a recent study to the east that shows evidence for similarly aligned faults beneath the

central Puget Lowland (Mace and Keranen, 2012). Fault F1 parallels the north edge of anticline A1 (Fig. 3), suggesting that the anticline is a fold above the fault. The fault may be one of several thrust faults similar to those imaged on seismic profiles within the Seattle fault zone beneath and east of Puget Sound (Johnson et al., 1999; Haeussler and Clark, 2000; Liberty and Pratt, 2008). We interpret these faults and folds to be related to the Seattle fault zone that defines the southern margin of the Seattle Basin. The folding along BB and CO may be related to the Seattle monocline, as interpreted by Haeussler and Clark (2000), or to backthrusts of a Seattle fault that projects farther to the north. We cannot distinguish between these two interpretations because of the short profile lengths. Regardless, the southwest-striking faults and folds showing late Quaternary motion demonstrate that the strain accommodated by the Seattle fault zone may extend farther west than the western limits of the Seattle Basin and is instead characterized by a broadening zone of deformation that becomes increasingly distributed as it crosses Hood Canal and links with the Saddle Mountain deformation zone.

The seismic profiles along Hite Road (HI), State Route 101 (SR), Feather-Minnig Road (FM), and Hood Canal were acquired west of the BB and CO seismic profiles outside the limits of the Seattle Basin as defined by gravity anomalies (Fig. 2B; Finn, 1990) and seismic tomography (Snelson et al., 2007), but along strike of the Seattle fault zone (Fig. 3). These profiles exhibit less deformation than the BB and CO profiles to the east (Figs. 5 and 6) and appear west of the Green Mountain magnetic high (Fig. 3). Although data quality along the HI profile is poor, the profile shows predominately west-dipping reflectors that we interpret as Quaternary strata overlying Tertiary Crescent Formation (Fig. 5C). There are no direct constraints to help interpret the Quaternary-Tertiary boundary on the HI profile; however, we can use the strength of the magnetic anomalies as a proxy for the depth to the Crescent Formation, assuming that the magnetization of Crescent Formation basalts remain approximately uniform. Our interpretation for the top of Crescent Formation therefore relies on correlating bedrock exposures and well logs to the amplitudes of the corresponding magnetic anomalies, and applying this relationship to our seismic interpretations. Through this exercise, we interpret the Quaternary-Tertiary boundary along the HI profile to be at depths of 0.2-0.6 km, compatible with well logs that do not show Tertiary strata but show Quaternary sediments at depths as great as ~130 m. We interpret the west-dipping strata to encompass the north limb of the A1 anticline.

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Our interpretations for the Quaternary-Tertiary boundary along the SR, FM, and Hood Canal seismic profiles were obtained by a method similar to that described above. Projecting the broad north limb of anticline A1 westward from the HI profile, we interpret anticline A1 along the southern portions of SR and FM seismic profiles (Fig. 3) at a depth of ~0.35 km (Fig. 6) and along the Hood Canal seismic profile at a depth of ~0.4 km (common depth point, CDP 4400 in Fig. 7C). We interpret a more prominent anticline termed A2 at a depth of ~0.4 km along the FM profile that is north of the A1 structure and north of the SR profile limits. We infer a west trend for the more prominent anticline A2 from the Hood Canal seismic interpretation and magnetic data (Figs. 7B, 7C). The east-west synclines S2 and S3 imaged beneath Hood Canal are also observed on the FM seismic profile. The Hood Canal seismic section shows additional faults and folds to the north (A3, A4, A5, S3, S4, S5, F1, F2, and F3) that

produce west-east lineations on the magnetic data (Figs. 3 and 7C). It is important to note that each interpreted anticline and syncline correlates with a magnetic high or low, respectively, seen in high-resolution marine magnetic data from Hood Canal (Fig. 3).

From the Hood Canal and FM seismic profiles, we interpret a series of east-west-striking, low-angle thrust faults (F2, F3, and F4) that may indicate strain partitioning in the Seattle fault zone across a number of faults beneath



Figure 7. (A) Time-migrated, time-depth converted, and uninterpreted seismic section for the Hood Canal seismic lines 84 and 91 shown in Figure 3. CDP—common depth point. (B) Reduced-to-the-pole aeromagnetic (blue) and marine and/or ground magnetic (red) anomaly values that correspond with the location of the Hood Canal seismic lines 84 and 91. (C) Time-migrated, time-depth converted, and interpreted seismic section for the Hood Canal seismic lines 84 and 91. A1, A2, A3, and A4—interpreted anticlines; S2, S3, S4, and S5—interpreted synclines; F2, F3, and F4—interpreted faults. See legend for additional explanations.

Hood Canal. Faults F2 and F4 are along strike of faults previously interpreted (Blakely et al., 2009) as possible links between the Seattle fault zone and Saddle Mountain deformation zone. The seismic profiles show no clear indication of offset strata above the Tertiary bedrock surface and are complicated by out-of-plane reflections from the Hood Canal boundaries. This lack of evidence for younger offset strata suggests that these low-angle thrust faults may be older, inactive faults, or that northward shortening is distributed along a series of faults that show little late Quaternary displacement. The data quality along the Hood Canal line 91 seismic section does not enable us to confidently determine the source of the corresponding eastward decrease in the aeromagnetic and gravity values (Figs. 7 and 2B) and whether there is related faulting. These data do suggest that these potential field gradients represent the northern limb of the Seattle fault zone and delineate the margins of the 7-9-km-deep Seattle Basin.

We interpret ~5°-8° north-dipping Quaternary strata along the southern portions of the SR and FM profiles south of anticline A1 to indicate that Quaternary deformation continues to the west of Green Mountain and farther south than the westward projection of the Seattle fault (Figs. 3, 6B, and 6D). The west to southwest trend of these imaged structures also suggests that the prominent, collinear, southwest-striking magnetic lineation that wraps around Green Mountain may be an expression of the southern limits of the Seattle fault zone. Unfortunately we have no seismic data that extend through the southwestern strike of this magnetic lineation, so we must rely on the potential-field data to examine this link.

Structural folding and faulting that follow the trend of Green Mountain bedrock exposures, along with our seismic interpretations of inactive or smaller displacements on structures farther west, suggest three possible scenarios for the active Seattle fault zone: (1) termination east of the FM and SR profiles; (2) change in trend to wrap around the bedrock exposures and pass south of the FM and SR profiles; or (3) distribution over a broad zone west of Green Mountain that we call a strain transfer zone. The strain transfer zone scenario best matches our observations of the staggered faults and folds between the Seattle fault zone and Saddle Mountain deformation zone. The strain transfer zone is bounded to the north by the Seattle Basin, to the east by the Seattle uplift, and to the west by the Olympic Massif. Our interpretations offer further support for a link between the Seattle fault zone and Saddle Mountain deformation zone. We cannot determine if this link is between active faults, but the synchroneity of

large earthquakes on both the Seattle fault zone and Saddle Mountain deformation zone 1100 yr ago suggests that this is a possibility.

#### WESTERN EXTENT OF TACOMA FAULT

The Tacoma fault dips northward beneath the Seattle uplift and deforms strata of late Quaternary age (Fig. 1; Brocher et al., 2001; Johnson et al., 2004; Clement et al., 2010). The Crescent Formation in the hanging wall of the Tacoma fault has been uplifted from ~5-7 km depth beneath the Tacoma Basin to ~213 m depth in a borehole on the Seattle uplift (Sceva, 1957; Brocher and Ruebel, 1998). The Catfish Lake scarp imaged on Lidar data provides evidence for Holocene deformation in the center of a seismically imaged kink band along the Tacoma fault (Johnson et al., 2004; Sherrod et al., 2004; Liberty, 2006; Clement et al., 2010). The Tacoma fault appears as a prominent westtrending magnetic lineation on the southern margin of the Seattle uplift, but deformation associated with the Tacoma fault has not been identified west of Hood Canal or east of Puget Sound. Johnson et al. (2004) interpreted the Tacoma fault as an ~40° north-dipping backthrust of the Seattle fault zone based on their analysis of seismic reflection data.

A gravity low and slow upper crustal seismic velocities define a basin immediately west of the Seattle uplift that has previously been called the Dewatto basin (Fig. 2; van Wagoner et al. 2002; Johnson et al., 2004). Along the east edge of this basin and west edge of the Seattle uplift is a north-striking magnetic and gravity anomaly that we term the Dewatto lineament (DL in Figs. 2A, 2B; Pratt et al., 1997; Brocher et al., 2001; van Wagoner et al., 2002). The southern end of the Dewatto lineament at the southwestern corner of the Seattle uplift intersects the west-trending Tacoma fault. It has been previously suggested that the Tacoma fault extends beneath Hood Canal to just east of the Frigid Creek fault (FCF in Fig. 2) based on the presence of a broad, low-amplitude (~200 nT and 10-20 km wide), west-trending magnetic anomaly (Johnson et al., 2004) that is along strike with the Tacoma fault. However, the magnetic anomaly west of the Dewatto lineament is extremely weak compared to the Tacoma and Dewatto lineaments, and neither gravity nor seismic tomography data (Brocher et al., 2001) are consistent with uplifted basement rocks along this anomaly. This weak magnetic anomaly is similar in amplitude to other anomalies throughout the Puget Lowland and may be caused by near-surface deformation resulting from glacial deposition or scour (e.g.,

Sherrod et al., 2008). Gravity, magnetic, and tomography data do not support a separation between the Tacoma and Dewatto basins.

We propose that the Dewatto basin is a northwestern arm of the Tacoma Basin. Furthermore, we suggest that the Tacoma and Dewatto basins have evolved as a single structure, and refer to both as the Tacoma Basin. The kidney-shaped Tacoma Basin thus defined is bounded by the Olympia fault to the south, the Saddle Mountain deformation zone to the west, and the Seattle uplift to the north (Figs. 2A, 2B).

We acquired a 7.5-km-long west-east seismic profile southwest of Green Mountain to image strata across the Dewatto lineament (Figs. 2A, 2B, and 8D; line DW). Relatively flat-lying reflectors suggest undeformed strata in the upper 0.5 km depth along the eastern portion of the profile and gently dipping  $(\sim 2^{\circ})$  strata along the western 2 km of the Dewatto profile (Fig. 8D). We interpret an apparent reflector divergence as an unconformity marking the boundary between deposits of late Quaternary age or younger and ~6°-8° west-dipping Tertiary strata on the eastern and middle portions of the profile. There is no clear evidence of stratigraphic offset along this profile, but the reflector dip is consistent with late Quaternary folding of hanging-wall strata similar to that observed across the eaststriking Tacoma fault to the southeast (Johnson et al., 2004).

#### **Geophysical Investigations**

To constrain deformation along the western margin of the Seattle uplift, we forward modeled gravity and magnetic data using constraints from previous potential-field modeling to the west (Blakely et al., 2009), deep well logs (Brocher and Ruebel, 1998), seismic tomography velocity models (Brocher et al., 2001), and stratigraphic constraints for the top kilometer from the seismic data presented in Figure 8D. The model is along a 45-km-long west-east transect crossing the Dewatto lineament positioned where the magnetic and gravity gradients are well defined (B-B' in Fig. 2). Magnetic and density values used in the model are consistent with physical property measurements (Blakely et al., 2009) along a northwest-southeast transect that crosses the Saddle Mountain fault and the Tacoma Basin (Fig. 2A, profile A-A'). Densities for the primary formations were taken from regional well logs (Brocher and Ruebel, 1998) and are modeled as density contrasts relative to normal crust (2670 kg/m<sup>3</sup>).

Our model (Fig. 8C) based on gravity and magnetic profiles B–B' suggest asymmetry in the shape of the northwestern arm of Tacoma Basin and ~5 km of Tertiary and younger sedi-

Figure 8. (A, B) The calculated (RMS-root mean square) and observed (Obs.) anomalies (anom.) using forward modeling for the 45-km-long Dewatto transect B-B' shown in Figure 2A. The model extends to infinity in both directions perpendicular to the profile. (C) The magnetic and density distributions used to interpret the geological structure from the forward model where  $\Delta \rho$  is the density contrast (in kg/m<sup>3</sup>) relative to normal crust (2670 kg/m<sup>3</sup>) and  $\chi$  is the magnetic susceptibility (in SI units). The modeled thrust fault is termed the Dewatto fault. V.E.-vertical exaggeration. (D) Seismic section for the 7.5-km-long Dewatto profile (DW) shown in Figures 2A and 2B that extends east-west across the western margin of the Seattle uplift (SU). This cross section shows ~2° west-dipping tilt in the interpreted Pliocene and younger sedimentary deposits and the more severe ~6°-8° tilting of west-dipping Oligocene-Miocene sedimentary rocks below 0.6 km.



mentary strata overlying rocks of the Crescent Formation. Steeply dipping Tertiary rocks near Saddle Mountain west of Hood Canal are consistent with previous potential field interpretations (Blakely et al., 2009), and basin depths are in agreement with previous estimates from seismic tomographic studies (Brocher et al., 2001; van Wagoner et al., 2002). The magnetic low that defines the northwestern arm of the Tacoma Basin is ~4 km west of the gravity low. Due to the offset in gravity and magnetic lows (Figs. 8A, 8B), the Dewatto lineament is best modeled as dense magnetic Crescent Formation rocks thrust westward over less dense, nonmagnetic basin sediments and sedimentary rocks. Thus, we show the Dewatto lineament modeled with a 25° east-dipping thrust fault (the Dewatto fault) similar in nature to the north-dipping Tacoma fault (Brocher et al., 2004; Johnson et al., 2004). Our model is consistent with east-west compression and with thrusting along the eastern boundary of the Olympic Massif (Hurricane Ridge fault) to the west of the basin. Tilted strata of late Quaternary age observed in the western portions of the Dewatto seismic line (Fig. 8D) suggest continued folding of strata in the forelimb of the Dewatto fault.

#### DISCUSSION

The decreased deformation and faulting along the SR, FM, and Hood Canal seismic profiles relative to profiles BB and CO farther east (Figs. 3, 6, 7C) indicate that either the active Seattle fault zone diminishes to the west of Green Mountain or that deformation is being radially distributed across Hood Canal to the Saddle Mountain deformation zone. Deformation of Quaternary strata on seismic profiles BB and CO (Figs. 3, 5A, and 5B) on the north flank of Green Mountain suggests that deformation related to the Seattle fault zone extends southwestward from north of Green Mountain (Fig. 9). Continued westward deformation is supported by north-dipping strata along the southern ends of profiles SR and FM. Furthermore, folded glacial sediments and faults within Green Mountain bedrock (Haeussler and Clark, 2000; Tabor et al., 2011) are parallel to a magnetic lineation that wraps around Green Mountain bedrock exposures. This southwestward trend of the Seattle fault zone may be influenced by the adjacent Olympic Massif and may mark the southern limits of a zone of deformation that transfers strain between the Seattle fault zone and Saddle Mountain deformation zone.

The magnetic lineation that corresponds with fault F2 was originally interpreted as a fault (Blakely et al., 2009) using a maximum horizontal gradient method (Phillips, 2007). The structures A2, F2, and S3 responsible for this lineation are more clearly expressed by our marine magnetic survey (Fig. 2C), and their presence is evident in the Hood Canal seismic data (Fig. 7C). We have no seismic data south of line 84 (Fig. 3) to determine the southern limit of the fold and fault belt; however, the seismic data presented in Figure 7C, along with the absence of strong east-west magnetic lineations south of anticline A1, suggest that the relatively large displacement on west-striking structures between A1 and the eastern end of seismic line 91 all form a distributed area of deformation related to the Seattle fault zone projecting westward through a radially distributed strain transfer zone. The zone of strain transfer may continue southward, but we believe, on the basis of the Hood Canal magnetic survey, that strain is



Figure 9. Summary interpretation of the western portions of Seattle fault zone. Rainbow colors indicate reduced-to-the-pole magnetic anomaly field intensity. The yellow arrow shows the regional direction of strain relative to North America (Mazzotti et al., 2002; McCaffrey et al., 2007). Solid black lines show previously mapped faults; structures introduced in this paper are in red. The two blue lines represent the location of the Coho Road (CO) and Big Beef Road (BB) seismic lines. DF—Dewatto fault; F2—thrust fault (Figs. 3, 6, and 7); FCF—Frigid Creek fault; GM—Green Mountain; HRF—Hurricane Ridge fault; OF—Olympia fault; OU—Olympia uplift; SB—Seattle Basin; SFZ—Seattle fault zone; SMDZ—Saddle Mountain deformation zone as interpreted from magnetic data (Blakely et al. 2009); SMF—Saddle Mountain East and Saddle Mountain West faults; TB—Tacoma Basin; TF—Tacoma fault.

concentrated between the Seattle Basin margin to the north and anticline A1 to the south. The broad potential field gradients associated with these lineations suggest that the sources are either deeper than the FM and SR profile imaging depths, or that the gentle gradients are the result of the high altitude used for the aeromagnetic data acquisition. Based on the available data, late Quaternary deformation likely continues southwest around Green Mountain, where gravity and magnetic highs are likely caused by structures that connect the Seattle uplift with the Olympic Massif to the west. Late Ouaternary deformation also continues to the west, but is distributed over a larger area, causing smaller displacements on active transfer faults that are difficult to image using seismic and magnetic methods. In addition, the dip-slip component observed on the transfer faults farther to the east (e.g., as observed on the BB and CO seismic lines) may partly transition to an increasing strike-slip component as they strike westward. Such deformation would be less evident in seismic and magnetic imaging.

Seismic tomography, gravity, magnetic, and geologic data suggest that the Tacoma Basin is an ~5–7-km-deep, kidney-shaped basin bounded by the Tacoma, Saddle Mountain, and Olympia fault zones (Fig. 9; Brocher et al., 2001; van Wagoner et al., 2002; Blakely et al., 2009). The low-amplitude, ~200 nT magnetic anomaly crossing Hood Canal along strike with the Tacoma fault may mark a minor component of deformation related to the Tacoma fault. However, we propose that the Tacoma fault terminates at the southern end of the Dewatto lineament, where it links with a north-south fault, here termed the Dewatto fault, that strikes along the Dewatto lineament. We model the Dewatto fault as a low-angle thrust fault separating the Tacoma Basin from the Seattle uplift to the east (Figs. 8 and 9). The lowangle Dewatto fault thrust model may be best explained by east-directed shortening caused by exhumation of the accretionary terrane in the Olympic core complex (Wells et al., 1984; Johnson, 1985; Brocher et al., 2001). However, given modern north-northeast-directed motion inferred from global positioning system measurements and earthquake focal mechanisms (Mazzotti et al., 2002; McCaffrey et al., 2007), and clockwise rotation of the Cascadia forearc at  $1.5^{\circ} \pm 0.5^{\circ}$ /m.y. (Wells et al., 1998), the Dewatto fault now may be accommodating predominantly dextral strike-slip motion. Assuming that formation of the Seattle uplift commenced ca. 14 Ma (ten Brink et al., 2002), this low-angle thrust fault, which previously accommodated east-west shortening, may now be accommodating predominantly north-south compression by facilitating slip partitioning between the Seattle uplift and the Olympic Massif. The northward compression that would result from dextral strike-slip motion along the Dewatto fault may be a component of the strain transfer zone west of Green Mountain.

Recent work by Mace and Keranen (2012), who jointly interpreted several types of geophysical data in the central Puget Lowland, found evidence for a zone of recent northeastsouthwest faulting that crosses the Seattle Basin and Seattle uplift. By examining offsets of east-west-aligned structures in the Seattle fault zone, they interpreted dextral strike slip along this northeast-southwest-aligned fault system and suggested that these northeast-trending structures may accommodate eastward transport of the Olympic Massif. Mace and Keranen (2012) further proposed that strain partitioning cycles between the east-west-oriented Seattle fault zone and these northeast-southwest-oriented structures, to facilitate north-south and east-west shortening, respectively. Our data and interpretations of east-west- to northeast-southwest- to north-south-trending structures at the western margins of the Seattle fault zone and Seattle uplift independently support partitioning of strain between the Seattle fault zone and Saddle Mountain deformation zone.

Figure 9 illustrates the map expression of a conceptual model for the west to southwestward continuation of deformation related to the

Seattle fault zone. Seismic reflection data and magnetic anomalies presented here indicate that the deformation observed along the southern boundary of the modern Seattle fault zone extends west and southwestward from north of Green Mountain (Figs. 3, 5, 6, and 7). We propose that strain between the western part of the Seattle fault zone and the Olympic Massif is transferred by way of a broad, west- to southwest-striking zone of deformation reflected in the gravity and magnetic highs that traverse Hood Canal along the northern limits of the Tacoma Basin (Figs. 2B and 9). We believe this is a strain transfer zone that links the Saddle Mountain and Seattle fault zones through a series of smaller displacement faults and folds as observed to some extent in our data (Fig. 9). The strain transfer zone merges with the Saddle Mountain deformation zone and defines the northern boundary of the Tacoma Basin. This model requires that faults and folds mapped on profiles BB and CO are in the hanging wall of the Seattle fault zone and that the faults project to the surface farther north. We suggest that the southwest structural trend observed on the BB and CO seismic profiles defines the southern margin of the strain transfer zone. The northern margin of this strain transfer zone is characterized by the east-west-aligned structures interpreted from our seismic and magnetic data near Hood Canal (Figs. 6 and 7).

The fault-controlled western boundary of the Seattle uplift suggests strain partitioning along the western limits of the Seattle fault zone in order to accommodate rigid block uplift of the Seattle uplift and Saddle Mountain deformation zone. This may represent a complex interplay with east-directed Olympic subduction and north-directed (modern) Cascadia motion as observed on the Hurricane Ridge fault (Tabor and Cady, 1978b; Wells et al., 1984; Johnson, 1985; Brandon et al., 1998). Our model suggests a direct link of the Seattle fault and Saddle Mountain deformation zones. This model is consistent with studies of the Saddle Mountain West and Saddle Mountain East faults that show that these faults were formed by east-west compression that caused thrust faulting and displacement of Pleistocene glacial deposits and underlying Eocene Crescent Formation rocks (Wilson, 1975; Wilson et al., 1979; Witter and Givler, 2008; Blakely et al., 2009). Trench excavations across the Saddle Mountain faults also show that both are southeast-dipping thrust faults with left-lateral movement. There is further paleoseismic evidence that both of these faults produced earthquakes between 1000 and 1300 yr ago (Hughes, 2005). The possible synchroneity of motion on these faults with the >M7 earthquake that occurred on the Seattle fault ~1100 yr ago is consistent with rupture of linked faults. These results suggest that the Seattle fault zone extends >100 km and is capable of >M7 earthquakes (Wells and Coppersmith, 1994). Our interpretation of the Dewatto fault along the western margin of the Seattle uplift has implications for conventional risk assessments in the region; however, until a slip rate and recurrence interval for the fault are established, the risk is unknown.

The principal uncertainties in our model are related to the sparseness of our data and the inherent nonuniqueness of potential field interpretations. We have minimized these uncertainties by using an integrated approach that incorporates a range of geophysical and geological data. We have investigated a number of possible scenarios that honor these data and conclude that a distributed zone of strain transfer across Hood Canal provides a robust fit to our data and offers an explanation for interaction between the western Seattle fault zone and Olympic Massif. Our interpretation could be improved and tested with additional gravity and seismic data both east-west across the Dewatto lineament and north-south along Hood Canal. A three-dimensional, balanced crustal model would assure that interpreted structures can be restored back in time to balanced stratigraphy.

### SUMMARY

We have presented evidence that suggests that the Seattle fault zone and Saddle Mountain deformation zone are linked along the northern margin of the Tacoma Basin west of the Seattle uplift, and that the basin's eastern margin is controlled by the Dewatto fault where it is expressed as the Dewatto lineament. Late Quaternary deformation interpreted on our BB and CO seismic profiles implies that the Seattle fault zone continues to the west of the Seattle Basin and may merge with the Saddle Mountain deformation zone through a broad strain transfer zone. Potential-field lineaments and westdipping late Pleistocene strata near the Dewatto lineament suggest that the Seattle uplift acts as a rigid block, juxtaposing Crescent Formation rocks to the east against the northwestern arm of the ~5-7-km-deep Tacoma Basin (previously defined as the Dewatto basin). The strain transfer zone at the northwestern margin of the Tacoma Basin and western extension of the Seattle fault zone may kinematically link the Seattle, Tacoma, and Saddle Mountain fault systems. This zone facilitates strain partitioning between the Olympic Massif and Puget Lowland. Rupture along the overall length of these linked faults systems could produce a >M7 earthquake.

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