Synthesis of crustal fault deformation history in Puget Sound Washington from new and legacy marine geophysical data

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Abstract

We conduct a synthesis of newly acquired seismic reflection datasets with complementary geologic and geophysical data to characterize crustal faulting behavior in Puget Sound, with a specific focus on the segment of the Seattle fault system that extends from roughly southern Bainbridge Island to eastern Lake Washington. This work utilizes a new high-resolution multichannel seismic (MCS) reflection and seismic chirp survey collected in February 2017, along with complementary data such as high-resolution bathymetry, terrestrial Lidar, and marine magnetics, to improve our understanding of the geometry and rate of currently deforming fault structures in the Puget Sound region. Using this collective dataset, we explore deformation patters of the primary thrust and backthrust structures of the Seattle fault zone (including offshore extensions of the Toe Jam Hill, Mac's Pond, and Waterman Point Scarps) that are expressed as both surface fault scarps, apparent in seafloor morphology, and tilted glacial units. Although significant marine geophysical studies have been conducted throughout the main basin of Puget Sound in the past to characterize Seattle fault tectonics, previous seismic reflection imaging has largely focused on deep structure, looking for offsets in bedrock Crescent and Blakely Harbor formations. Here, co-located seismic chrip and high-resolution MCS transects throughout the Puget Sound main basin, Possession Sound and Lake Washington, image the top ~100 m of the marine sediment record at resolutions on the order of 0.25 cm (chirp) and ~1 m (sparker, MCS). Evidence of recent faulting and folding of glacial, post glacial and Holocene strata in the shallow subsurface provides new information on the location and relative timeframe of active deformation structures. New seismic data clearly images dipping seismic horizons, apparently associated with variable uplift that correlates with interpreted coseismic or interseismic fault offsets along primary south-dipping thrust faults and north-dipping backthrusts. In concert with insight from marine magnetic data, sensitive to offsets across magnetic units within the Blakely Harbor and deeper Crescent formation and correlative evidence from uplifted paleo-shorelines, we gain a more detailed view of the detailed location of faulting throughout the marine portions of the Puget Lowland and the amount of deformation accommodated by primary thrust and secondary backthrust features associated with the Seattle fault system.

Publications and presentations supported by this work

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Moore, G., Roland, E., Watt, J., Bennett, S. E., Kluesner, K. J., Brothers, D. S., Shallow offshore deformation in the Seattle fault zone: insights from high-resolution seismic reflection imagery.” Seismological Society of America Annual Meeting, Seattle Washington, 2019.

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Technical Report

Introduction

Earthquakes that occur on shallow crustal faults have the potential to cause significant damage and loss of life. In the last decade, some of the most devastating earthquakes globally occurred on blind thrust faults that accommodate strain within the crust away from a primary plate boundary (e.g. 2008 Haiti Earthquake, ~160,000 deaths, 2008 Sichuan China ~70,000 deaths, 2011 Eastern Turkey earthquake ~600 deaths, 2011 Christchurch, 185 deaths). Many of these events occurred on faults with relatively long recurrence intervals or low slip rates, in locations where the regional tectonic forces driving slip are well known, but individual fault zones have not been well mapped. Compounding matters, crustal faults are particularly dangerous when they occur very close to large population centers in regions that do not experience frequent large earthquakes.

In the Pacific Northwest, the Puget Lowland sits ~250 km east of the Cascadia convergent margin, where oblique subduction leads to north-south compression and crustal faulting within the North American subduction forearc (McCaffrey, 2002; McCaffrey et al., 2007). Although the largest magnitude earthquakes in the region may be generated from the Cascadia subduction plate boundary, paleoseismic evidence (Nelson et al., 2003a, 2003b, 2014; Ten Brink et al., 2006; Kelsey et al., 2008) indicates that large (M ~7) earthquakes have occurred on east-west trending thrust faults throughout the Puget Lowland. Prominent fault zones that extend across the Puget Lowland include the Seattle, Tacoma, South Whidbey Island fault (SWIF) and Devil’s Mountain fault (Fig. 1). Although these faults are expected to accommodate much less strain than plate boundary faults (collectively 4.4 mm/y through Puget Lowland, (McCaffrey et al., 2007)), and thus have longer recurrence intervals, they extend directly under the

Seattle-Tacoma-Everett corridor, the most densely populated region of the Pacific Northwest, and would likely produce relatively shallow earthquakes, sourced ~10-20 km. Ground motion simulations and observations of ground shaking from historical events indicate that energy from a moderate sized (M ~6.5) event would likely be trapped in the sedimentary basin located beneath downtown Seattle (Hartzell et al., 2002). Rupture directivity and 3D basin amplification associated with such an event are expected to produce significant ground motions and worsen landslides triggered throughout the area (Frankel and Stephenson, 2000; Pratt et al., 2003; Frankel et al., 2009; Allstadt et al., 2013). In this way, significant local ground shaking from a Seattle fault event and the anticipated damage to buildings and bridges (Ballantyne et al., 2002), landslides (Karlin et al., 2004; Allstadt et al., 2013) and tsunami events throughout Puget Sound (Atwater and Moore, 1992; González and Sherrod, 2003), make it one of the most dangerous faults along the western US margin.

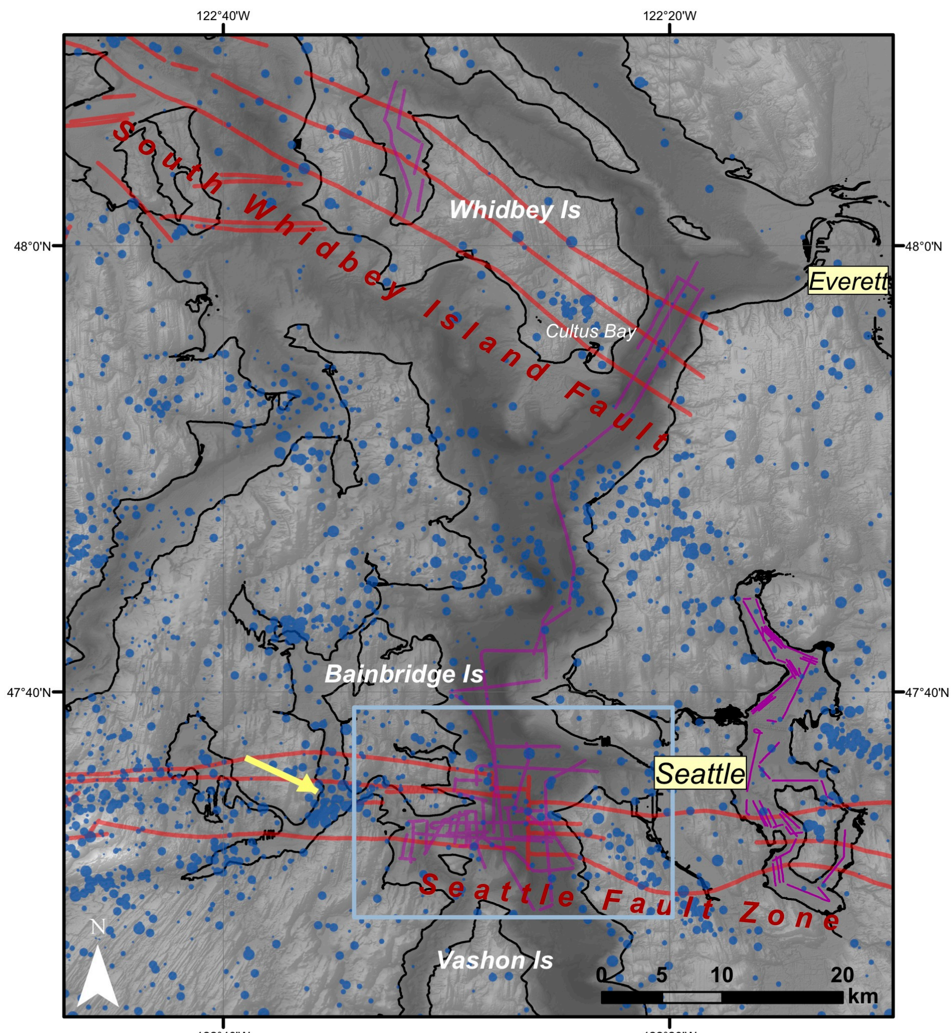

Figure 1: *Regional map showing Puget Lowland. Red faults are the Seattle fault zone and South Whidbey Island Fault from the USGS Quaternary fault and fold database (accessed April 2017, from USGS web site: https://earthquake.usgs.gov/hazards/qfaults/). Magenta lines show newly acquired (Feb, 2017) high-resolution multichannel seismic and collocated seismic chirp data. Greyscale digital elevation model shows combined topography and bathymetry (Finlayson, 2005). Blue circles show seismicity from the Pacific Northwest Seismic Network from 200-2017, with the size of the symbol indicating the relative size of the event (most events are between M 0.5-2.0). The yellow arrow is pointing to the recent Bremerton seismic swarm of May 2017 (possible Seattle fault, largest event M3.3 at the time of writing). Blue square shows location of Figure 2.*

Mapping the precise location of crustal faults can be difficult for many reasons, but is necessary for characterizing deformation patterns and developing detailed hazard mitigation plans. It is common for deformation to be accommodated in in regions of distributed convergence (like those associated with the Tibetan Plateau, New Zealand, and Cascadia) as blind thrusts that do not propagate to the surface, on faults that have often not sustained a large earthquake in historical time. Complex geologic framework associated with accreted and deformed terranes inbound and adjacent to convergent margins often makes primarily deformation features difficult to identify. Furthermore, seismicity in these settings may be dispersedly distributed, and thus may be a poor indicator of the most dangerous earthquake source faults. A earthquake swarm near Bremerton, Washington that occurred in May, 2017 is a good example of this, it generated several M3 events along a lineation subparallel to the mapped Seattle fault (Fig. 1) and at greater depths than expected for this fault (Young, 2017). Paleoseismology and field mapping can be critical tools for identifying locations where significant fault slip has occurred in the past (Atwater and Moore, 1992; Sherrod et al., 2000; Nelson et al., 2003a, 2003b, 2014a; Ten Brink et al., 2006; Kelsey et al., 2008; Reid et al., 2016), but as is the case for the Puget Lowland, paleo-proxies for significant fault slip, such as instantaneous widespread uplift or subsidence, still leave questions about the precise location of currently active fault structures, how locally-mapped faults extend horizontally and in depth, and what features are most likely to accommodate strain in the future.

Many of the crustal faults thought to accommodate north-south compression in the Puget Lowland strike roughly east-west, and thus extend both across terrestrial settings as well as into the marine environment. The onshore-offshore nature of these faults presents challenges, as well as opportunities. Where, for example, the Seattle, Tacoma, and South Whidbey Island faults extend across Puget Sound basins, significant packages of unconsolidated Quaternary sediments associated with glacial and post-glacial deposition overly bedrock (Easterbrook, 1986; Booth, 1994; Troost and Booth, 2008), and modern high sedimentation rates have delivered stratified layers of Holocene sedimentation throughout recent past (Carpenter et al., 1985). This configuration provides an opportunity to use marine seismic reflection data to explore the seismic stratigraphy of sediment overlying inferred locations of faulting, specifically exploring for evidence of Holocene surface or shallow subsurface deformation or growth faulting that can be an indication of faulting or deformation prior to, during, or after sediment deposition (e.g. (Suppe et al., 1992; Hardy and Poblet, 1994; Hardy and Ford, 1997; Vergés et al., 2002). Offsets in distinctive sediment packages associated with glacial, and postglacial deposition, as well as the most recent Holocene sediment which is being deposited at rates ranging form 0.12-0.72 cm/year (Carpenter et al., 1985), should inform models of primary deforming structures, and potentially provide information on the timeframe and magnitude of modern deformation across these fault structures.

With this goal, we have conducted an onshore-offshore synthesis of geophysical and geological datasets available in Puget Sound, including a recently acquired high-resolution multichannel seismic reflection (MCS) and seismic chirp survey collected in February 2017 (Fig. 1), along with new and existing high resolution bathymetry, terrestrial LIDAR (Haugerud et al., 2003), and new and existing magnetics (Blakely et al., 2002), to improve our understanding of the geometry, along-strike extent, and rate of currently deforming fault structures in the Puget Lowland. Specifically, we focus on characterizing deformation patters of the primary thrust and backthrust structures of the Seattle fault (including the offshore extensions of the Toe Jam Hill, Waterman Point, Orchard Point and related scarps, Fig. 2). Although marine geophysical studies have been conducted throughout the main basin of Puget Sound in the past to characterize crustal faulting patterns (Johnson et al., 1994, 1999; Pratt et al., 1997, 2015; Brocher et al., 2001, 2004; Ten Brink et al., 2002; Clement et al., 2010; Mace and Keranen, 2012) previous seismic reflection imaging has largely focused on deep structure, looking for offsets in bedrock Crescent and Blakely Harbor formations, and modern seismic reflection has not been collected in the past two decades.

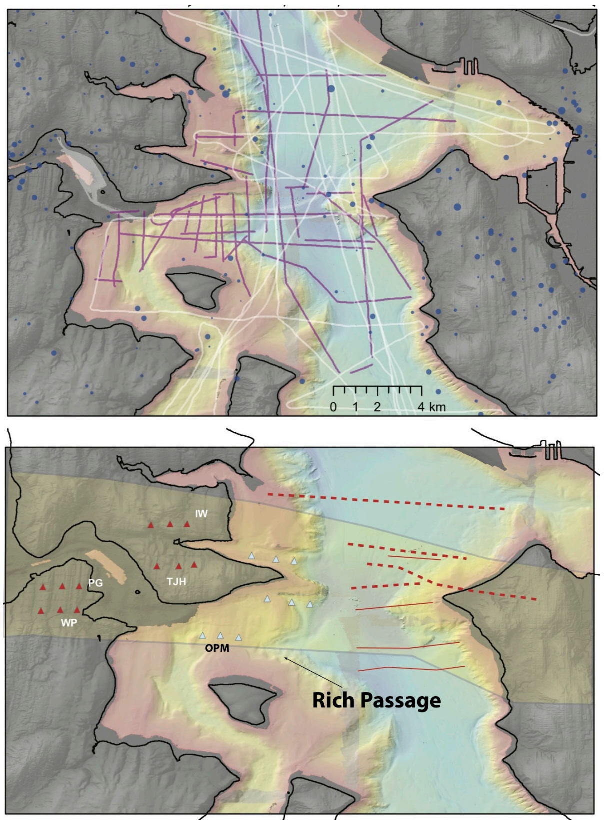

Figure 2: *(Top) The location of new multichannel seismic reflection and collocated seismic chirp lines (magenta) crossing the Seattle fault and legacy USGS and industry MCS data (white lines). (Bottom) Map of Puget Sound in the vicinity of the Seattle fault. Available multibeam bathymetry grids from recent NOAA surveys are plotted in color and along with topography in greyscale from Puget Sound LIDAR data show several locations where possible fault scarps are visible on land (shown by red arrows) and along the seafloor (blue arrows). Named scarps have hosted paleoseismic studies: WP - Waterman Point Scarp, PG- Point Glover scarp, TJH – Toe Jam Hill scarp, IW – Island wood Fault (Kelsey et al., 2008). Additionally well-resolved Orchard Point Marine scarp is labeled. Red dashed and solid lines are approximate locations of structures mapped in legacy deep penetration seismic datasets by Pratt et al., (2015) and interpreted to be main thrust faults and back-thrusts, respectively. Yellow shaded region shows approximate location of coseismic uplift associated with the ~900AD event from Kelsey et al. (2008).*

Here, we utilize a new, state of the art high-resolution dataset that images the top ~100 m of the marine sediment record at resolutions on the order of 0.25 cm (chirp) and ~1 m (sparker, MCS) to characterize evidence of recent faulting, uplift and folding of bedrock, glacial, and post glacial Holocene strata with the goal of gaining new information on the distribution and time history of active deformation structures.

Initial results of this work, still underway, indicate the amount of tilting and uplift in horizontally-deposited glacial units, particularly throughout the region of Rich Passage (Fig. 2), newly imaged in high-resolution seismic data correlate with the amplitude of uplifted shoreline terraces, associated with the most recent large Seattle fault zone earthquake (Ten Brink et al., 2006). The pattern of tilting and apparent uplift visible in the shallow subsurface suggests that the deformation is ongoing across a complex array of subfaults making up the Seattle fault system, that extends at least as far south as Blake Island (Fig. 2). The new, relatively dense dataset of marine MCS data illuminates some instances of shallow geologic units that appear to be juxtaposed by fault surfaces, and we interpret these to be the shallow extensions of backthrust strands. However, this data does not show evidence for great continuity of near-surface backthrust features in the east-west direction, suggesting that individual fault strands may be variably continuous along strike, but does show evidence for consistency in uplift rates across the primary Seattle fault thrust system extending from at least southern Bainbridge Island to Eastern Lake Washington. Collectively this work highlights both the complexity of the shallow faulting system associated with the Seattle fault zone. It also reinforces the importance of refining existing fault models with more detailed geophysical information to constrain regions of concentrated deformation apparent in the geologic units, and the most likely sources for future large, shallow earthquake ruptures in the densely populated Puget Sound region.

Data and Processing Methods

This work has utilized new high-resolution multichannel and high-resolution chirp dataset that sampled the shallow structure throughout Puget Sound. The primary seismic reflection dataset was augmented by complementary geologic and geophysical data including preexisting earlier-generation crustal scale industry and USGS-collected marine seismic reflection data (Fig. 2), information from paleoseismic studies on land, and regional magnetics data. New high-resolution seismic data was collected in the winter of 2016-17, and includes 240 km of collocated 16-channel MCS mini-sparker and seismic chirp data. This data was collected aboard the R/V Clifford A. Barnes, a ~70 ft. vessel operated by the University of Washington. The resulting high-resolution seismic reflection dataset sampled the top several hundred meters of the subsurface geologic units throughout Puget Sound, extending primarily over the mapped region of the Seattle fault zone, and up through Possession Sound and into Holmes Harbor over the trace of the SWIF (Figs 1, 2). Additionally, 85 km of collocated MCS boomer and chirp data was collected throughout Lake Washington (Fig 1). Magnetics data is also currently being used to augment seismic reflection interpretations drawn from both published aeromagnetic surveys (e.g. Blakely et al., 2002) as well as marine magnetic surveys collected throughout the main basin of Puget Sound, primarily during student teaching cruises coordinated for undergraduates at the University of Washington.

MCS data processing included first generating brute stacks of the mini-sparker and boomer data, picking the water bottom and performing velocity analysis, and then applying an appropriate 1D velocity model hung from the seafloor for NMO-correction and stacking that was based on semblance analysis where the quality of reflections was the best. Independent hung 1D velocity models were developed for Puget Sound and Lake Washington. Additionally, predictive deconvolution was applied to reduce the effect of the broad source-signature from the sparker bubble pulse (Duchesne et al., 2007). Post-stack time migration was applied using a modified velocity model similar to that used for NMO and stacking. Collectively, improved resolution of shallow structures achieved by advanced data processing (Fig. 3), relatively good penetration of MCS data (sparker/boomer source) and ultra-high resolution of shallow structure from seismic chirp data provides us with a multi-scale (0.25-1.0 m resolution) imaging capability to resolve structures in the top ~200 m of the subsurface, or above the multiple throughout the survey region (Fig. 3).

Marine magnetics data used in this work was generated using a Marine Magnetics Explorer magnetometer, towed with a 30 m cable. Magnetics processing included simple reduction of the raw observed magnetic field by removing the diurnal field as observed at the Victoria Magnetic Observatory, with data accessed via the Natural Resources Canada server (http://www.geomag.nrcan.gc.ca/obs/vic-en.php). Additionally the background International Geomagnetic Reference Field was also removed across the survey area to produce a magnetic anomaly.

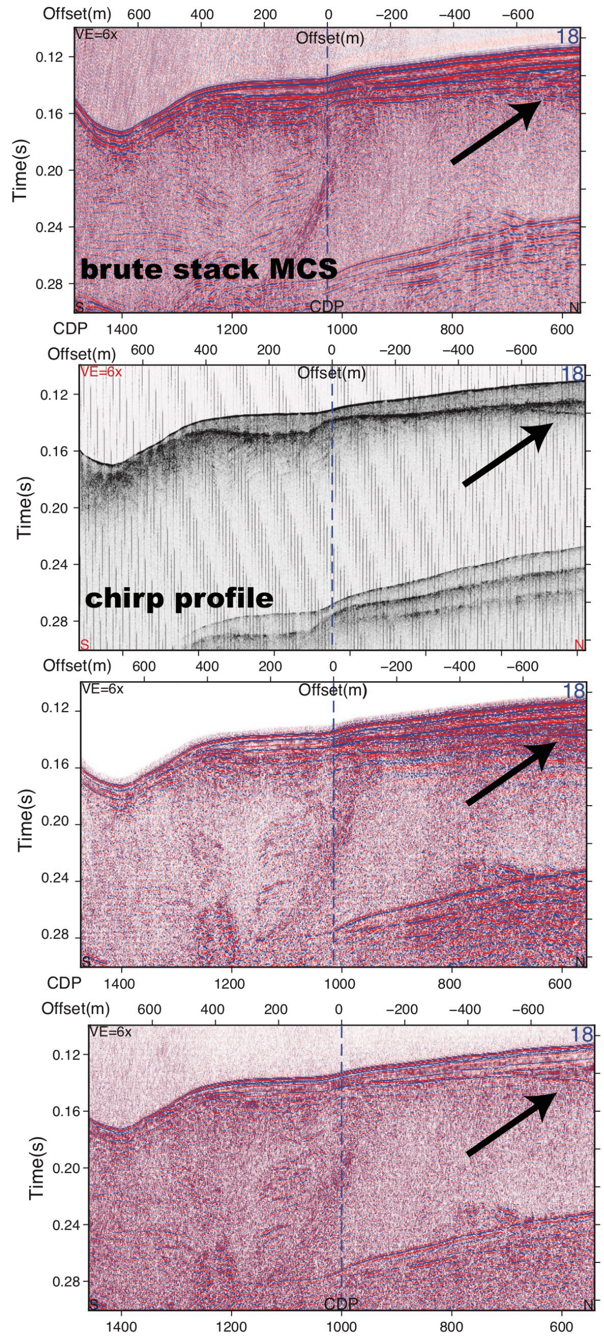

Figure 3: *Example of data processing and resolution of shallow features. Line 18 extends through the Rich Passage area, south of Bainbridge Island. Top figure shows MCS brute stack assuming 1600 m/s. Second from top shows co-located ultra-high resolution chirp profile. Third figure from top shows improved resolution time migration image using a hung velocity model. Bottom figure shows time migration with improved workflow targeted at refining predictive deconvolution to reduced the broad source signature of the sparker bubble pulse in the shallowest ~0.01 s. Black arrows throughout highlight improved resolution of shallow reflectors providing improved shallow imaging.*

New interpretations of fault-related deformation

Based on interpretations from new high-resolution seismic data, we have gained new insight into Seattle fault zone deformation structures and fault locations based on two independent observations: 1. broad-scale tilting of shallow glacial units, linked to expected uplift and subsidence during seismic events on the Seattle fault, and 2. evidence of shallow-propagation of fault detachment surfaces, particularly related to backthrust faults in the southern Bainbridge Island region. Simple interpretations of fault surfaces have been challenging using the high-resolution seismic reflection data alone, either because they are not present in all locations (as would be expected for blind thrusts) or due to geologic complexity of the glacial units and variability in penetration of high-frequency seismic waves, particularly through gas-occupied strata within the Puget Sound and Lake Washington surveys. Nonetheless, correlating structure resolved in seismic profiles with previous observations from uplifted shorelines, morphological and potential fields observations of geomorphic and geophysical features thought to be fault-related has lead to new insights into the specific location and patterns of crustal faulting features.

Quantitative analysis of broad deformation patterns across the Seattle uplift

A primary new observations made from new seismic reflection data is the fault-related pattern of tilted stratigraphic layering across the expected fault-influenced deformation zone. We assume glacial units prevelant throughout this portion of the Puget Sound region such as pre-glacial Oligocene Blakely formation, and Holocene sediments were deposited as horizontal layers. Evidence of folded, tilted and irregularly deformed stratigraphy in the shallow subsurface is not only clear in seismic record sections (Fig. 4), but also can be objectively picked using a workflow that provides the average dip of coherent geologic contacts across seismic transects. Figure 4 shows representative MCS profiles crossing from south to north across the Rich Passage area of Puget Sound, aligned with the region of previously-proposed north-dipping backthrust faulting, south of the primary south-dipping blind thrust detachment of the Seattle fault. Here, we can see clear evidence variably tilted stratigraphic horizons from south to north.

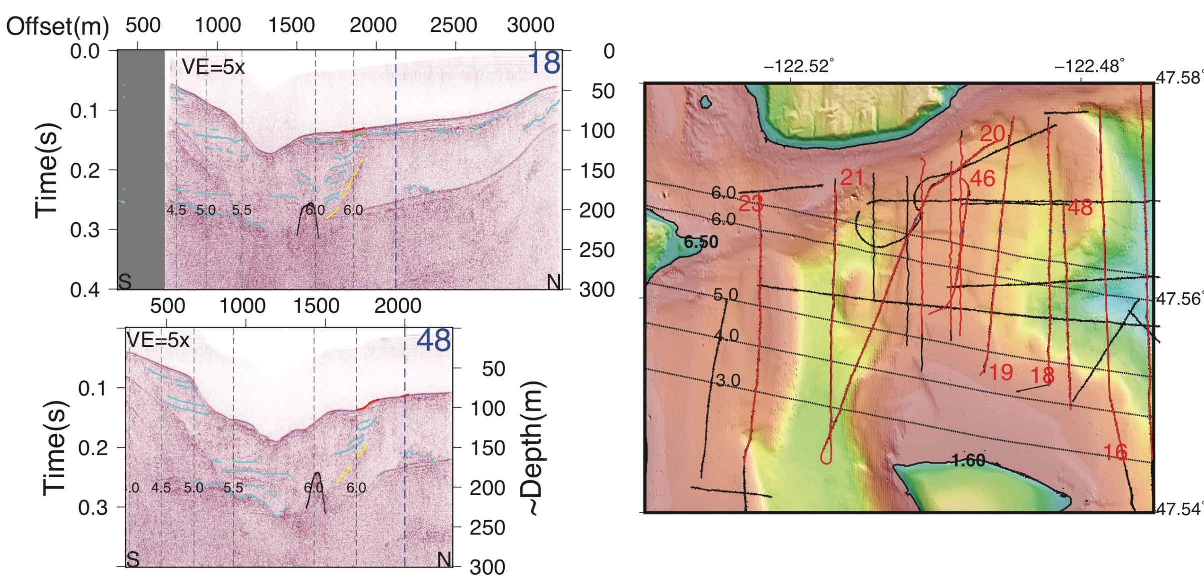

Figure 4: *Two representative interpreted MCS profiles crossing Rich Passage from south-north. Cyan horizons show general trends in manually identified coherent reflectors, yellow horizon shows an interpreted boundary surface juxtaposing geologic units with variable dips and reflectivity character, and red seafloor reflector highlights the location of a fault scarp visible in the bathymetry (Figure 1). Black feature is a yet poorly understood feature that has been seen across multiple lines in the vicinity of the fault scarp and may be associated with shallow propagation of the backthrust detachment that influences the broad structural trends seen here. Map on the righ shows the location of seismic profiles and black labeled contours extending east-west*

across map and also on seismic profiles show modeled uplifted paleo-shorelines from Ten Brink et al. (2002), extrapolated parallel to the Seattle fault zone deformation front (Pratt et al., 2015).

In order to quantify the degree and orientation of deformation in shallow subsurface structure, we take a two-step process to first identify coherent reflectors, and then calculate the average dip of stratigraphy, which should provide new information on the amount of deformation since deposition. We apply a coherence filter to MCS profiles as a way of objectively picking reflectors (Fig. 5) and identifying a structure-orientation (Hale, 2009). Using this method the seismic profile can be treated as a pixelated image, and a directional coherence and coherence strength is calculated by searching for the direction of similarity, in this case influenced by the reflectivity structure. In this way, coherence is defined as the amount of similarity between an original pixel and a pixel that has been smoothed in the direction indicated by the vector. As can be seen in Figure 5, this method for defining the orientation of subsurface structure provides a means of quantifying stratigraphic tilting that we think is linked to the amount of fault-related deformation across the Seattle fault system. Our data is the best quality within the Rich Passage area, south of Bainbridge Island, and along the shallow-water margins of the main basin of Puget Sound, crossing the primary Seattle fault thrust. We see evidence of a pattern evolving from south to north of horizontal, south-dipping, north-dipping and again horizontal orientations that correlates well with the hypothesized location of the Seattle fault primary and secondary thrusts, and magnetic anomalies thought to be representative of an offset in magnetic units across a deeper fault detachment at depth (Blakely et al., 2002; Ten Brink et al., 2002; Brocher et al., 2004).

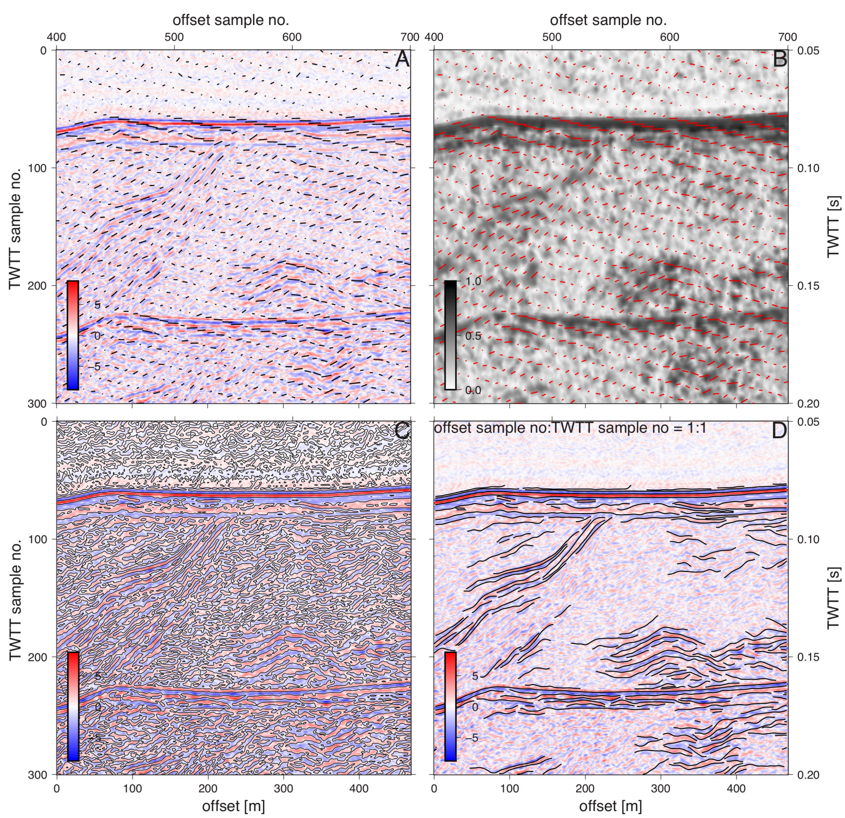

Figure 5. *The methodology for automatically identifying coherent reflectors, or geologic contacts, in seismic reflection imagery. The same two axes are included for each panel, one indicating the offset-TWTT (two way travel time) space, and one indicating the sample number along each respective axis. In the 1:1 sample number space, seismic reflection data can be interpreted as a pixelated image. (A) A seismic reflection image is shown, with red indicating positive pixel values and blue indicating negative pixel values. Black lines indicate the direction perpendicular to the steepest image gradient for a subset of pixels in the image. Longer lines indicate more linear continuity (referred to here as coherence) in that direction. Coherence values are queried from the grid shown in B. (B) A measure of coherence is shown, with darker values indicating higher coherence. Directional coherence lines shown in A are shown again here in red. Note that longer lines correspond to higher coherence values. (C) The zero contour of the image shown in A is indicated in black. The transition from positive to negative pixel values can either be interpreted as a geologic contact or some form of noise. (D) The contours from C are filtered by coherence value shown in B, removing boundaries that would be interpreted as noise. This returns reflectors that would be manually interpreted as geologic contacts. The filtered contours are shown in black.*

Evidence of shallow faulting

Embedded in new observations of variably-tilted shallow stratigraphy there is also new evidence for shallow faulting in discrete locations throughout Puget Sound. As previously described, the Seattle fault has been interpreted to be a series of south-dipping primary thrust faults or a single master thrust that is blind, meaning it does not propagate to the surface, along with secondary north-dipping backthrust faults that in certain locations, appear to propagate to the surface. However, the location of these surface-propagating backthrusts through the marine portions of the region has not been well constrained and is poorly imaged in lower-frequency marine seismic datasets. Here we see complex evidence of shallow faulting in certain locations of our study area (i.e. Fig. 4). Although no discrete offsets are visible in Holocene sediment layers, juxtaposition of glacial units can be identified within the top ~150 m of the surface in the Rich Passage area, apparently reflecting the shallow extent of a fault strand that appears to be the marine extension of a backthrust fault we identify as the Orchard Point Marine fault. Based on its location and morphological character, this feature appears to be similar to faults mapped and trenched on Bainbridge Island (Nelson et al., 2003a, 2003b, 2014; Kelsey et al., 2008) like the Toe Jam Hill fault. Ongoing interpretation work is focused on exploring whether additional marine faults can be identified east of the Toe Jam Hill fault and within Lake Washington (i.e. Fig. 6), and whether variable acoustic shadowing associated with gas-filled sediments that initiate and terminate abruptly may also be correlated with possible faulting structures seen throughout the study region.

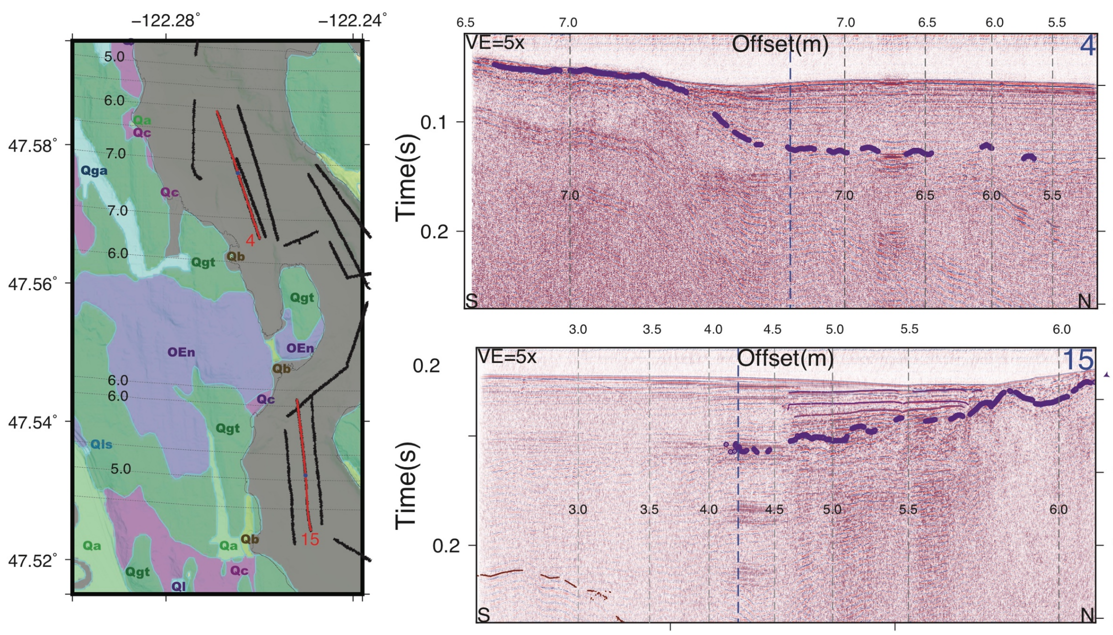

Figure 6. *Geologic map modified after Troost et al., (2005) showing distribution of Oligocene (Blakely Formation, OEn) and Quaternary glacial units (Vashon Till, Qgt), at the western side of Lake Washington. Seismic profiles show interpreted top of Oligocene 'bedrock' unit with subhorizontal sediment, we suspect to be Quaternary deposits above. Labeled contours extending east-west across map and also on seismic profiles show modeled uplifted paleo-shorelines from Ten Brink et al. (2002), extrapolated to the west parallel to the Seattle fault zone deformation front (Pratt et al., 2015).*

Correlation to coseismic uplift from paleoseismic observations

Based on our observation we can obtain new information about fault processes from the regional pattern of tilted stratigraphic units if we assume that this reflects fault-related deformation. Additionally, identified locations of shallow faulting, like those seen in Rich Passage should represent zones of localized deformation. In order to assess whether our observations are consistent with existing fault models or paleoseismic work, we have compared the patterns of deformation in shallow strata and location of possible fault strands to observations of uplifted paleo-shorelines that have been used to infer the location and magnitude of the last Seattle fault zone earthquake (Ten Brink et al., 2006). Although tilted strata are not a direct measurement of coseismic uplift or subsidence, they should be correlated with deformation amplitudes, with steeper dipping beds indicative of greater uplift of subsidence. In Figure 7 we show two examples of ways deformation inferred from seismic data can be correlated with paleoseismic uplift surfaces. Both the spatial gradient of bedding plane orientations (change in dip angle) as measured in Rich Passage MCS data, as well as the depth to the top of the Oligocene Blakely Formation seen in Lake Washington data correlate with the smoothed uplift curve based on observations made in ten Brink et al. (2006). Although this observation is preliminary, exploring how surface-extending backthrust fault locations may be correlated with second-order variability superimposed on the smooth uplift pattern across the Seattle fault zone (i.e. Fig. 7a) provides a strategy for not only strengthening subjective structural interpretations made in seismic reflection images (like those presented in Fig. 4) but also identifying the location of variability in spatial deformation rates, potentially indicative of localized deformation or the location of individual fault strands.

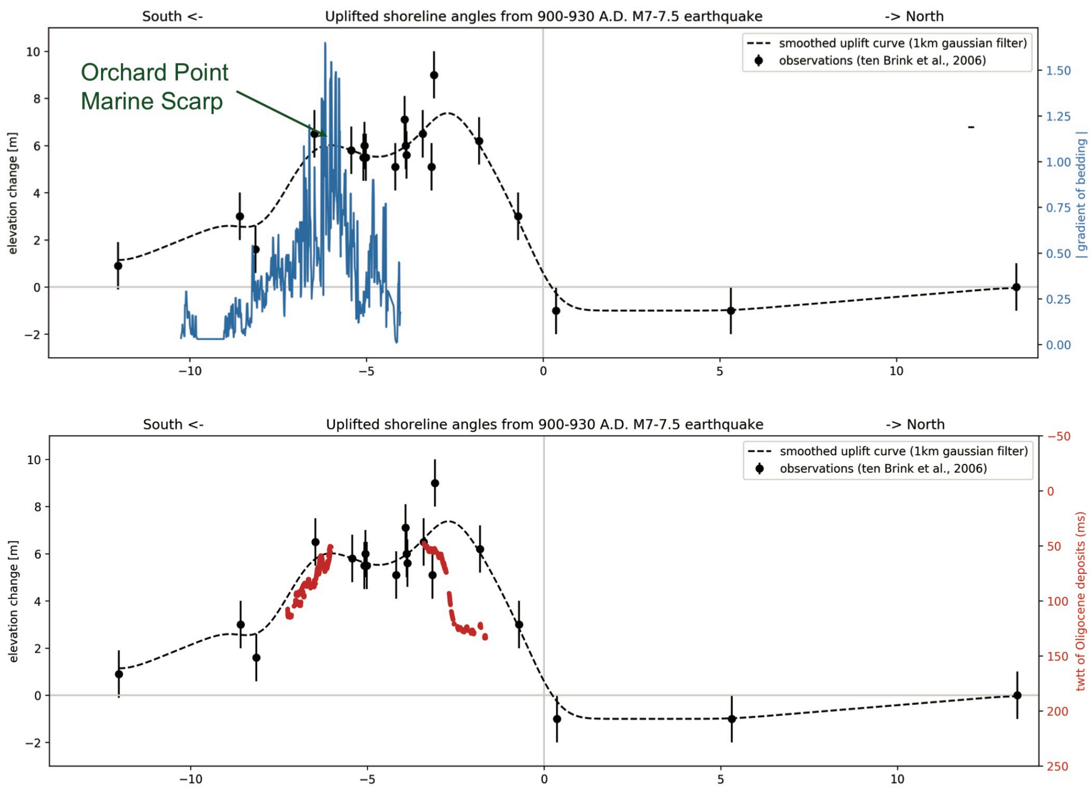

Figure 7. *(Top) Comparison of coseismic uplift inferred from observations presented in ten Brink et al., (2006) to the orientation of assumed horizontally-deposited geologic units imaged in high-resolution seismic reflection data through Rich Passage. The gradient of bedding is a normalized apparent dip derived from the change in travel time over change in distance observed in time-migrated images. The gradient defined in this way has been arbitrarily scaled to be compared to the smoothed uplift curve. (Bottom) a similar comparison made between the depth (two-way travel time) to the top of the pre-glacial Blakely Formation geologic unit across the region of coseismic uplift. In both figures the x-axis shows distance from the deformation front as identified by the northern-most south-dipping thrust in Pratt et al., (2015).*

Ongoing and Future Work

Ongoing work is focused on extending new observations made in the seismic reflection data as outlined above in certain key locations (i.e. Rich Passage, western Lake Washington) across the entire Puget Sound region sampled by the new high-resolution MCS dataset. We are currently working toward the goals of summarizing structure orientation across the entire study region using the objective coherence-filtered dataset, and continuing to compare this to existing fault models and past rupture models (i.e. Pratt et al., 2015, Blakely et al., 2002, ten Brink et al., 2006). Because both the geologic framework and reflection imaging quality are variable throughout the study area, evidence for shallow faulting is most apparent when structure in seismic profiles can be correlated with complementary geophysical or geologic data. Probably the most prominent feature that appears to be a fault-related contact between two discrete geologic units is what we are interpreting to be the marine extension of the Orchard Point fault, (yellow and red lines in Fig 4). This feature correlates with a clear surface fault scarp, visible in high-resolution bathymetry (Figs., 2 and 4) and is also the location of discrete changes in subsurface bedding dips (Fig 5). In order to continue exploring this feature, and using it as a template for identifying additional shallow marine faults, we are comparing the seismically-interpreted fault model to marine magnetic anomalies and geomorphic patterns apparent in high-resolution bathymetry. Specifically, we are in the process of exploring how surface-extending backthrusts like this one might be modeled and interpreted in high-resolution marine magnetics data as second-order magnetic anomalies superimposed on top of an anomaly associated with deep offset magnetic bedrock, like that modeled using aeromagnetic data in Puget Sound (Blakely et al., 2002). By continuing to correlate structures seen in new seismic data with marine magnetics and seafloor morphology from high-resolution bathymetry, we are in the process of developing a precise model for the location and amount of deformation across surface-extending faults throughout the marine extent of Puget Sound. This addition of complementary geophysical models and the final synthesis should be completed by the summer of 2019.

Data Archival

New high-resolution seismic data are currently in the process of being made available via the USGS-operated ***National Archive of Marine Seismic Surveys*** (https://walrus.wr.usgs.gov/NAMSS/). The USGS is currently in possession of the data, and is in the process of getting it approved for public release. This will include all navigation and seismic field records as well as brute-stacks of seismic record sections in SEGY format, available for download. Additionally, advanced processed seismic data or marine magnetic data used in this work will be available immediately upon request from eroland@uw.edu.

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