Seismic reflection imaging across the eastern portions of the Tacoma fault zone

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Abstract

This report summarizes the results from seismic reflection profiling across the eastern projection of the Tacoma fault zone (TFZ) during the summer 2007 field season. I collected 2 seismic transects totaling more approximately 20 km to locate and characterize faults and related structures associated with the TFZ. All new profiles are located east of Puget Sound between Puyallup and Kent, Washington. In addition to new seismic data, I examined gravity, magnetic, industry seismic reflection and tomography data to characterize the upper few km of the Muckleshoot Basin, a separate structural feature located along strike of the TFZ east of Puget Sound. I identify late Quaternary deformation east of Puget Sound that suggests both north-directed shortening and a component of (possibly older) east-west shortening are present. Although the Tacoma fault and Rosedale monocline that define the backthrust of the Seattle fault zone in Puget Sound are not clearly identified to the east, active faulting may extend across the Puget Lowland and possibly connect to faults that cross the Cascades.

Introduction

Seismic reflection imaging for neotectonic studies across the Tacoma fault has thus far been conducted on the waterways that cross the region (e.g., Pratt et al., 1997; Johnson et al., 2004) and land-based seismic profiles west of Puget Sound (Liberty, 2006). These studies have characterized the Tacoma fault as an active north-dipping backthrust of the Seattle fault system. The active Seattle fault is located along the southern boundary of the Seattle Basin and extends for more than 70 km west from Hood Canal and east to the Snoqualmie River Valley (Figure 1; Johnson et al, 1999; Blakely et al., 2002; Liberty and Pratt; 2008). The Tacoma fault controls the boundary between the Tacoma Basin to the south and the Seattle uplift to the north. However, gravity and seismic tomography data do not show strong evidence to suggest the Tacoma Basin extends more than a few km east of Puget Sound (e.g. Pratt et al., 1997; Brocher et al., 2001; vanWagoner et al., 2002; Johnson et al;, 2004;). This inferred laterally changing tectonic framework of the Tacoma fault suggests the Seattle fault system may not be best represented by a simple thrust fault (Seattle fault) and backthrust (Tacoma fault) that separates an uplift (Seattle uplift) from two basins (Seattle and Tacoma). I acquired a seismic transect along the projected location of the Tacoma fault east of Puget Sound to constrain the tectonic model for the area and identify faulting in the upper one km related to the Seattle fault zone (Figure 2). In addition, I have analyzed industry seismic and borehole data from the Muckleshoot Basin area along the eastern portions of the Puget Lowland to identify and characterize the presumed Seattle fault backthrust south of Bellevue and Sammamish, Washington. Here, I will describe the methods used to collect and analyze the new seismic data. I then integrate existing geophysical and geological data with these new data to suggest deformation may be present east of Puget Sound, but in a different subsurface expression from the observations to the west within Puget Sound. These observations may force a new tectonic model for the region.

Geologic and Tectonic Setting

The broad valley west of the Cascade Range and east of the Olympic Mountains in the vicinity of Seattle and Tacoma, Washington is termed the Puget Lowland. This forearc

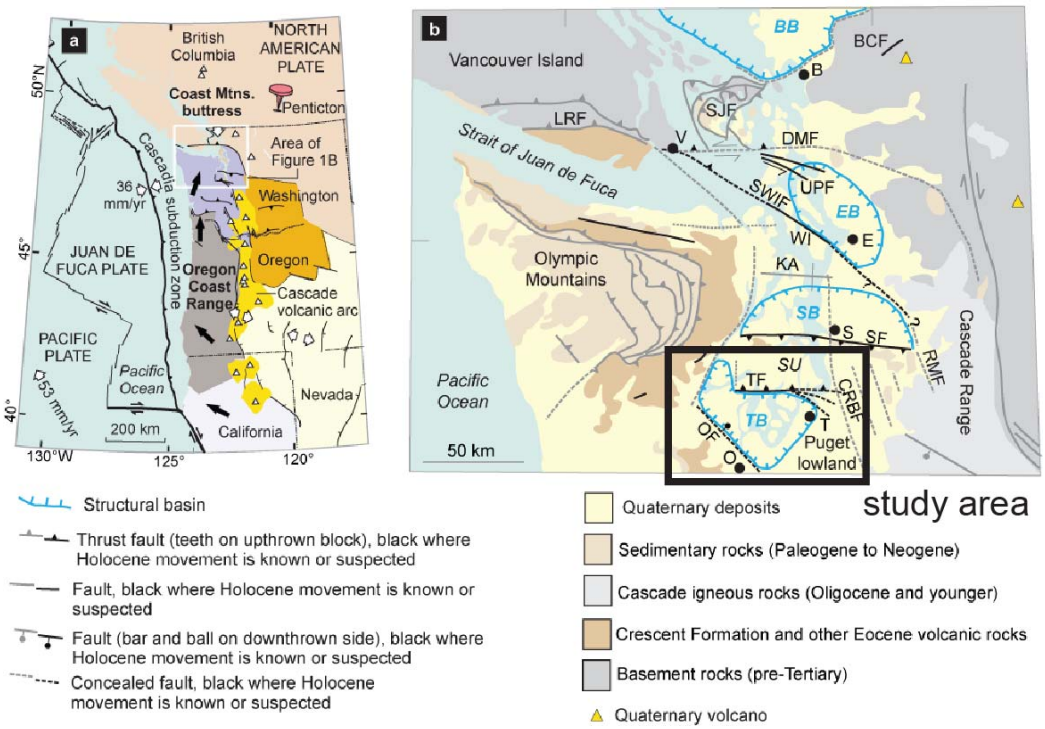

Figure 1. a) Map of the Cascadia region or northwestern U.S. showing the study area at the north end of the northward-moving Coast Range block. b) Map of the Puget Sound region showing major faults and exposures of basement rocks. Study area is shown in the box. BB=Bellingham Basin; B=Bellingham; V=Victoria; DMF=Devil's Mountain Fault; SWIF=Southern Whidbey Island Fault; EB=Everett Basin; KA=Kingston Arch; SB=Seattle Basin; S=Seattle; SF=Seattle Fault; SU=Seattle Uplift; TF=Tacoma Fault; TB=Tacoma Basin; T=Tacoma; CRBF=Coast Range Boundary Fault; OF=Olympia Fault; O=Olympia.

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 Seattle fault zone has shaped the Seattle basin, Seattle uplift, and Tacoma Basin and possibly the Muckleshoot and Dewatto basins (e.g., Pratt et al. 1997; Johnson et al. 1999; van Wagoner et al., 2002; Brocher et al. 2004; Johnson et al., 2004). The Seattle fault is a 5-7 km wide, >70 km long south-dipping blind fault that separates the Seattle Basin to the north from the Seattle uplift to the south (Figure 1). The Tacoma fault separates the Seattle uplift to the north from the Tacoma Basin to the south, as interpreted from the broad Rosedale monocline and narrow kink band controlled by north-dipping faults. Potential field anomalies, LIDAR identified paleoseismic scarps, and marine seismic profiling suggests the Tacoma fault zone may broaden to the east, yet little subsurface information is available east of Puget Sound.

The Puget Lowland contains a cover of young glacial deposits and vegetation that makes it difficult to map fault from the surface (Schuster, 2005). High-resolution aeromagnetic data show lineaments that correlate with the mapped locations of Tertiary-age volcanic rocks and volcanic sediments (Blakely et al. 2002; Johnson et al., 2004). The well documented M>7 earthquake ca. A.D. 900 (e.g., Atwater et al. 1992; Bucknam et al. 1992; Jacoby et al. 1992) and LIDAR imagery and trenching of fault scarps (Sherrod,

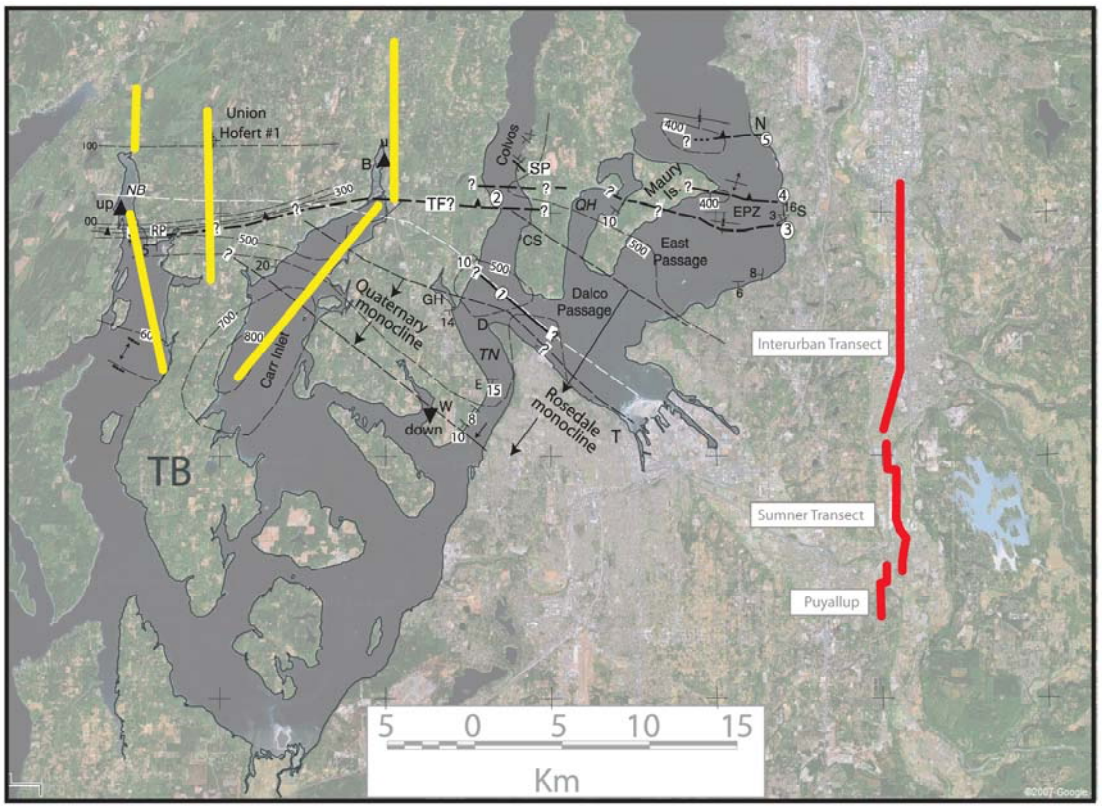

Figure 2. Aerial photo of the study area with 2007 seismic lines (red), past seismic lines (yellow) select structures (black), and locations of uplifted shorelines (triangles). Other seismic lines and geologic and tectonic interpretations are from Johnson et al. (2004) and Liberty (2006).

2003; Haugerud et al. 2003) confirm that multiple late Quaternary earthquakes have occurred on the Seattle and Tacoma faults. Yet the geometry, connectivity, and location of these faults are unknown. Numerous tectonic models have been proposed (Pratt et al., 1997; ten Brink et al. 2002; Brocher et al., 2004). The models range from faulting along a single blind fault zone (Pratt et al. 1997) a broadly distributed passive roof duplex model that deforms the crust between the Seattle and Tacoma fault zones (Brocher et al., 2004). The complexity, length, and potential connectivity of the upper crust faults suggest that additional structural and paleoseismic studies are required to properly assess the earthquake hazards posed by faults within the Seattle fault zone.

The new seismic profiles collected during the summer of 2007 were all located east of Puget Sound, north and east of the city of Tacoma, and along the projected location of the Tacoma fault, Rosedale monocline identified west of Puget Sound, and faults and folds mapped in Puget Sound near Vashon Island (Figure 2; Johnson et al., 2004). Surface exposures in the region consist almost entirely of Pleistocene glacial and interglacial deposits and generally control the surface topography. Regional borehole information suggests Tertiary strata lie within the upper one km, a contrast to the late Quaternary fill that appears within the Tacoma Basin (Johnson et al., 2004).

Gravity/Magnetic/Tomographic Studies

Potential field and tomographic maps show a clear expression of many tectonic features in the region (Figure 3). The ~4 km deep Tacoma Basin appears west of the study area and beneath Puget Sound as a velocity and gravity low with a long-wavelength magnetic signature (e.g., Pratt et al., 1997; Brocher et al, 2001; Johnson et al., 2004). The Tacoma Basin is fault controlled on its northern, western, and southern boundary, and possibly the eastern margin. However, unlike the Seattle Basin that extends for more than 70 km to the foothills of the Cascade Mountains, the Tacoma Basin does not extend a significant distance east of Puget Sound.

The Muckleshoot Basin lies east of the Tacoma basin and is characterized as a gravity low and a strong short wavelength magnetic component (Figure 3). This basin extends east to the foothills of the Cascade Mountains in line with the easternmost extension of the Seattle Basin. Boreholes logs, industry seismic reflection and tomographic data suggest the Muckleshoot Basin is comprised of mostly Tertiary and older sediments (e.g., Rau and Johnson, 1999; vanWagoner et al., 2002). The newly acquired seismic transect presented here is located along the western margin of the Muckleshoot Basin as defined by tomographic and gravity data.

Seismic Reflection Studies

Past seismic reflection studies across the Tacoma fault were acquired in the many waterways of the region (Pratt et al., 1997; Johnson et al. 2004) and land-based seismic profiles on the Kitsap Peninsula (Liberty, 2006). These seismic profiles, as well as the regional compilation of sonic and density logs (Brocher et al. 1998; Rau and Johnson, 1999), geologic mapping information, and aeromagnetic data (Blakely et al., 2002; Johnson et al., 2004) provide the basis for geologic and tectonic interpretations of the newly acquired seismic data. P-wave seismic velocities for latest Pleistocene and Holocene strata average 1,600 m/s when saturated and 1,200 m/s when unsaturated. Tertiary strata within the Seattle uplift and below the Quaternary fill of the Tacoma and Muckleshoot Basins measure more than 2,800 m/s.

I acquired approximately 25 km of hammer seismic reflection data along a series of north-south profiles (Figure 2). I acquired 120 channel seismic reflection data in an off-end spread configuration to acquire offsets up to 600 m. Source and receiver spacing was 5 m with nominal 60-fold data. I used a Boise State trailer-mounted seismic source along city streets and a bike path. This 200 kg hammer is accelerated with a rubber band with has imaging capabilities (depth and frequency content) equivalent to the IVI Minivib II (e.g., Liberty and Pratt, 2008). I processed the seismic reflection data using ProMAX, a Landmark Graphics software package. Processing included bandpass and notch filters, velocity analyses/dip moveout iterations, common mid-point sort, ground roll and refraction mutes, automatic gain control, and stack. Signal penetration was restricted to the upper one km. Here, I present unmigrated images in travel time with interpretations.

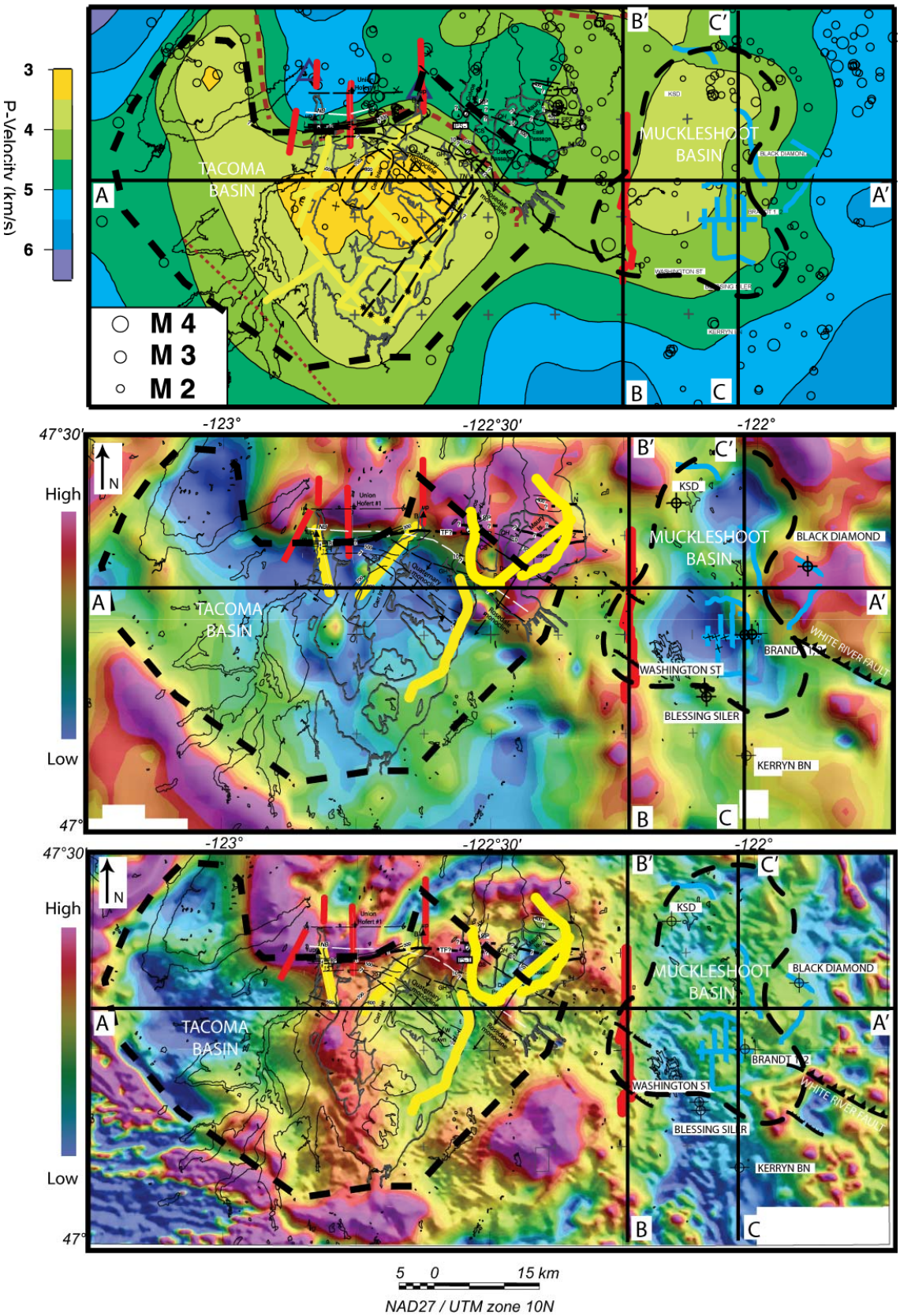
P-Velocity (km/s)
3
4
5
6
M 4
M 3
M 2
TACOMA BASIN
MUCKLESHOOT BASIN
A
A′
B
B′
C
C′
-123°
-122°30′
-122°
47°30′
47°
High
Low
N
Union Hofert #1
KSD
BLACK DIAMOND
WASHINGTON ST
BLESSING SILER
KERRYN BN
BRANDT
WHITE RIVER FAULT
5 0 15 km
NAD27 / UTM zone 10N

Figure 3. Seismic tomography image from 2.5 km depth (revised from vanWagoner et al., 2002), isostatic residual gravity map and magnetic anomaly map (R. Blakely, personal comm.) for the Tacoma, Washington area with the location of industry seismic lines (blue), Boise State high-resolution land-based seismic reflection profiles (red), and USGS marine profiles from Puget Sound (yellow). The Tacoma and Muckleshoot Basins are approximately constrained by a tomography, gravity, and magnetic lows. A high-density, high velocity saddle separates the two basins with a short wavelength magnetic signature and higher velocities in the vicinity of the Muckleshoot Basin. A gravity high (reds) defines the segmentation of two subbasins, possibly related to the White River and Tacoma fault systems. Cross sections (black lines) are discussed in the text.

Puyallup-Sumner Transect

The Puyallup-Sumner transect consists of 3 segments that include the Puyallup, Farm Road, and Sumner profiles (Figure 4). This transect is located mostly along a topographic low near Sumner, Washington but rises in elevation along the southern portions of the Puyallup profile. Data quality was highly variable due to both geologic conditions and cultural interference. Lahar deposits shed from Mount Rainier occupy much of the low lying areas (Hoblitt et al., 1998), and heavy street traffic and buried utilities were present beneath the roads. At the change in elevation along the Puyallup profile, Finnegan et al. (2008) identify a northeast-striking InSAR lineament that is likely a barrier to lateral groundwater flow and a possible fault. The Sumner profile crosses a southeast-striking magnetic linement that may represent the trace a fault or may be related to the edge of lahar flows shed from Mount Rainier (Figure 4; R. Blakely, personal comm.). The new seismic data show reflections upwards of 1.0 s two-way travel time (twtt) dipping toward the southern portions of the Sumner profile.

I interpret the Puyallup-Sumner transect as a faulted sedimentary basin associated with the southwestern edge of the Muckleshoot Basin (Figure 4). Gravity and seismic tomography data are consistent with Puget Group equivalent seismic velocities in the upper few km below the Puyallup-Sumner transect. I interpret a prominent reflector at ~0.5 s twtt as the base of Quaternary sediments at approximately 500 m depth. Changing dip and reflector offsets of the Puyallup-Sumner transect suggest late Quaternary motion on the faults including near the identified magnetic and InSAR lineaments. Offset reflectors within the upper 10’s of meters may imply these faults are active; however, reflections in the upper 10 m and associated lithologic ages are not available. Although the southern portion of this transect is along strike with the Rosedale monocline within the Tacoma basin (Johnson et al., 2004), this south-dipping structure affiliated with the Tacoma fault and Tacoma basin does not appear.

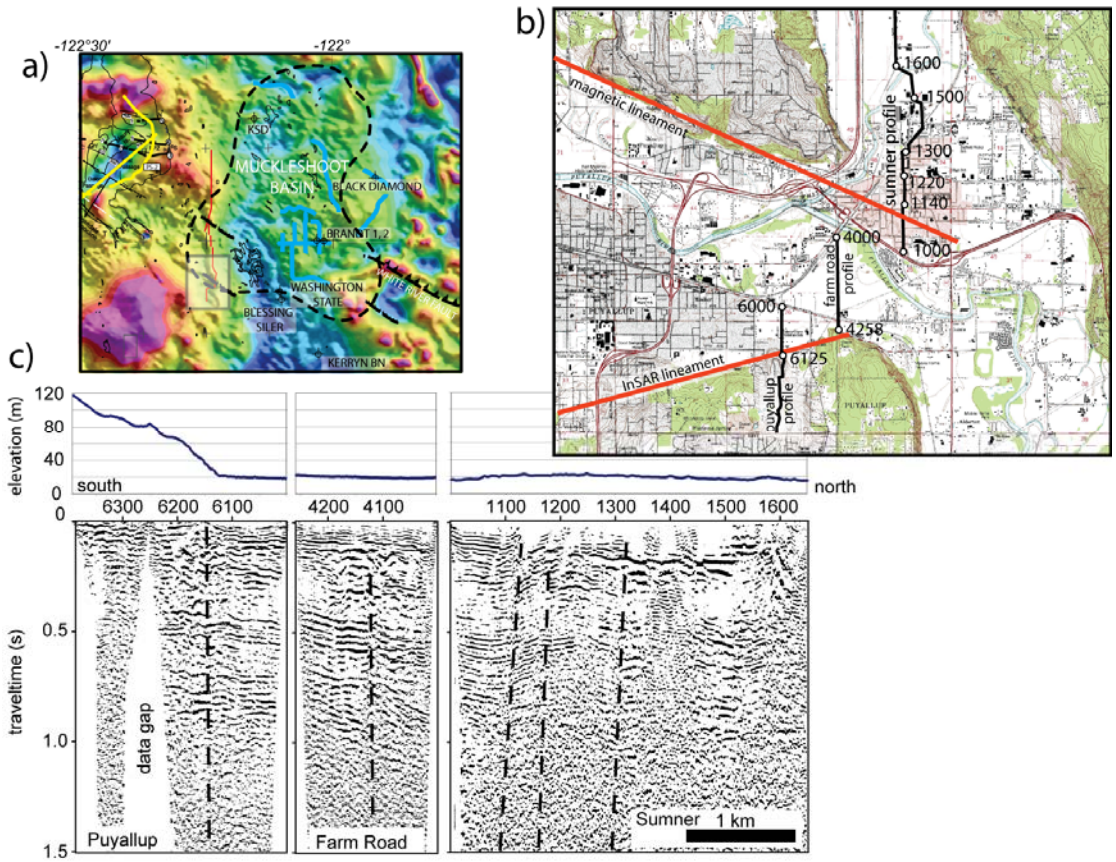

Figure 4. a) Total magnetic field in the vicinity of the new seismic data. Box represents study area in (b) and (c). b) Topographic map for the Sumner-Puyallup transect that shows location of InSAR lineament (Finnegan et al., 2008) and magnetic lineament (a). c) Seismic transect from the 3 profiles shown on (b). Note the change in reflector dip along the south end of the Sumner profile and faults near the InSAR and magnetic lineaments. Vertical exaggeration is ~2:1.

Interurban Transect

The Interurban Seismic transect was acquired along the shoulder of the Interurban Bike Trail from Pacific to Kent, Washington (Figure 5). The 13.5 km long profile is located along a flat topographic surface, but contains highly variable data quality that resulted, in part, from cultural interference and poor source and receiver coupling. High tension power lines, road crossings, and a soft bike path shoulder contributed to the variable quality. In the central and southern portions of the profile, reflections from greater than 1 s time were observed, whereas the northern portions of the profile, where large power lines were present, signal penetration was limited to the upper 0.5 s time.

South-dipping strata to greater than 1.0 s time suggest the southern and central portions of the profile are part of a sedimentary basin (Figure 5). Gravity and tomography data suggest the Interurban transect is located along western limits of the Muckleshoot Basin (Figure 3). Steeper dips with increasing depth in the central portion of the profile suggest tectonic activity with basin evolution. The base of Quaternary deposits is estimated from borehole logs in the area (Figure 6) and reflector character. The increase in Quaternary

strata depth to the south suggests the Muckleshoot Basin has experienced late Quaternary deformation. Steeper dipping Tertiary strata suggests deformation predated the late Quaternary strata. The northern portion of the profile shows shorter wavelength folding similar to that observed east of Maury Island in Puget Sound (Figure 2; Pratt et al., 1999; Johnson et al., 2004).

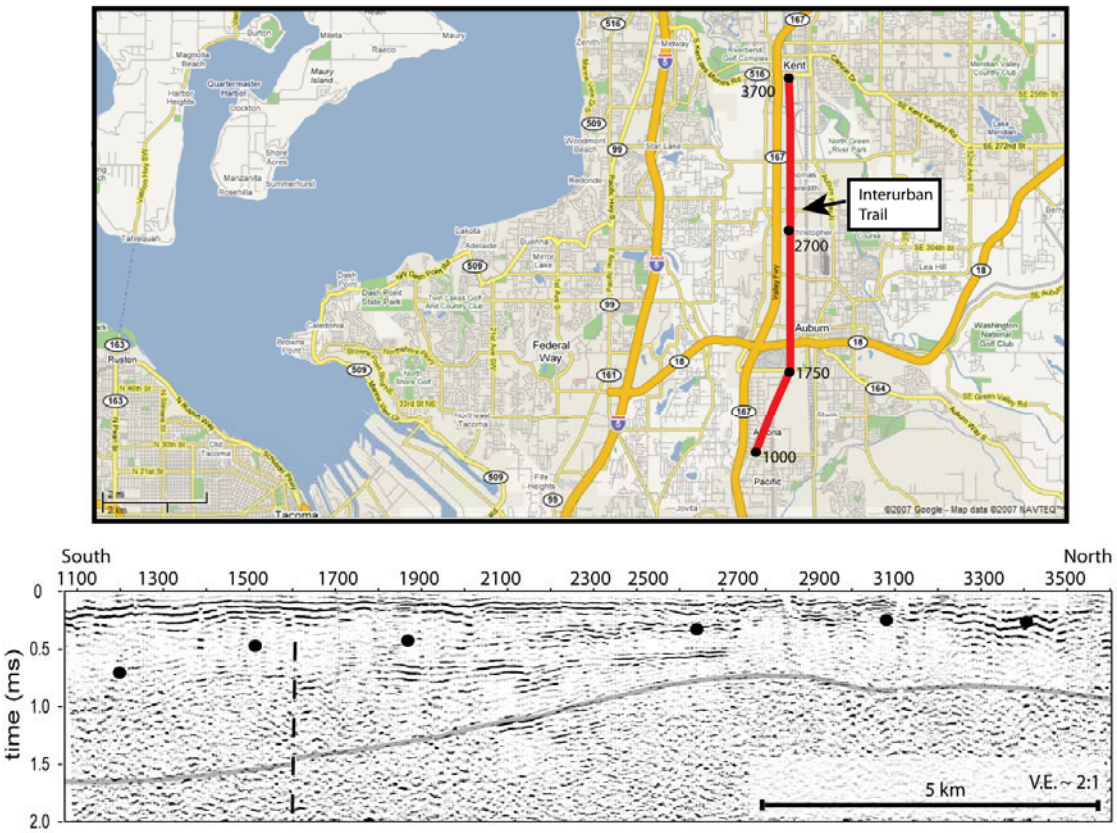

Figure 5. a) Interurban seismic profile location map and b) seismic reflection section. Note the south-dipping strata along the southern portions of the profile likely associated with the western extent of the Muckleshoot Basin.

Muckleshoot Basin

The Muckleshoot Basin was first described by vanWagoner et al (2002) based on seismic tomography and gravity data (Figure 3). The 7-9 km deep basin contains higher seismic velocities in the upper few km and slower seismic velocities below compared to the Tacoma and Seattle basins. Gravity data suggest a basement high lines up with the projected White River fault (Figure 3). The tomography, gravity, and magnetic data all suggest the Seattle, Tacoma and Muckleshoot basins are distinct, but are likely tectonically linked.

Industry seismic profiles from the Muckleshoot basin (Figure 3), coupled with borehole information, suggest a clear unconformity at the base of Quaternary strata in the upper one km (Figure 6). A north-south profile shows the Quaternary base at less than 0.4 s time or less than 400 m depth. Below, an anticline appears along strike with the White

River fault where Quaternary and older strata dip away from the structural high. A west-east profile shows Quaternary strata to ~600 m depth along the western portions of the profile shallowing to less than 200 m depth along the eastern limits of the Muckleshoot basin. Below, Tertiary strata show folding that suggests east-west shortening. The dipping unconformity at the base of Quaternary strata may represent post erosional tilt with the uplift of the Cascades. Reflectors below the unconformity on the west-east profile show clear folding of the underlying Tertiary strata suggesting the Muckleshoot basin has experienced tectonic shortening through the Quaternary. The east-west component of shortening is not identified in either the Tacoma or Seattle basins, suggesting either the Muckleshoot basin has exposed an older component of deformation not related to the present-day north-directed shortening or that the Muckleshoot basin is tectonically unique.

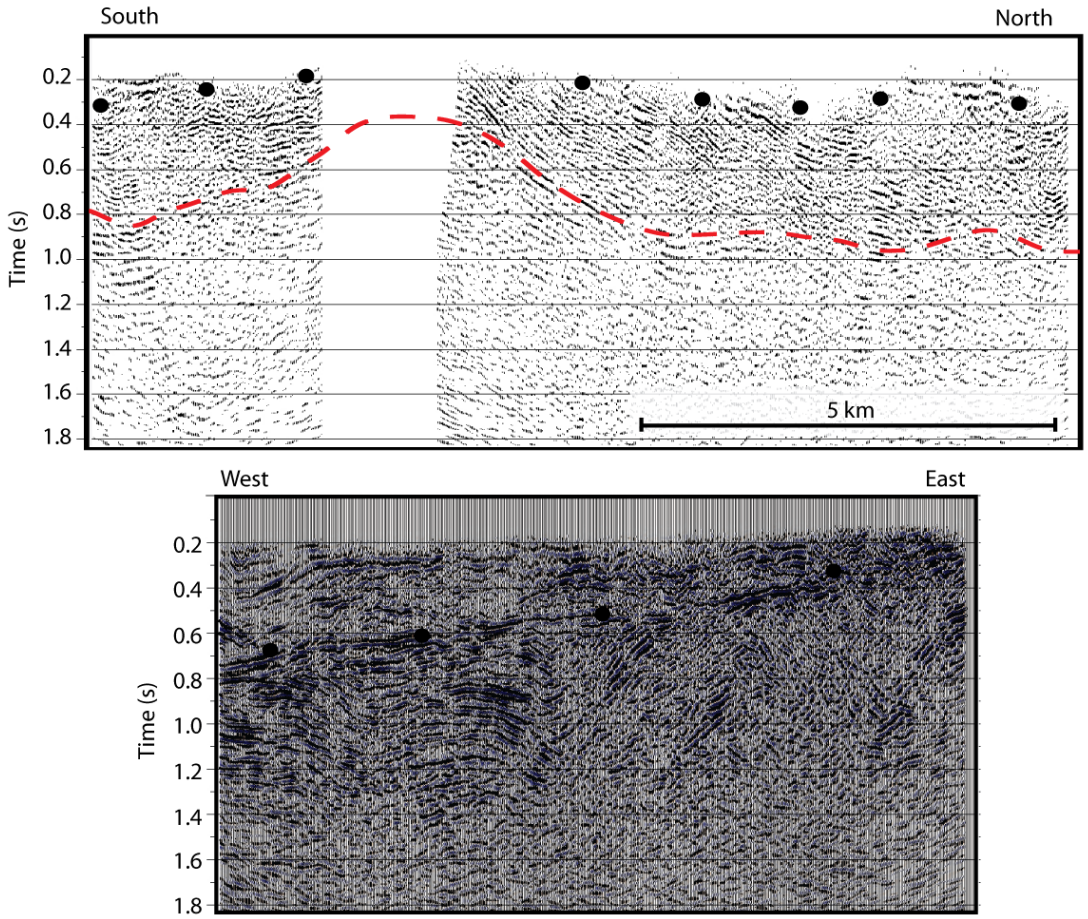

Figure 6. Seismic reflection profiles from the Muckleshoot Basin. A) South-north seismic profile showing a structural high in the central Muckleshoot Basin area. B) West-east seismic profile showing tilted base of Quaternary strata (dots) and deformed Tertiary strata below.

Discussion and Conclusions

New land-based high-resolution seismic reflection data were collected in the Puget Lowland using a low cost, low impact hammer seismic source. This includes geologic targets within the Muckleshoot Basin and Seattle uplift upon a variety of glacial deposits. Seismic profiles were collected on city streets and a bike path. Additionally, industry seismic, gravity, magnetic and seismic tomography data were integrated to describe the Muckleshoot basin and its relationship with the Seattle fault, Tacoma fault, Tacoma basin and Seattle uplift.

The Muckleshoot basin shows clear evidence for both north-south and east-west shortening. Uplift and faulting within Quaternary strata suggest late Quaternary and possibly recent faulting has shaped the Muckleshoot basin and areas to the west. The location of the Muckleshoot basin relative to the Tacoma and Seattle faults suggest syntectonic basin development and possibly multiphase shortening. East-west shortening has not been documented in the region, in part due to mostly north-south seismic profiling. However, northeast-striking magnetic lineaments may indicate additional west-directed shortening on the Seattle uplift (Figure 3). Additionally, the industry profiles from the Muckleshoot basin suggest the north-south Interurban and Sumner-Puyallup transects may not fully represent the structural complexities of the region and perhaps a high-resolution east-west profile may be needed to best characterize the regional deformation. The segmentation of the Muckleshoot subbasins may be related to the White River fault system that extends across the Cascades and perhaps link to other fault systems to the southeast.

Figure 7 shows three upper crustal cross sections from the study area. The west to east tomographic cross section shows the structural high that separates the Tacoma and Muckleshoot basins (van Wagoner et al., 2002) to emphasize the distinct basin characteristics between the two basins. Whereas the Tacoma basin contains a few km of low velocity Quaternary marine sediments, the Muckleshoot basin contains a thin cover of Quaternary fill. Higher velocity strata fills the Muckleshoot basin, however, the basin dimensions are roughly equivalent. The south-north cross sections on Figure 7 suggest folds and faults are present east of Puget Sound, consistent with regional north-directed shortening. However, faults and folds observed in Puget Sound, including the Rosedale monocline are not apparent in the new seismic data east of Puget Sound. Therefore, the presumed Tacoma fault backthrust of the Seattle fault system must change character east of Puget Sound or the tectonic model for the region must be reconsidered. Perhaps the backthrust is buried much deeper to the east, perhaps east-directed shortening accommodates some of the strain, or perhaps backthrusts are present but fault segments are bisected by north-south faults.

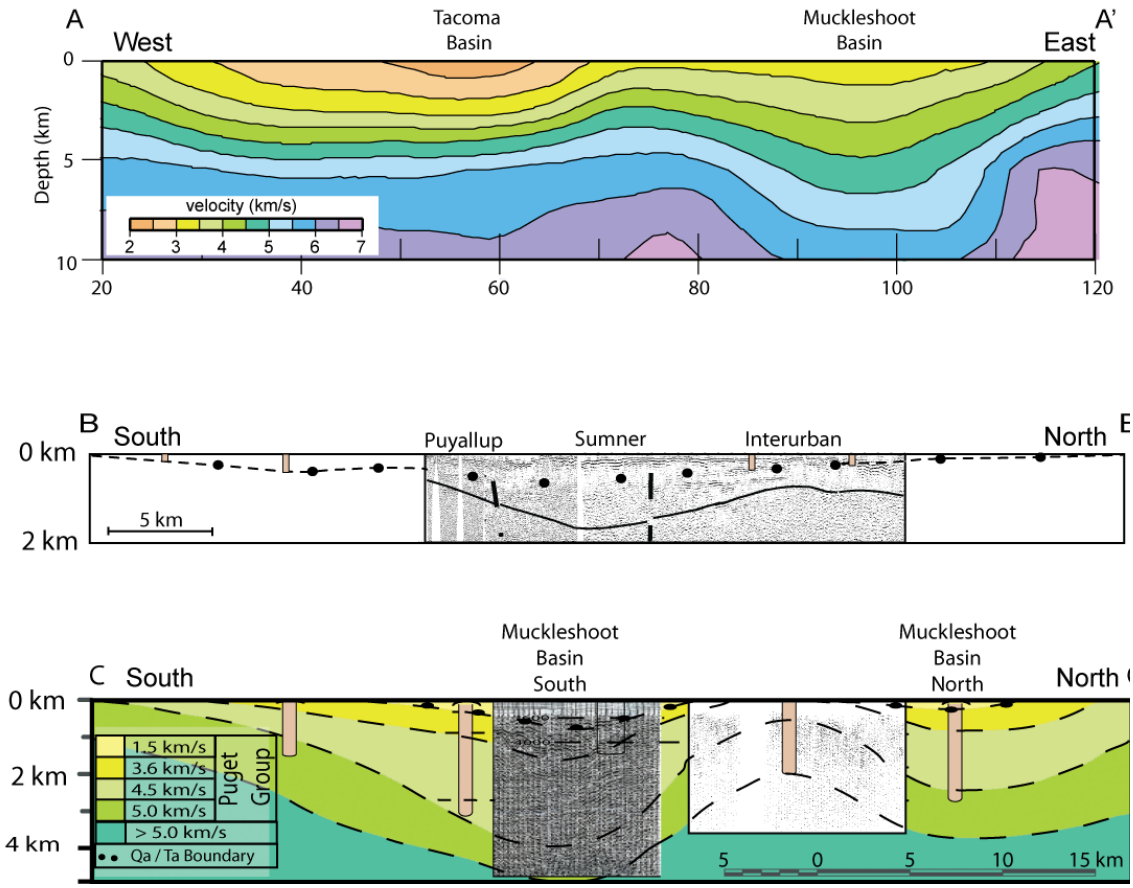

Figure 7. A) West-east tomographic cross section showing the relative depth and velocities of both the Tacoma and Muckleshoot basins. B) North-south transect with newly acquired seismic data, borehole control, and interpreted depth of Quaternary strata. C) North-south tomographic profile of the Muckleshoot basin with industry seismic profiles controlling the interpretation.

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