Seismic Profiling of the Seattle Fault, Lake Sammamish Region, Washington

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Abstract

This report summarizes the results from vibroseis seismic reflection profiling across the Seattle fault zone (SFZ) during the summer 2004 field season. I collected two seismic transects consisting of 13 north-south profile segments. Each transect crosses the southern portions of the Seattle Basin, extends across the main strand of the SFZ and Seattle monocline, and terminates on the Seattle uplift. I sited both transects east of Lake Washington, where a published seismic profile defines the character of the SFZ. One vibroseis transect extends 10 km through Bellevue and Newcastle, Washington, with the profile segments located 5-10 km east of Lake Washington. The second transect is located 5-7 km east of Lake Sammamish and extends more than 4 km in a north-south direction. The survey objectives were to characterize the eastern reaches of the SFZ to better estimate fault length, to characterize the style of deformation in the upper one km where Quaternary-age glacial sediments appear, and to identify fault strands for future paleoseismic studies to further constrain fault history.

My results show that the SFZ extends beneath my eastern profile, which is further east than it has previously been imaged. This clearly demonstrates that the SFZ extends at least 7 km east of Lake Sammamish for a total fault length of more than 50 km. Both transects show a similar reflection character that generally matches the reflection character observed on the Lake Washington profile. The similarity of the fault zone on these profiles suggests that the eastern portion of the SFZ is not segmented, and that the fault may rupture along its entire length during a large event. My observations also support a tectonic model where back thrusts accommodate near-surface faulting along the SFZ, constistent with a passive roof duplex system.

The Seattle monocline defines the southern boundary of the Seattle Basin and is characterized by uplifted Tertiary sediments. Eocene and Oligocene beds within this monocline dip to the north at approximately 40 degrees west of Lake Sammamish and at about 20 degrees east of Lake Sammamish. The Quaternary sediments that lie upon the Seattle monocline contain deformed Pliocene and younger glacial, marine, and non-marine sediments. The continuous, but dipping Tertiary-age strata of the Seattle monocline, with overlying short-wavelength Quaternary folding, suggests south-directed bedding-plane slip may accommodate near-surface shortening within the SFZ. The deformation front extends approximately 2 km north of the main strand of the Seattle fault, as defined by a lineament on LIDAR imagery and associated paleoseismic trenches. This scarp defines a fault segment that last ruptured A.D. 900 during a M7 event. North of the deformation front, I do not observe deformation in the upper one km of the Seattle Basin. The Tertiary strata that I image south of the deformation front show a complex fault history. These strata are tilted, and km-scale folding prevails. Faults cut these broad, regionally continuous folds; however, tectonic timing within the Tertiary package is unclear. The decrease in Seattle monocline dip to the east is consistent with a broadening of the magnetic lineament associated with Miocene-age volcanic sediments. It is unclear whether this decrease in structural dip is associated with a decrease in uplift rates along the eastern reaches of the Seattle fault. Further studies are needed if we are to characterize the SFZ east of our existing profiles.

Introduction

Seismic reflection imaging for neotectonic studies in the Seattle region has thus far been conducted on the extensive waterways that cross the region, where high-quality results have been obtained (e.g., Johnson et al., 1994; Pratt et al., 1997; Johnson et al., 1999; Calvert et al., 2003). However, Sherrod (2002) identifies deformation across a LIDAR lineament along the western shore of Lake Sammamish (Figure 1), and Blakely et al. (2002) identifies a magnetic lineament related to the Seattle fault that extends east of Lake Sammamish. In the vicinity of Lake Sammamish, a land-based approach is necessary to provide seismic reflection images that can ground-truth paleoseismic trenching and can identify deformation within glacially-derived modern sediments that were not scoured and replaced, as in the topographically low regional waterways. To assess the hazards associated with faulting in this region and to characterize the relationship between identified faults and deformation style, I acquired two new high-resolution seismic reflection transects to characterize the deformation of the upper one km. Transect 1 is a 10 km long survey consisting of 11 overlapping profiles, located west of Lake Sammamish and east of Lake Washington through the cities of Bellevue and Newcastle (Figure 1). Transect 2 is a 4-km long survey located east of Lake Sammamish that extends through the city of Sammamish. I acquired the profiles with a 12,000 lb vibroseis truck to image Neogene and younger sediments within the Seattle Basin, south across the Seattle fault, and onto the Tertiary sediments and volcanic rocks of the Seattle uplift. Here, I will describe my results and describe each profile. I will then summarize the results for each transect and describe the implications of my study.

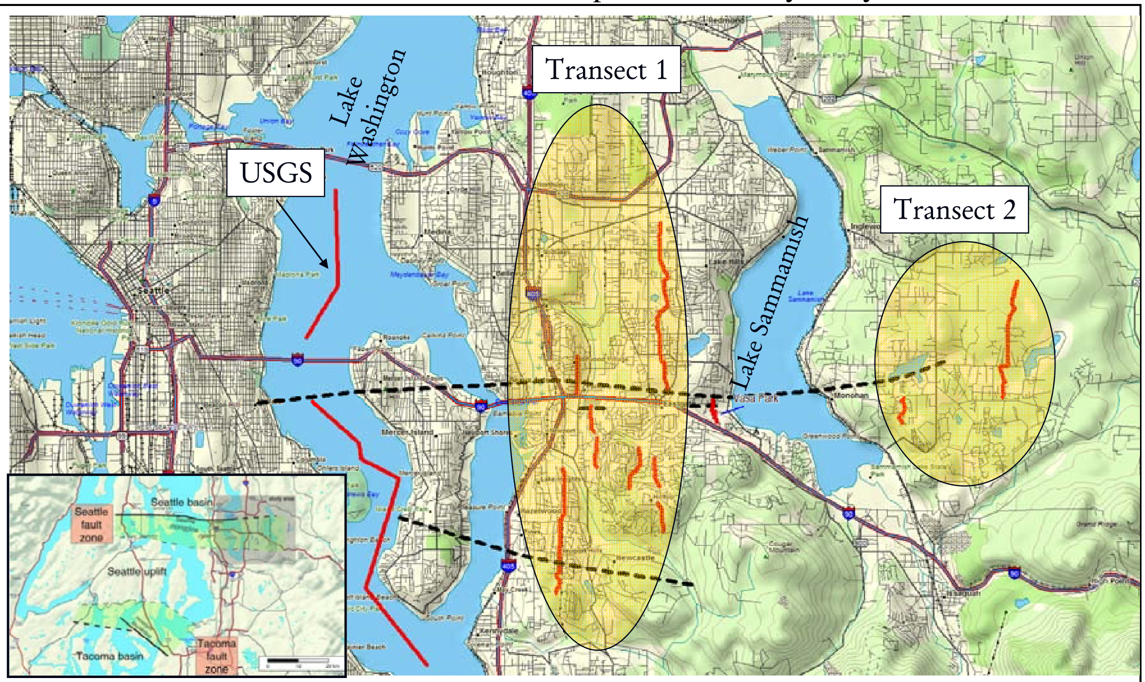

Figure 1. Location map for USGS Lake Washington seismic profile and new vibroseis seismic reflection profiles defined as two transects. Inset map shows the relationship of the Seattle fault to the Tacoma fault system described in Figure 2.

Geologic and Tectonic Setting

The broad valley west of the Cascade Range and east of the Olympic Mountains in the vicinity of Seattle, Washington, is termed the Puget Lowland. This forearc basin lies above terranes accreted to North America along the Cascadia subduction zone. Oblique convergence along the continental margin (Wells et al., 1998) is accommodated by north-south shortening in the Puget Lowland (Miller et al., 2001). The Seattle fault is a north-directed thrust fault separating the Seattle basin on the north, from the Seattle uplift and Tacoma Basin to its south (e.g., Pratt et al., 1997). The surface expression of the Seattle fault is a 5-7 km wide fault zone, perhaps part of a passive roof duplex (Figure 2; Brocher et al., 2004) termed the Seattle fault zone (SFZ). The SFZ has been characterized by steeply dipping strata cut by numerous, steeply-dipping upper crustal faults (Johnson et al., 1994; Johnson et al., 1999), yet the region contains a cover of young glacial deposits and vegetation that makes it difficult to map fault segments. Recently published high-resolution aeromagnetic data (Blakely et al., 2002) show lineaments that correlate with the mapped locations of Tertiary-age volcanic rocks and volcanic sediments. One 50-km long magnetic lineament defines a steeply-dipping Miocene-age volcanic sedimentary unit that is less than a few hundred meters thick. The well documented M>7 earthquake ca. A.D. 900 (e.g., Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992) and recent LIDAR imagery and trenching of fault scarps (Sherrod, 2002; Nelson et al., 2003) confirm that multiple earthquakes have occurred on the Seattle fault in late Quaternary time along the northern edge of this regional magnetic lineament. 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 the Seattle fault zone.

The eastern extension of the Seattle fault zone is poorly constrained. Aeromagnetic data suggest lineaments associated with the fault zone extend to at least 10 km east of Lake Sammamish. However, documented deformation in this region is not definitive. Additionally, since no waterways cross the SFZ here, marine seismic profiling that has characterized the regions further west is not possible. The eastern extent of the SFZ is important because of the implications of fault length that directly correspond to potential earthquakes magnitudes. Characterizing the eastern

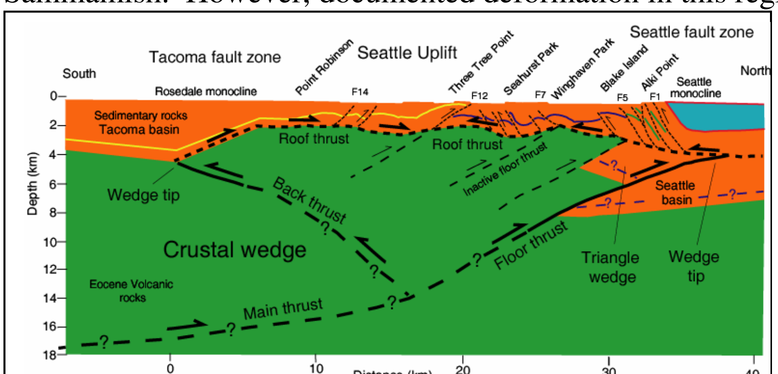

Figure 2. Brocher et al. (2004) model for the Seattle and Tacoma fault systems. The main thrust of the fault system is a blind north-directed thrust. Surface expression of the SFZ appears as south-directed back thrusts.

portions of the SFZ also has implications as to the evolution of the Seattle Basin and the interaction of the South Whidbey Island fault to the north. Speculation as to the regional nature of the north-directed Seattle fault thrust and its relationship to the north-side up scarps that are exposed in paleoseismic trenches suggest more studies that focus on the upper 1 km in this region will provide valuable information to better define the SFZ.

Seismic Reflection Studies

Past seismic reflection studies across the SFZ were acquired in the many waterways of the region. Data from these studies include Lake Washington seismic profiles (Johnson et al., 1999) and seismic profiles from Puget Sound (e.g, Johnson et al., 1994; Calvert et al., 2003). These seismic profiles, as well as the Brocher and Ruebel (1998) report compiling regional sonic and density logs, geologic mapping information (Yount and Gower, 1991), and aeromagnetic data (Blakely et al., 2002) provide the basis for geologic and tectonic interpretations of the newly acquired vibroseis data. Johnson et al. (1999) measured seismic velocities for different materials in the area. These measurements, in addition to my new seismic measurements, suggest that P-wave seismic velocities for latest Pleistocene and Holocene strata average 1600 m/s when saturated and 1200 m/s when unsaturated. Pleistocene strata appear within the Seattle Basin and average 2000 m/s. Miocene and older sediments within the Seattle uplift and below the Quaternary fill of the Seattle Basin measure upwards of 2800 m/s. Glacial till that appears in outcrop throughout the region and is likely contained within the upper few hundred meters, contains measured seismic velocities up to 2500 m/s. These seismic velocity values are important to note when converting seismic travel time measurements to depth, especially in regions where large lateral velocity variations appear (e.g., where glacial till juxtaposes fine-grained Pleistocene and Holocene strata).

USGS Lake Washington Profiles

Seismic reflection results from Lake Washington (Johnson et al., 1999) represent the easternmost images from the Seattle Basin and Seattle uplift published to date. Johnson et al. (1999) tie their results to a nearby deep geologic borehole (e.g., Mobil Kingston #1; Brocher and Ruebel, 1998) to correlate reflectors in the Seattle Basin with Quaternary and older sediments (Figure 3). Johnson et al. (1999) identify a prominent reflector as the top of an unconformity separating Tertiary sediments from the overlying Quaternary section. They place the top of the Tertiary section below Lake Washington at approximately 600 ms twtt within the Seattle Basin, or approximately 520 m depth (Figure 3). Reflectors associated with this contact shallow and define the southern margin of the Seattle Basin in an abrupt north-dipping fold termed the Seattle monocline (Brocher et al., 2004). The top of the ~40 degree dipping reflection package within the Seattle monocline is truncated at a few hundred meters depth and represents an angular unconformity that resulted from post-Tertiary erosion and subsequent emplacement of non-marine fill (Johnson et al., 1999). The Lake Washington profile does contain a one km gap located near the Interstate 90 Mercer Island bridge (Figures 1 and 3). Unfortunately, this gap includes the projected location of the main strand of the SFZ, as defined by a LIDAR lineament and associated trenches (e.g., Sherrod, 2002; Nelson et al., 2003). The southern portions of the USGS Lake Washington profile shows a complex package of reflections that represent the stratigraphy and structure within a Tertiary sedimentary and volcanic rock package (Figure 3). These geologic units are exposed both to the east and west of Lake Washington within a structurally complex tectonic setting.

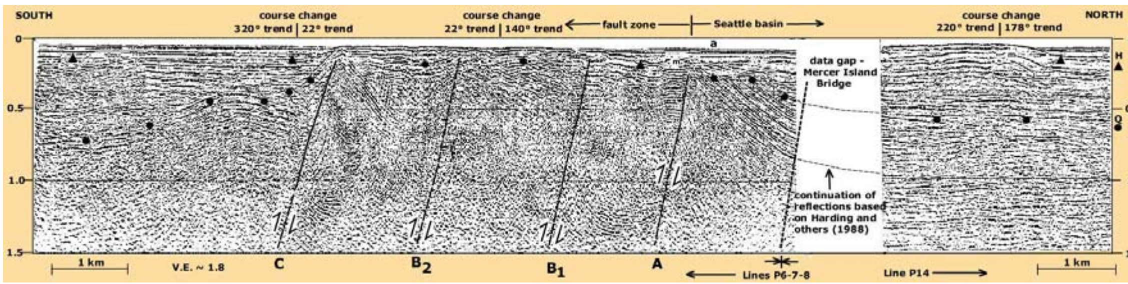

Figure 3. USGS Lake Washington seismic profile. See Figure 1 for profile location. Note the gap in seismic recording near the I-90 Mercer Island Bridge. Figure from Johnson et al. (1999).

Vibroseis Seismic Acquisition

I acquired approximately 20 km of vibroseis seismic reflection data along 13 north-south profiles (Figure 1). Thomas L. Pratt from the US Geological Survey in Seattle secured permits for right-of-way access from the following municipalities: city of Bellevue, city of Newcastle, city of Sammamish, in addition to a number of private entities. I acquired north-south profiles that extend approximately 5 km north into the Seattle Basin and south across Miocene and Oligocene sedimentary rocks to exposed Eocene volcanic basement rocks associated with the Seattle uplift.

I collected the vibroseis data with a12,000 lb IVI minivib II vibroseis truck (Figure 4). I collected data mostly on residential streets using a12 s, 20-160 Hz linear sweep. I recorded an additional 2 s to produce 14 s shot gathers. I acquired the data with a 120-channel 24-bit Geometrics RX system with 5-m station spacing. I acquired most data in an off-end geometry with 5 m source and receiver intervals to produce nominal 60-fold data with offsets up to 600 m. A few survey profiles include a fixed geophone spread and source points acquired through the spread (e.g., BV3, BV6, SM2). I recorded uncorrelated, individual field records to include pre-correlation processing to attenuate cultural noise that is common with urban seismic surveys.

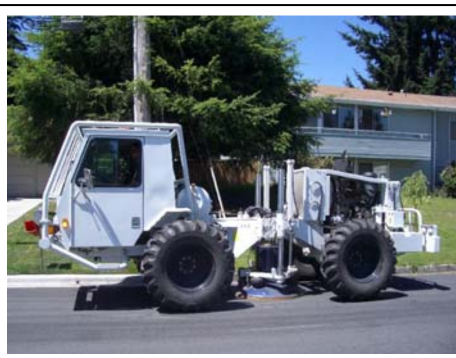

Figure 4. Minivib II truck used during this seismic survey.

I processed the seismic reflection data using ProMAX, a Landmark Graphics software package. Pre-correlation processing included bandpass and notch filters and gains to attenuate electrical noise at 60, 120, and 180 Hz, to minimize the effects of traffic noise that dominated many of the records, and to boost reflection signal. Post-correlation processing included geometry, filters, multiple velocity analyses/dip moveout iterations, common mid-point sort, ground roll and refraction mutes, automatic gain control, and stack. Signal penetration ranged from more than 1.3 s within the Seattle Basin to less than 0.4 s on the Tertiary sediments of the Seattle uplift. I selectively migrated key seismic images. Here, I present unmigrated images in travel time to remove migration and depth conversion artifacts. All profiles are displayed at approximately 1:1 aspect ratio assuming a velocity of 2000 m/s.

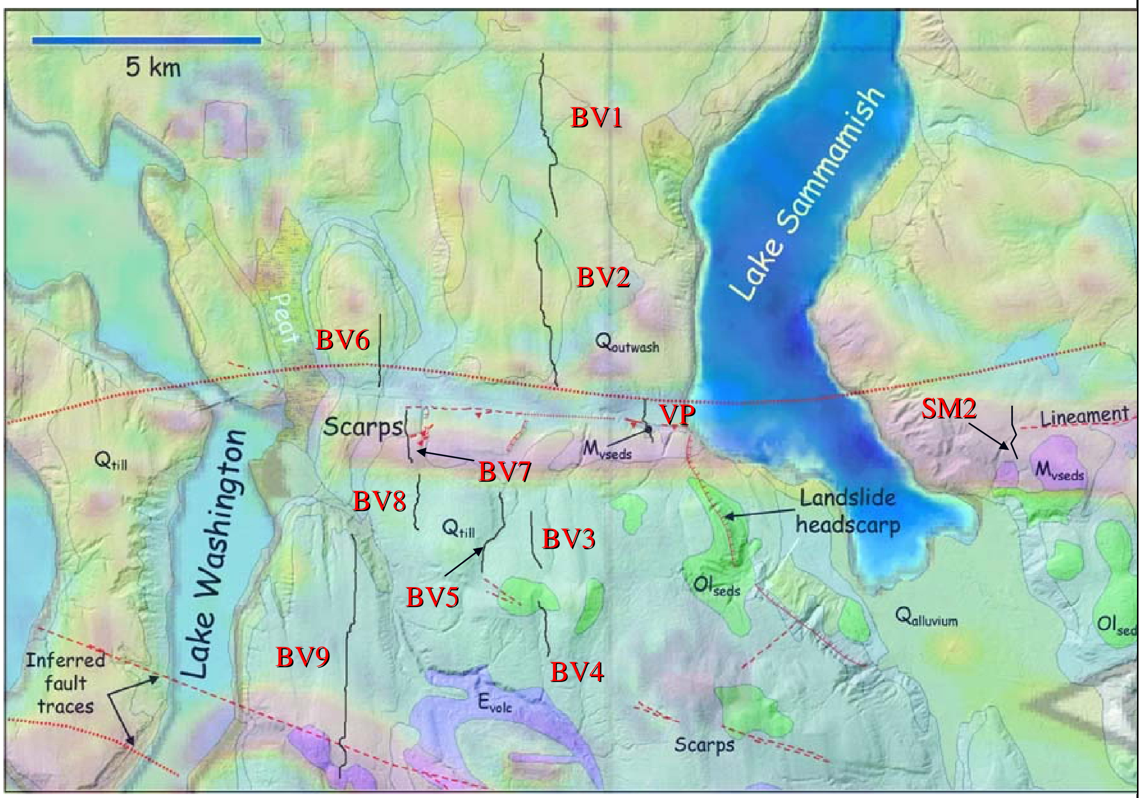

Figure 5. Vibroseis seismic line locations (black lines). The map shows geologic contacts (from Sherrod, 2002) with a superimposed aeromagnetic anomaly map (from Blakely et al., 2002). The red dotted line across the center of the figure represents the inferred location of the main strand of the Seattle fault zone (from Sherrod, 2002) with sediments from the Seattle Basin exposed to the north of this line and sediments and volcanic rocks associated with the Seattle uplift appear to the south of this line. Profile SM1 is located east of this map (see Figure 1).

Profile BV1

BV1 is a 2.5 km north-south profile located approximately 10 km east of the USGS Lake Washington seismic profile (Figures 1 and 5; Johnson et al., 1999). I acquired this profile to image the sediments in the upper one km of the Seattle Basin north of the projected surface location of the Seattle fault blind thrust (Pratt et al., 1997; Brocher et al., 2004). The profile begins south of NE Bellevue-Redmond Road in Bellevue along 151st Place NE. The profile terminates to the south on 152nd Place SE at Lake Hills Blvd. Road crossing restrictions were in place for Main Street, 8th Street, and Lake Hills Blvd., therefore a data gaps appear at these locations. Elevations along the profile range from 80-100 m (Figure 6). A 25 nT long-wavelength decrease in the total magnetic field appears from north to south and glacial outwash and till are mapped along the profile (Figure 6).

BV1 (Figure 6) shows a strong continuous package of reflections from ~100-300 ms and also below 700 ms twtt. I was unable to extract information below ~1.2 s twtt due to the seismic acquisition parameters. The upper reflection package correlates with Quaternary deposits, as observed in nearby boreholes and marine seismic profiles (Brocher and Ruebel, 1998; Johnson et al., 1999). Below approximately 300 ms twtt, I interpret marine and non-marine Pliocene to Pleistocene deposits as a shorter wavelength, relatively transparent reflection package. The top of the Tertiary-age sequence appears at 700-800 ms twtt and, accounting for elevation differences, is equivalent to the depth and reflection character from the Lake Washington seismic profile (Figure 3; Johnson et al., 1999). Although discontinuities may appear across the relatively coherent reflections, no large reflector offsets appear within this section. The undulations on individual horizons are not likely associated with deformation related to the SFZ, but represent lateral velocity variations from large seismic contrasts where glacial till and outwash are mapped (Figure 5). Reflections from undeformed sediments within the central Seattle Basin is consistent with studies from Lake Washington (Johnson et al., 1999) and Puget Sound (Pratt et al., 1997).

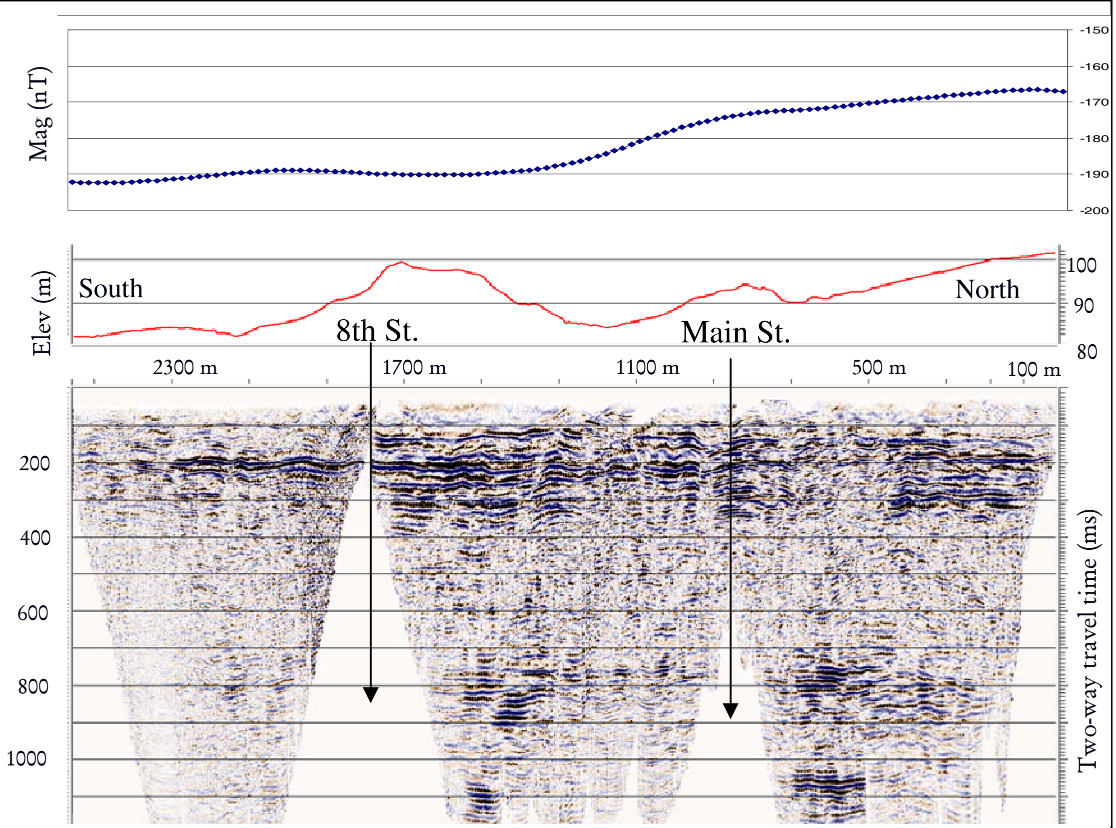

Figure 6. BV1 seismic reflection, elevation, and magnetic (from Blakely personal comm.) profiles located within the Seattle Basin. The data gaps at 900 m and 1800 m represent restrictions in road access. The top of the Tertiary section begins at approximately 700 ms twtt as seen by a large-amplitude reflection package.

Profile BV2

BV2 is a 2.5 km long profile located south and immediately west of BV1 (Figure 1). This profile starts at 150th Ave SE and Lake Hills Blvd and extends to Sunset Village on Eastgate Way, immediately north of I-90. Elevations range from 90-120 m along the profile with the topography decreasing near I-90 (Figure 7). The total magnetic field varies approximately 40 nT, with shorter wavelength anomalies appearing to the south. The surface geology is dominated by glacial till (Yount and Gower, 1991).

The northern portions of seismic line BV2 (Figure 7) show a similar signature to profile BV1, where a large amplitude reflection package appears from 100-300 ms twtt and a second large-amplitude reflection package appears below 700 ms twtt. This Seattle Basin character changes near position 500 m in the upper portions of the profile and near position 1200 m along the deeper reflection package. The southern portions of BV2 show reflections associated with the Tertiary-age section dipping to the north and rising to ~200 ms twtt along the southern margin of the profile. This dipping reflection package is similar to the reflection signature that appears along the Lake Washington profile (Figure 3; Johnson et al., 1999) and is termed the Seattle monocline (Brocher et al., 2004). Above the Tertiary-age section, reflections dip northward and appear more discontinuous and folded. Because no obvious faults cross the Tertiary-age section, the Quaternary-age sediments likely deformed via south-directed bedding plane slip. As the Seattle fault thrust northward to uplift the Seattle monocline, the Quaternary section responded with a 2 km wide zone of deformation. This interpretation is consistent with the Brocher et al. (2004) passive roof duplex model that integrates both north-directed thrusting observed with regional seismic data (e.g, Pratt et al., 1997) and the south-directed Holocene deformation observed in many trenches that cross the Seattle fault (Sherrod, 2002; Nelson et al., 2003).

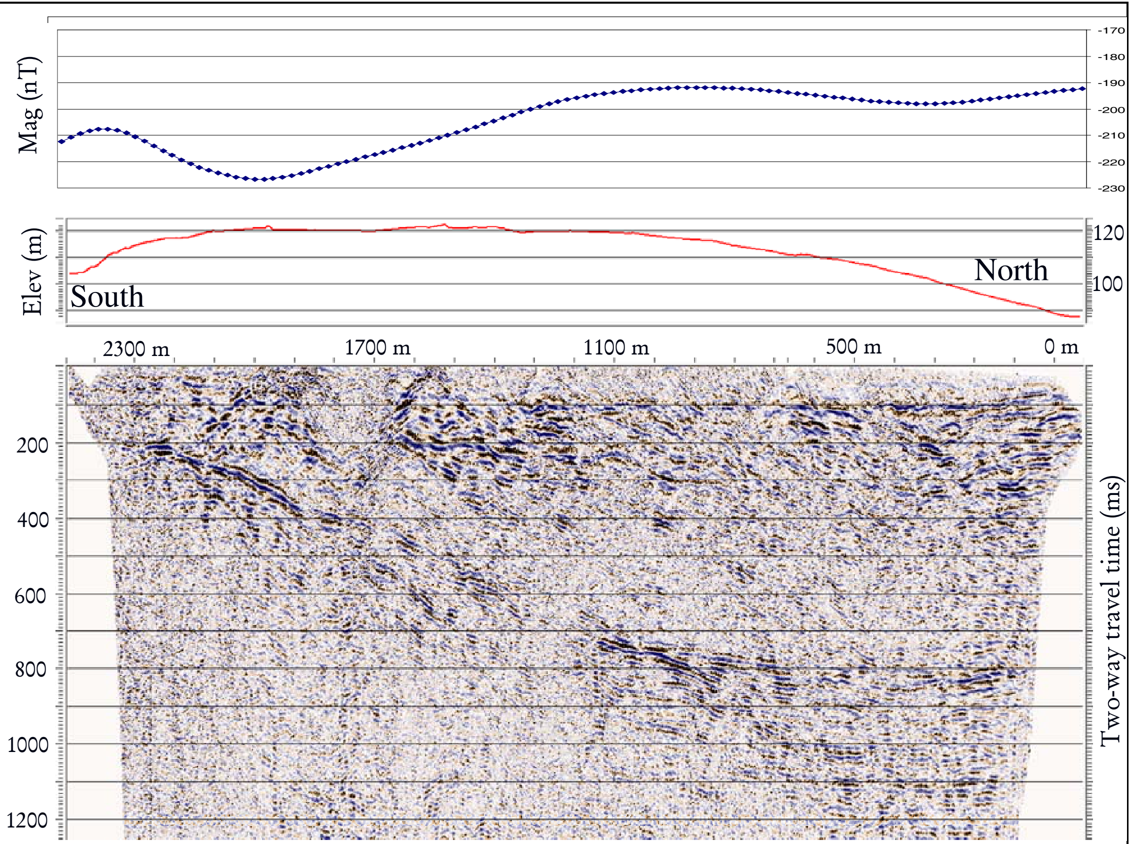

Figure 7. Seismic profile, elevation profile and total magnetic field profile for BV2. The seismic line is located north of I-90 in Bellevue and defines the northern portions of the Seattle monocline. The main strand of the Seattle fault system is mapped immediately south of this profile.

Vasa Park profiles (VP1 and VP2)

I acquired two seismic reflection profiles that cross the Vasa Park paleoseismic trenches described by Sherrod (2002). These seismic profiles were acquired with both a weight-drop and slide hammer seismic source prior to the arrival of the vibroseis truck. Geophone and source spacing for this profile was 3.0 m. Profile VP1 is a 350 m long north-south profile that extends north from the Vasa Park trench (Figure 8). This profile terminates near the southern reach of profile BV2 and extends across a small creek. Elevations rise both to the north and south, with the southern slope-break associated with the main strand of the Seattle fault (Figure 5). Much of VP1 was acquired on grass and road shoulders of 166th Ave and a private driveway. Profile VP2 is a 250 m long line that begins immediately north of I-90 and extends to the base of a topographic slope related to the Seattle fault (Figure 5). This profile was acquired on the steep road slope of 166th and 167th Ave. The paleoseismic trenches were located along a LIDAR lineament south of 164th Place and show Miocene volcanic sediments thrust to the north over late Quaternary drift (Sherrod, 2002). Unfortunately, due to cultural and physiographic boundaries, we crossed the trench location at the end of each seismic profile (Figure 8).

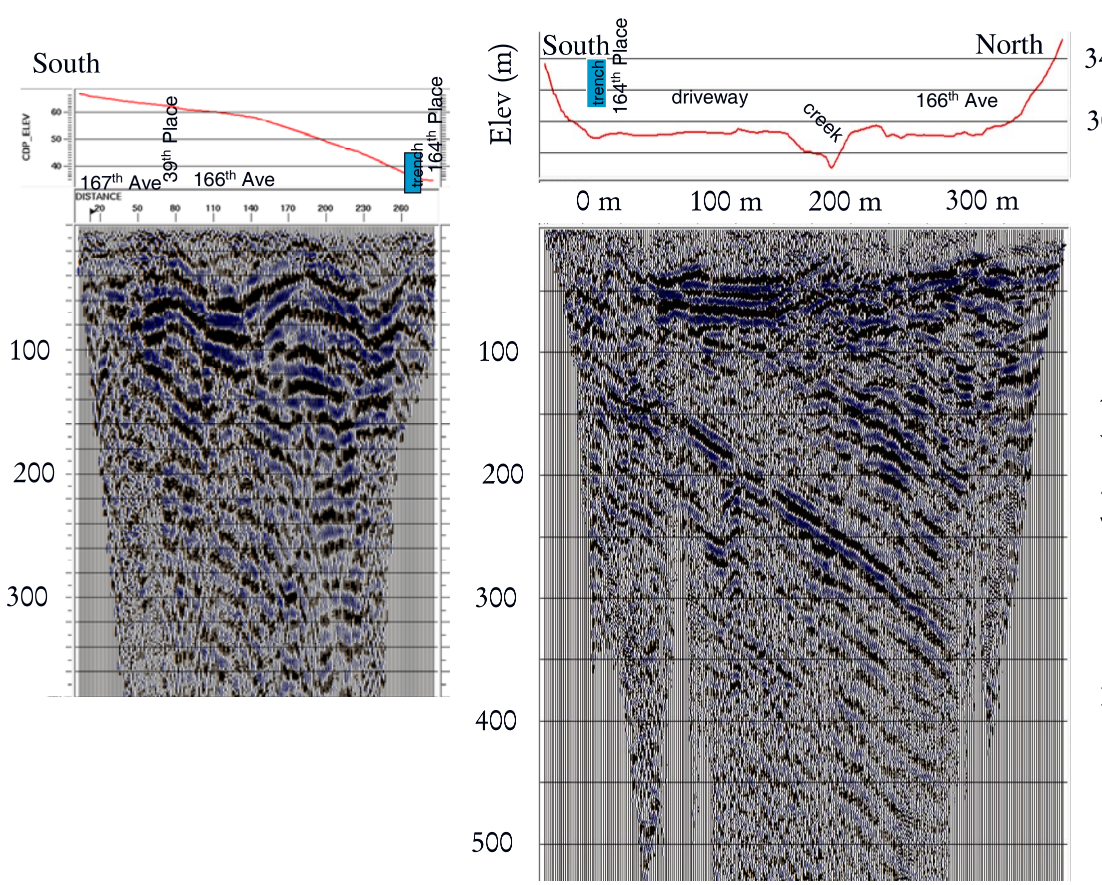

Figure 8. Vasa Park seismic profiles VP2 (left) and VP1 (right). Profile VP2 is located south of the paleoseismic trench at Vasa Park and profile VP1 is located immediately north of the trench. Exposures of Miocene volcanic sediments appear thrust over Quaternary drift in the trench.

VP1 shows steeply dipping reflections overlain by a relatively flat-lying reflection package (Figure 8). This steeply dipping (~40 degree) section represents the uppermost Tertiary-age units, topped by the Miocene-age volcanic sediments that are observed both in outcrop and in the trench logs (Sherrod, 2002). These steeply dipping reflectors are not vertically offset, suggesting that faults do not cut the Tertiary-age package at this location. At position 200 m, a reflection discontinuity suggests a south-side up fault offsets the shallow section. Again, clear offsets do not appear to cut the underlying reflections, suggesting that this fault is young, perhaps local in nature, and may accommodate the deformation observed in the trenches to the south. Profile VP2, south of the LIDAR lineament, sits upon Miocene volcanic sediments (Figure 5) and shows folded reflections. Below the folded reflections, north-dipping reflectors correlate with the top of the Oligocene sediments that appear in outcrop immediately south of I-90 (Figure 5).

The trench separates two very different seismic characteristics (Figure 8). To the north, the Seattle monocline represents an uplifted but not faulted package of reflections. To the south within the Tertiary-age package of sediments and along VP2, the reflections appear laterally discontinuous and deformed. This reflection pattern suggests that the rocks immediately south of the Seattle fault, as defined by the trench location, contain a very complex, faulted stratigraphy, whereas to the north, the sediments are deformed via bedding-plane slip that result in steeply dipping reflectors that are folded but not cut by faulting.

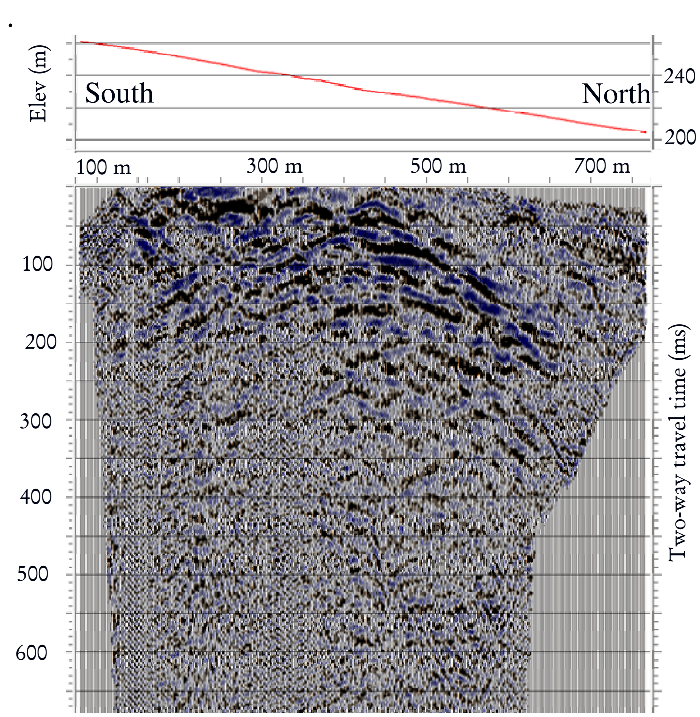

Figure 9. Profile BV3 located south of the Seattle fault and I-90, sits upon Oligocene sediments. Limited long offset coverage produced poor quality reflections below 300 ms.

BV3

BV3 is located south of I-90 along 151st Avenue in Bellevue from 50th Street to 45th Place (Figure 5). Since I did not obtain permission to acquire data within unincorporated King County, the line terminates to both the north and south by this boundary. BV3 is a short profile where I shot through a fixed spread of geophones. This acquisition geometry leads to an inconsistent set of offsets, and in this case, resulted in poor quality data below 300 ms twtt. The elevation along this profile rises approximately 40 m to the south. The profile sits upon mapped exposures of Oligocene marine and non-marine sediments along a relatively steep glacially-scoured topography (Figures 5 and 9).

The seismic reflection data show a package of reflections in the upper 300 m that appear as a broad fold whose axis is located at approximately 400 m distance (Figure 9). The lack of obvious reflector offsets suggests that this section is not faulted, but likely deformed by north-south shortening.

BV4

BV4 is located south of I-90 and south of BV3 along 152nd Avenue in Bellevue (Figure 5). The line terminates to the south along a topopgraphic and cultural boundary (63rd Street) and to the north along the boundary of unincorporated King County. Profile BV4 sits upon exposed outcrops of Oligocene marine and non-marine sediments along a relatively steep glacially-scoured hill slope (Figure 5; Figure 10).

The seismic reflection data show north-dipping strata that dip upwards of 40 degrees (Figure 10). Faults do not cut across bedding, but folds that appear in the upper 100 ms (100 m depth) may be related to bedding-plane slip via southward-directed thrusting, as observed in previous profiles.

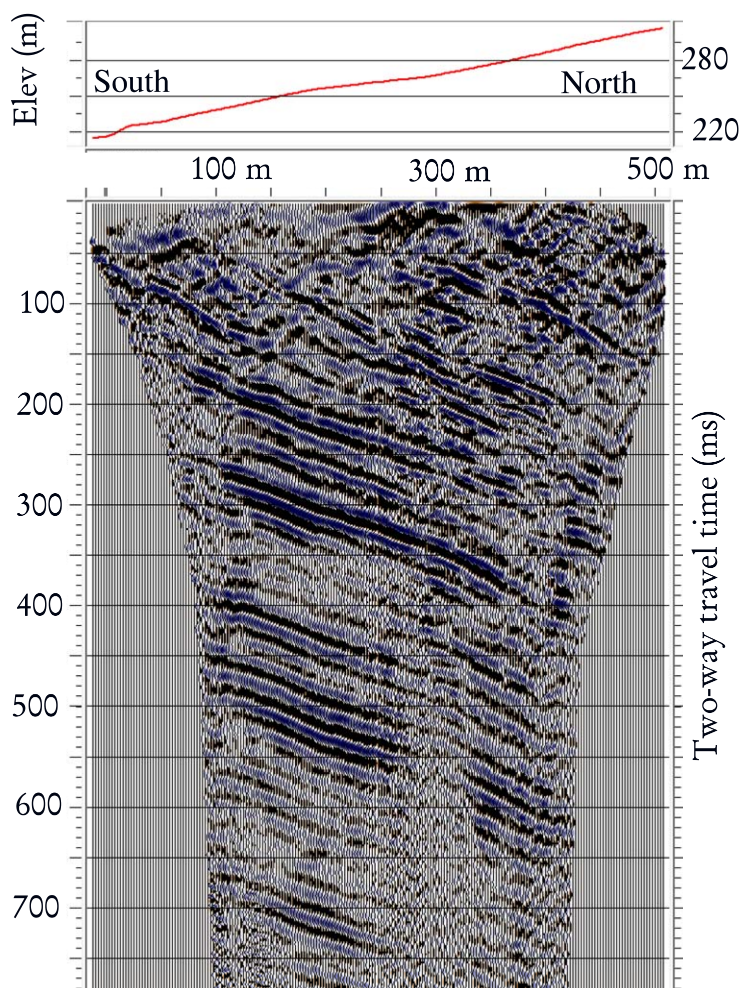

Figure 10. Elevation and seismic profile BV4, located south of BV3, sits upon Oligocene sediments. Note the consistent reflection dip below 100 ms twtt, and a more complex pattern of near-surface reflections.

BV5

BV5 is located south of I-90 and west of BV3 along 146th Avenue to Highland Drive in Bellevue (Figure 5). The profile terminates to the north along the boundary of unincorporated King County and the elevation increases approximately 40 m to the south. This profile trends north-south for the northern portions of the profile and then changes to a south-southwest trend near position 400 m. Profile BV5 lies immediately south of the southernmost exposures (and magnetic expression) of Miocene volcanic sedimentary rocks and lies upon older Oligocene marine and non-marine sedimentary rocks (Figure 5).

A complex reflection pattern on BV5, with south-dipping reflections along the northern portions of the profile changing to an arcuate and north-dipping reflection pattern in the central and southern portions of the profile, suggest a fault may bisect this profile (Figure 11). The general arcuate reflection style mimics BV3, located approximately 1 km to the east (Figure 5). Contrasting dips to the north may also relate to the ~40 degree change in profile orientation. The southern portion of BV5 appears similar to the seismic character of BV4, where a north-dipping tilted package of reflections lies below a more complex pattern of overlying strata. This contrasting structural style between BV3 and BV4 and along BV5 suggests a fault may appear within the Oligocene section. Yount and Gower (1991) identify a fault in this vicinity (Figure 5) that may correlate to the identified fault.

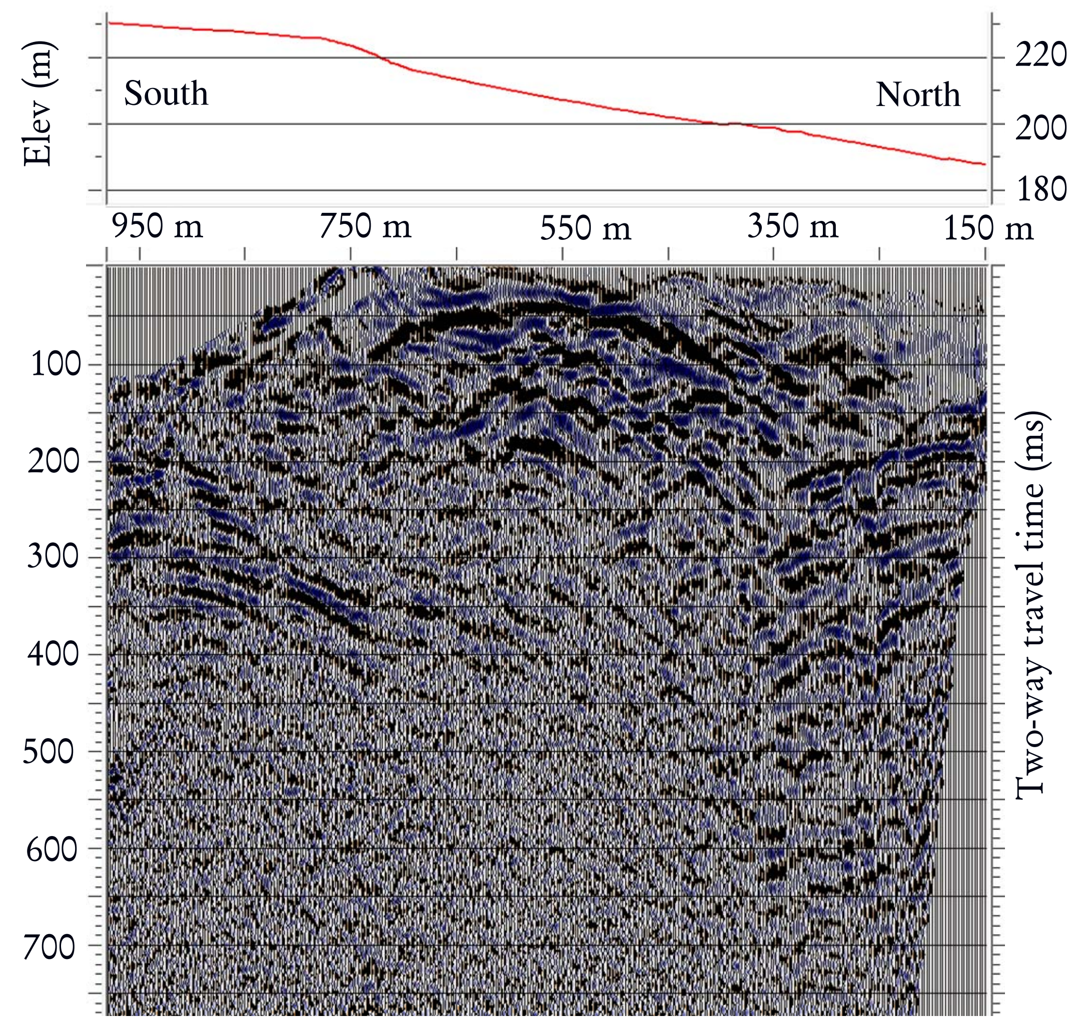

Figure 11. BV5 is located west of BV3 and BV4 and sits upon Oligocene sediments. A change in profile orientation occurs near 330 m.

BV6

BV6 is located north of I-90 and west of previous profiles (Figures 1 and 5). This profile represents the southern boundary of the Seattle Basin. BV6 is a short profile where I shot through a fixed spread of geophones. This acquisition geometry leads to an inconsistent set of offsets, and in this case, resulted in poor quality data below 300 ms twtt. BV6 gains 40 m in elevation to the north and sits upon mapped exposures of glacial till (Figures 5 and 12).

The seismic reflection results for BV6 show a strong amplitude (high-velocity contrast) reflector at 200-250 ms twtt that, based on seismic velocities, likely represents a glacial till layer (Figure 12). To the south, a steeply dipping arrival may represent the top of the Tertiary section. This arrival is not clearly imaged at increased travel times due to the acquisition parameters. Due to the poor quality of the results, I will not elaborate on interpretations along this profile.

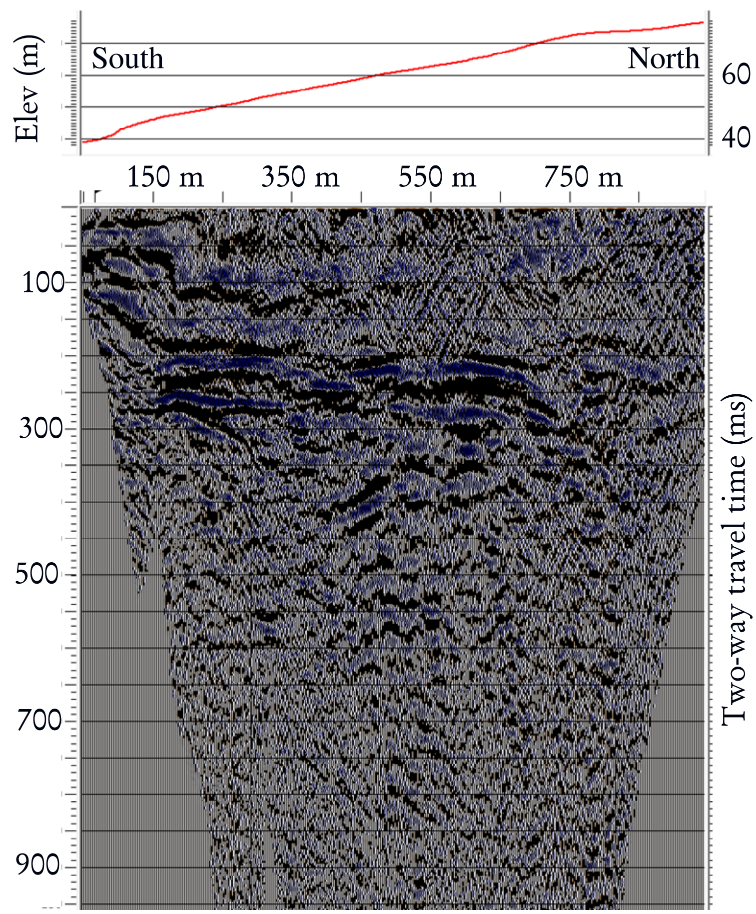

Figure 12. BV6, located north of I-90, sits upon glacial sediments.

BV7

BV7 is located south of I-90 near Factoria Mall (Figure 5). The profile begins at the intersection of SE Newport Way along 132nd Ave SE and 133rd Ave SE. BV7 continues to the north for more than 750 m, extends across Sunset Elementary School, and terminates to the north in the Homestead Hotel parking lot (position 750 m). BV7 crosses a steep topographic slope (Figure 13) immediately north of Sunset Elementary School, perhaps the same topographic slope described at Vasa Park and related to the main strand of the Seattle fault. Due to permitting problems, we were not able to vibrate within 200 m of I-90, thus we obtained very low fold across the steep topographic scarp and no data as we approached I-90. BV7 sits upon a strong magnetic lineament that directly corresponds to very near-surface

Miocene-age volcanic sediments (Figure 5; Blakely et al., 2002). Immediately south of the line, older Oligocene marine and non-marine sediments outcrop.

BV7 shows reflections dipping both to the north and south across what appears as a complex package of folded and faulted Miocene-age sediments (Figure 13). A reflector that dips steeply to the north and surfaces near position 50 m likely represents the top of the Oligocene-age sedimentary package. This reflection character is similar to the Vasa Park and BV2 profiles, where south-directed bedding-plane slip accommodates regional shortening along the top of the Oligocene-age section. The wavelength of these features is very short (~100 m) and suggests that this area is highly faulted.

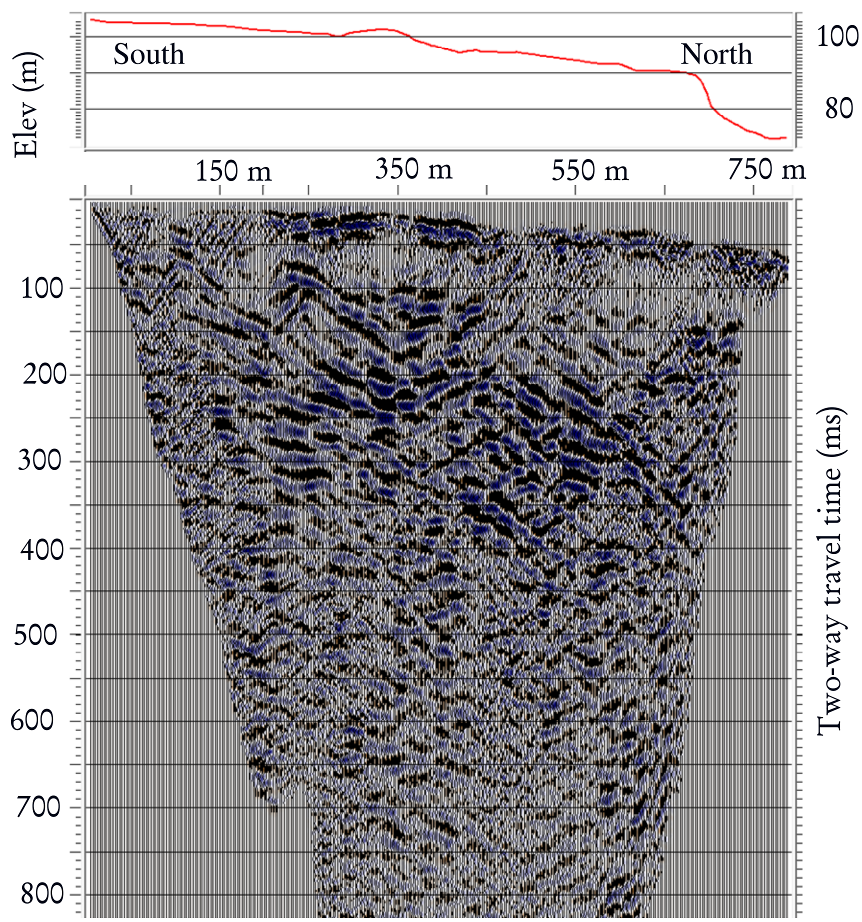

Figure 13. Profile BV7 crosses a topographic scarp that may be related to the main strand of the Seattle fault observed at Vasa Park. This profile sits upon Miocene-age volcanic sediments.

BV8

BV8 is located immediately south of BV7 along 134th Avenue (Figure 5). The profile begins at SE Newport Way and extends to the south approximately 900 m. The profile gains approximately 15 m elevation to the south and sits upon Quaternary glacial till with scattered outcroppings of Oligocene marine and non-marine sedimentary rocks.

BV8 shows reflections that dip to the north upwards of 20 degrees (Figure 8). This package of reflections extends to approximately 350 ms twtt where reflections with a slightly steeper dip appear below. In the very shallow portions of BV8, short-wavelength reflections appear along the northern portions of the profile. These reflections likely originate within Quaternary sediments. Reflections from older strata suggest that the Oligocene section is deformed via a broad fold similar to profiles BV3 and BV5. If these folds are related, the trend of the fold is south-southeast and varies slightly from the trend of the magnetic lineament that defines the Miocene-age section (Figure 5).

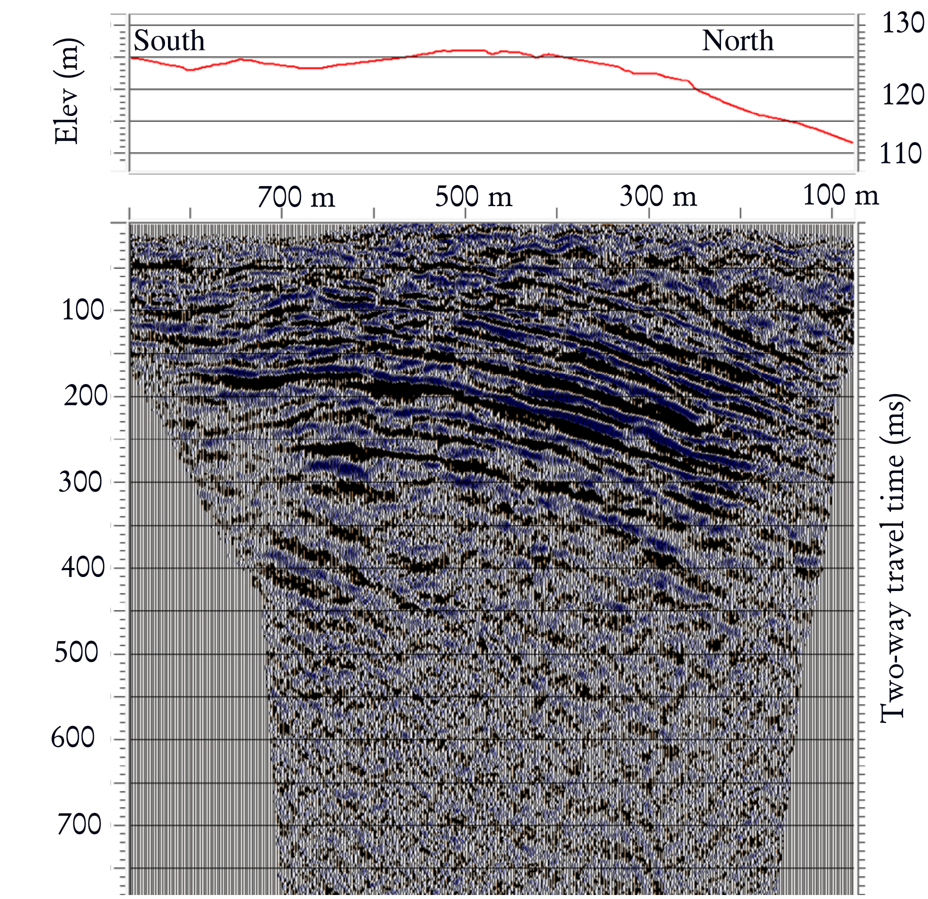

Figure 14. Profile BV8, located immediately south of BV7, sits upon Oligocene sedimentary rocks.

BV9

BV9 extends through Newport Hills and the city of Newcastle (Figures 1 and 5). This north-south line starts on 122nd and 123rd Avenues in Lake Hills immediately south of Coal Creek Parkway. The line extends across SE 60th Street with a large source gap, then continues to the south on 123rd and 122nd Avenues. The profile ends approximately 3.5 km to the south at the southern termination of SE 122nd Avenue SE. Profile BV9 sits upon Quaternary glacial fill covers Oligocene marine and nonmarine sediments along the northern 2/3rd of the profile and Eocene volcanic rocks along the southern 1/3rd of the profile.

The northern portions of seismic profile BV9 (Figure 15) show reflections dipping to the north more than 30 degrees. This reflection package approaches the surface near position 1300 and is similar in character to BV4. Further north, a package of flat-lying and south-dipping reflections overlies the steeply-dipping reflection. It is unclear whether these flat-lying and south-dipping reflections are associated with a thick sequence of Quaternary fill or whether the Oligocene-age section contains two different structural styles. Borehole information from this region may help answer this question.

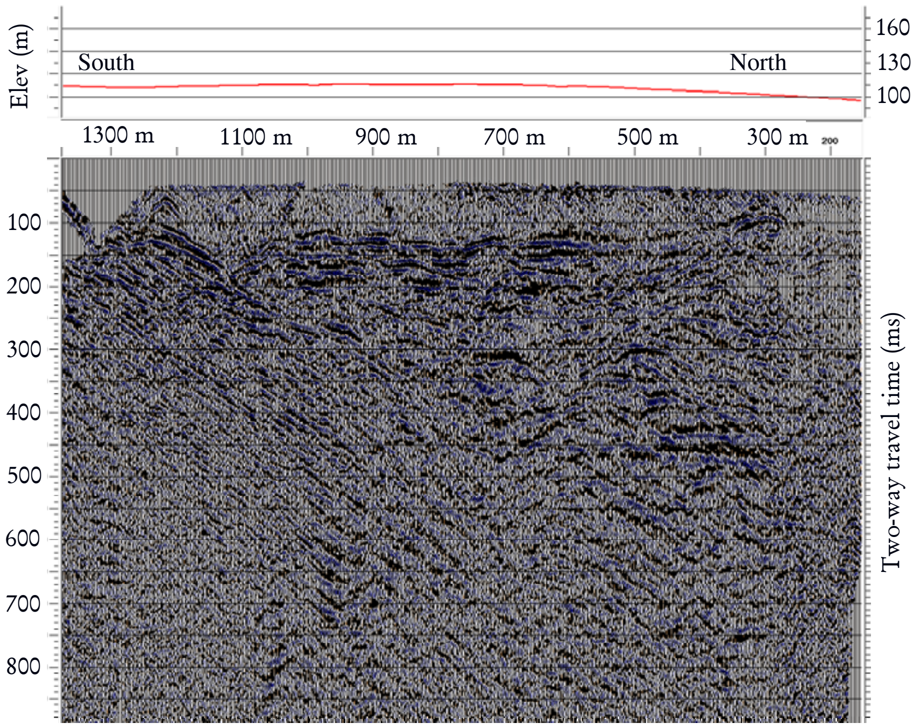

Figure 15. Northern portions of BV9. Note the angular unconformity that separates steeply dipping strata to the south from flat lying and back dipping sediments to the north.

Further south, BV9 sits upon Eocene bedrock. Eocene bedrock appears in outcrop near position 2850 m and a strong magnetic high associated with near-surface Eocene volcanic rocks appears near position 2250 m (Figure 5). The seismic signature from the Eocene section (Figure 16) shows north-dipping and flat-lying package of reflections that likely contains numerous faults that separate contrasting reflector dips. The age of associated faults is difficult to determine due to the lack of younger sediments in the area.

SM1

SM1 is located approximately 5-7 km east of Lake Sammamish and extends north-south for approximately 3.6 km. This profile extends into the Seattle Basin (Figure 1) to identify the northern extension of the deformation front associated with the SFZ. The line extends to the south to the King County boundary. The Seattle fault has not previously been identified east of Lake Sammamish, but a strong aeromagnetic lineament (Blakely et al., 2002) extends eastward to this location (Figure 17). SM1 sits upon glacial outwash and till and varies in elevation from 125-165 m above sea level. Below the glacial cover, sediments associated with the Seattle Basin extend to depths as great as 7 km (Pratt et al., 1997). The magnetic lineament associated with Miocene-age volcanic sediments appears near the southern portion of this profile (Figure 17).

The northern portions of the seismic image (Figure 17) show flat-lying reflections similar to the observed seismic data from BV1 and from the Lake Washington profiles (Johnson et al., 1999). This reflection pattern suggests no significant faulting is present in the

Quaternary section of the Seattle Basin north of the deformation front. Further south, a prominent reflection rises to within 100 ms (100 m depth) of the surface at position 3600 m (Figure 18). The projected surface location of this reflector matches the magnetic signature of the Miocene volcanic sedimentary section that marks the southern termination of the Seattle Basin (Figures 5 and 17), therefore I consider this tilted horizon the top of the Tertiary section. Reflections overlying the top of the Tertiary section appear as short-wavelength folds south of position 2000 m. This suggests that the deformation front related to the Seattle fault zone extends nearly 2 km north of the southern extent of the Seattle Basin, similar to the structural style observed in BV2 (Figure 7).

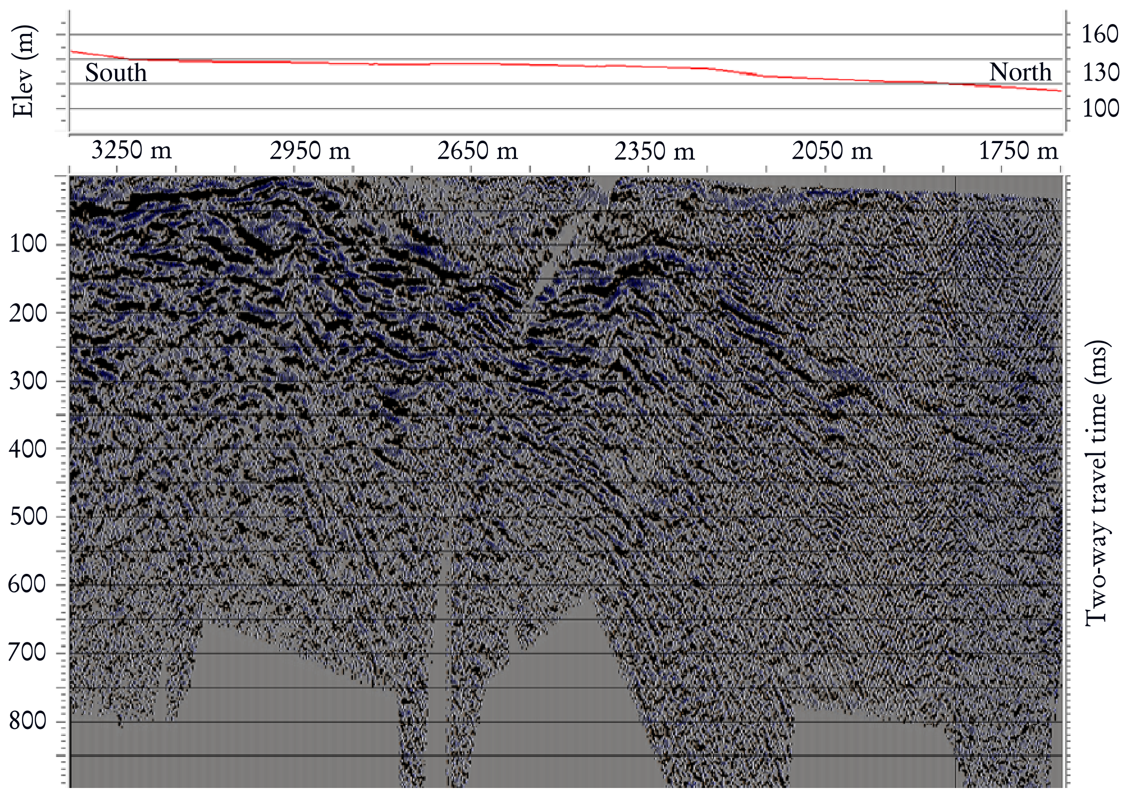

Figure 16. Southern portions of BV9. This southern half of this section sits upon Eocene volcanic rocks. Deformation within this zone appears, but the timing is poorly constrained.

Observed dips of approximately 22 degrees suggest the Seattle fault has uplifted Tertiary sediments that appear to the south in the Seattle monocline. The character and extent of the reflection section is nearly identical to that observed along BV2 and suggests that the Seattle fault extends further east than this survey. The dip associated with the top of the Tertiary appears less steep than profiles west of Lake Sammamish. This finding is consistent with the broadening of the magnetic lineament east of Lake Sammamish associated with Miocene volcanic sediments where a decrease in dip would increase broaden the surface exposures. A shallower dip may suggest the Seattle fault decreases in amplitude toward the eastern reaches of the fault zone.

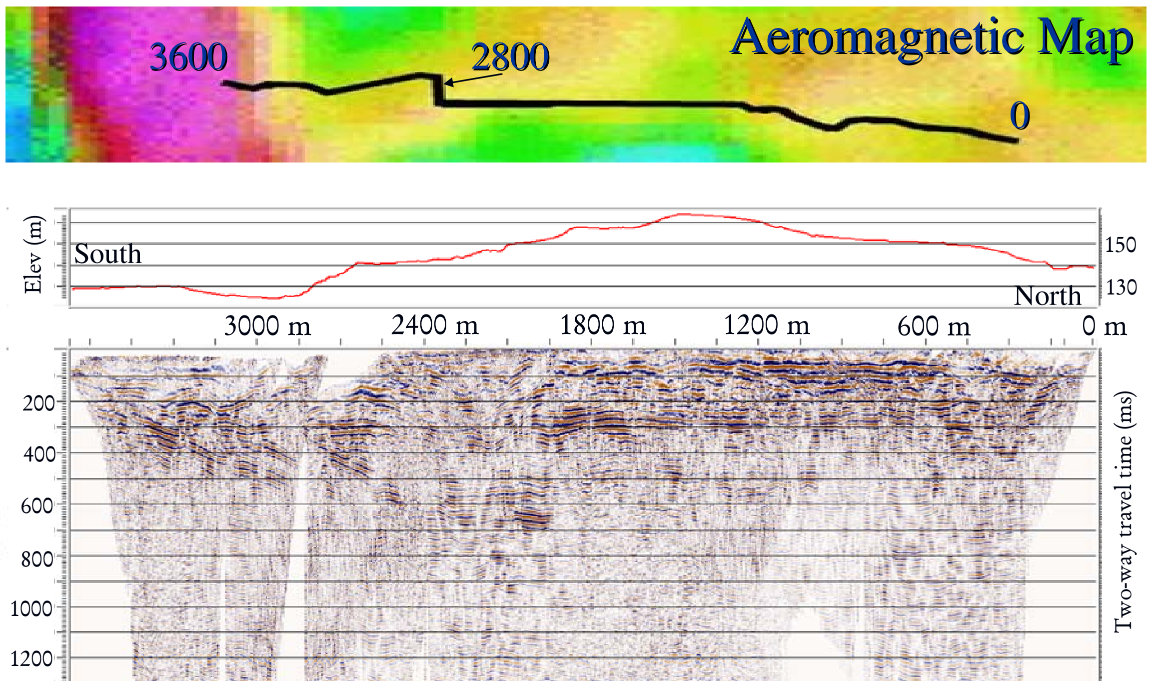

Figure 17. SM1 with elevation profile. Above lies the aeromagnetic map for a swath that parallels SM1. Note that near position 3500 m, a strong magnetic lineament appears that correlates with Miocene-age volcanic sediments.

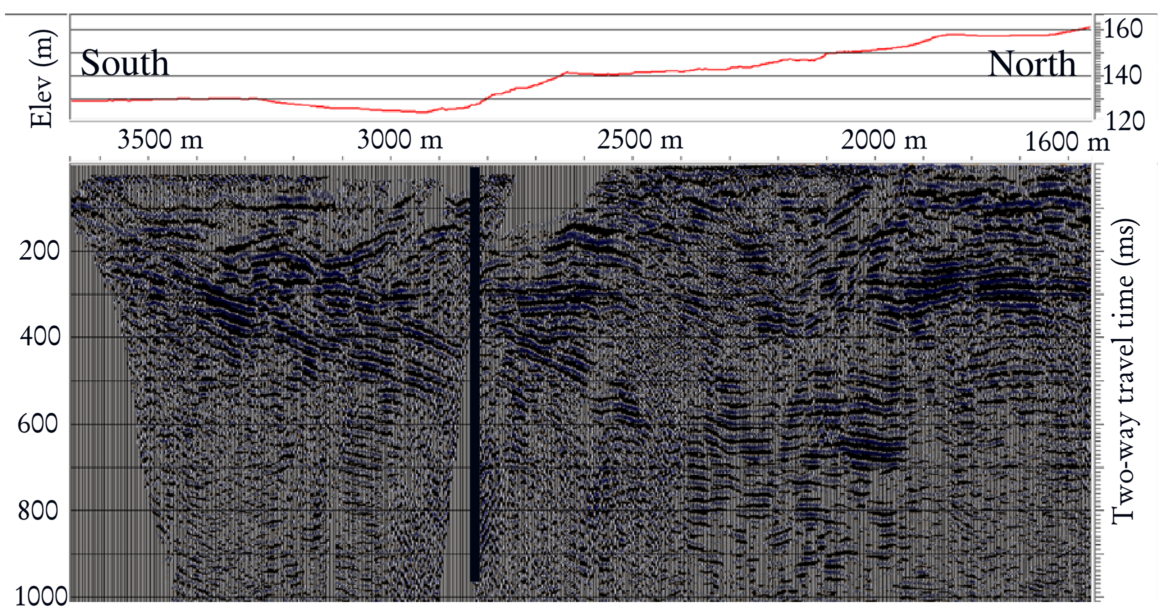

Figure 18. The southern portions of SM1 highlighting the deformation front associated with the SFZ.

SM2

Because SM1 did not extend south of the King County boundary, I acquired profile SM2. Profile SM2 is located south and west of SM1 on 219th Place SE in Sammamish (Figure 1). Elevations along this profile range from 120-135 m above sea level. Although the nearby Lake Sammamish sits near sea level (10 m elevation), Pine Lake sits a few hundred meters north of SM2 at an elevation of 115 m above sea level. The proximity of this lake suggests that water saturated sediments sit within a few meters of the land surface at this location.

SM2 crosses the inferred location of the main strand of the Seattle fault, latitudinally in-line with the Vasa Park profiles. However, we acquired this profile by shooting through the spread, due to line length limitations. The end result is a clear image of the upper 300 ms of the section, but the deeper arrivals were not imaged due to the limited far offsets.

The seismic reflection results show a strong reflection at ~100 ms twtt that likely represents the base of the glacial till sediments. Although this arrival does not appear flat-lying, it is unclear whether the topography has a glacially or structurally derived origin.

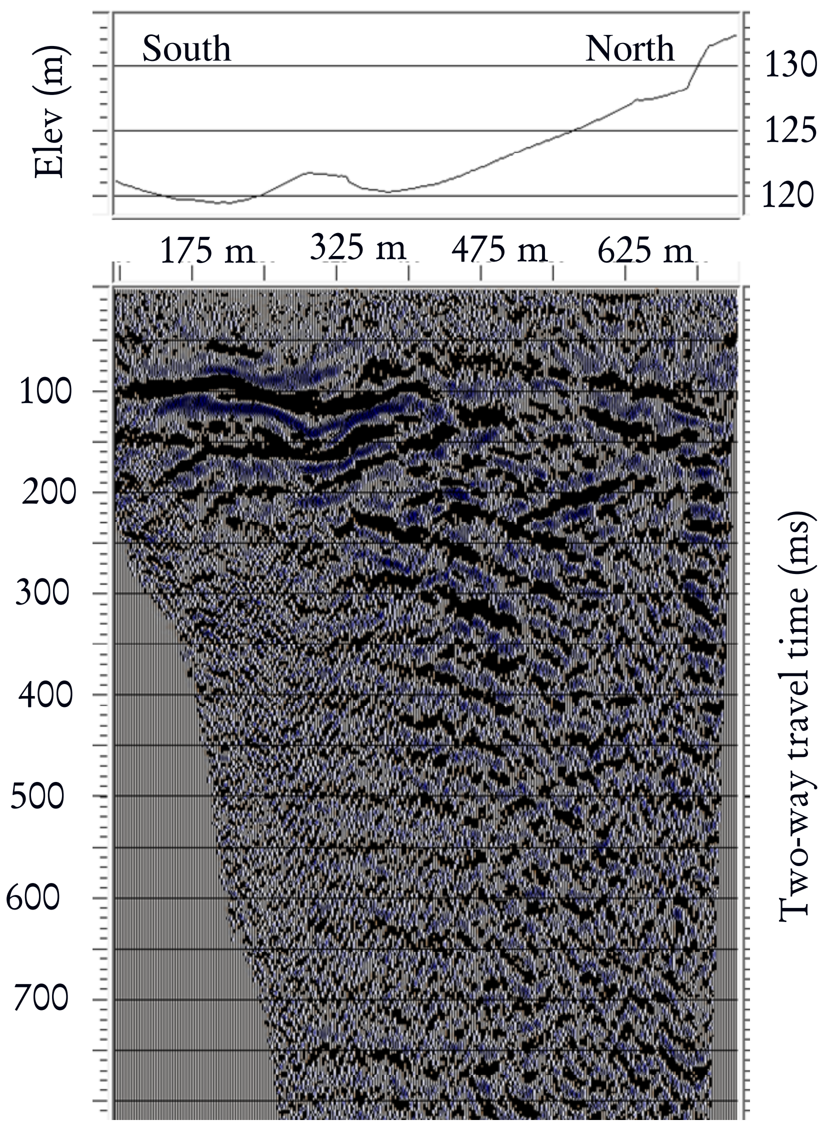

Figure 19. Profile SM2 extends SM1 to the south. This profile contains poor quality data below 300 ms twtt.

Discussion and Conclusions

Results from my study suggest that high-quality land-based high-resolution seismic reflection data can be collected in the Puget Lowlands. This includes geologic targets within the Seattle Basin, upon older Seattle uplift bedrock, and across a variety of glacial deposits.

For discussion, I will combine the seismic profiles west of Lake Sammamish together as a single transect, here termed Transect 1. The two profiles east of Lake Sammamish will constitute Transect 2. Transect 1 includes two profiles within the Seattle Basin (BV1, BV2), two profiles that cross the main strand of the Seattle fault (VP1/2 and BV7), and a number of parallel profiles that lie within the Seattle uplift. Transect 2 contains one profile that lies within the Seattle Basin (SM1) and two profiles that image the Seattle monocline (SM1 and SM2).

Transect 1 shows the SFZ deformation front extending roughly 2 km north from the main strand of the Seattle fault into the Seattle Basin. The northern deformation zone contains south-directed bedding plane slip above the uplifted and tilted Seattle monocline surface. Here, short-wavelength folding suggests many faults cut the Quaternary section, but a surface expression from individual fault strands is likely not regionally extensive. Below the Quaternary deformation, the age and angular unconformity on the top of the Tertiary section suggests the older sediments are tilted, but not faulted. South of the main fault strand, exposed Miocene and Oligocene sediments are tilted, folded, and faulted. BV7 and VP2 show short wavelength folds and faults within exposed Miocene volcanic sediments. Profiles BV3, BV5, and BV8 all show a fold within the Oligocene marine and non-marine sediments that broadens to the west. To the south, profiles BV4 and BV9 show a steeply dipping section of Oligocene sediments that does not appear faulted. BV9 shows a clear unconformity that separates this reflection package from the younger sediments to the north. Transect 1 suggests the region more than 5 km south of the Seattle fault lineament is deformed with alternating regions of tilted and deformed sediments. Deformation continues to the south upon the Eocene bedrock (south BV9). Here, faults and tilted horizons suggest deformation related to the SFZ extends more than 10 km. However, it is unclear whether sediments and volcanic rocks south of the deformation front continue to deform.

Transect 2 shows a very similar pattern of deformation 7 km east of Lake Sammamish. This is important because this profile increases the length of the Seattle fault to more than 50 km, consistent with aeromagnetic lineaments characterizing the eastern reaches of the SFZ. It is unclear how much farther east the SFZ continues, but the consistent style of deformation east of Lake Washington suggests no fault segmentation. The edge of the Seattle Basin and the edge of the aeromagnetic lineament is located 5 km east of Transect 2. It is unclear whether the SFZ is controlled by the basin edge, the Cascade foothills, or the southeast-trending South Whidbey Island fault. More studies on the eastern reaches of the SFZ are warranted.

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