Locating a strand of the Seattle Fault Zone in southeast Seattle, Washington through topographic analysis, borehole analysis and ground penetrating radar

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Abstract

Contributing to the evaluation of seismic hazards, a previously unmapped strand of the Seattle Fault Zone (SFZ), cutting across the southwest side of Lake Washington and southeast Seattle, is located and characterized on the basis of bathymetry, borehole logs, and ground penetrating radar (GPR). Previous geologic mapping and geophysical analysis of the Seattle area have generally mapped the locations of some strands of the SFZ, though a complete and accurate understanding of locations of all individual strands of the fault system is still incomplete. A bathymetric scarp-like feature and co-linear aeromagnetic anomaly lineament defined the extent of the study area. A 2-dimensional lithology cross-section was constructed using six boreholes, chosen from suitable boreholes in the study area. In addition, two GPR transects, oblique to the proposed fault trend, served to identify physical differences in subsurface materials. The proposed fault trace follows the previously mapped contact between the Oligocene Blakeley Formation and Quaternary deposits, and topographic changes in slope. GPR profiles in Seward Park and across the proposed fault location show the contact between the Blakeley Formation and unconsolidated glacial deposits, but it does not constrain an offset. However, north-dipping beds in the Blakely Formation are consistent with previous interpretations of P-wave seismic profiles on Mercer Island and Bellevue, Washington. The profiles show the mapped location of the aeromagnetic lineament in Lake Washington and the inferred location of the steeply-dipping, high-amplitude bedrock reflector, representing a fault strand. This north-dipping reflector is likely the same feature identified in my analysis. I characterize the strand as a splay fault, antithetic to the frontal fault of the SFZ. This new fault may pose a geologic hazard to the region.

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Acknowledgements

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1 Introduction

Geophysical surveys indicate that several fault systems exist in the Puget Lowland (e.g. Johnson et al., 1994, 1999; Blakely et al. 2002; ten Brink et al., 2002; Liberty and Pratt, 2008). The Seattle Fault Zone (SFZ) intersects the highly populated cities of Seattle and Bellevue, Washington and poses a significant seismic hazard. The precise location of the fault is not well constrained in these locations because of the lack of surface deformation and other indicators, due to thick Quaternary deposits, vegetation cover, water, and extensive urban development (Blakely et al., 2002). A thorough understanding of the fault zone is important for hazard assessment and mitigation and to better understand regional tectonics.

The SFZ has been active through the Holocene, and earthquakes associated with shallow crustal faults are relatively common in the Puget Lowland. The most recent rupture on the fault in 900-930 A.D caused a magnitude 7.0 earthquake that caused about 7 m of uplift on a wave-cut marine terrace at Restoration Point and a tsunami in Puget Sound (Sherrod et al., 2000). Surface deformation resulting from an earthquake of similar magnitude could have catastrophic consequences for the Seattle metropolitan area.

The location of a potential fault scarp in Lake Washington, indicated by a linear bathymetric feature, was suggested by B. Sherrod (personal communication, 2014). This information motivated a hypothesis that a strand of the SFZ is present in southeast Seattle extending from and continuous with the potential scarp in the lake. I constrained my study area based on this information.

The goal of this study is to compile multiple datasets and map the location of the hypothesized strand of the SFZ. Few surface traces of strands are present in Seattle (Sherrod et al., 2000), so geophysical techniques and other methods are often necessary to constrain fault strands. The primary objectives of my work are to 1) identify sources of data that narrow the study area and provide evidence of faulting, 2) analyze the datasets to locate and characterize the fault strand, and 3) assess the limitations of the data and recommend action for future work. The study area was narrowed using topographic and bathymetric data, aeromagnetic anomaly data, and observations from geotechnical boreholes. I acquired new data with GPR. Using these data, I located a previously unrecognized strand of the SFZ in southeast Seattle and southwest Lake Washington.

2 Geologic Background

The SFZ is an active, east-trending, south-dipping thrust fault that strikes through the highly populated cities of Seattle and Bellevue, Washington. The fault extends from the Kitsap Peninsula in the west to the foothills of the Cascade Range in the east (Figure 1). It has been active since 40 Ma, and it accommodates strain accumulating in the crust as plate interaction changes from a right-lateral strike-slip system in California to an east-dipping subduction zone in Oregon and Washington (Blakely et al., 2002). Its precise geometry and extent are still poorly understood because of the expansive urban development in Seattle. Buildings and infrastructure cover much of the land area in Seattle, and thick Quaternary deposits and dense vegetation obscure most undeveloped areas. Surface evidence of the fault has also been obscured by extensive Quaternary glacial processes in the Puget Lowland. Erosion and deposition by multiple ice sheets has erased the surface expression of all but the most recently active fault strands.

2.1 Tectonic setting

The compressional stress regime in the Puget Lowland is caused by plate interactions between the subducting Juan de Fuca plate and the North American plate (Wells et al., 1998). South of the Mendocino Triple Junction (MTJ) there is a shear margin between the Pacific plate and the North American Plate, and north of the MTJ there is a convergent margin between the Juan de Fuca plate and the North American plate (Nelson et al., 2014). Long-term monitoring of GPS sites in the western U.S. and Canada show a regional-scale clockwise rotating crustal block (Figure 2), as a result of these plate interactions (McCaffrey et al., 2013). Strain accumulating in the rotating crustal block is released in a series of shallow crustal faults zones, including the Tacoma Fault, the Seattle Fault, the South Whidbey Island Fault, and the Devils Mountain Fault. In the glaciated, forested, and urbanized lowlands, geophysical methods are necessary to identify these faults. Aeromagnetic, gravity, and seismic reflection surveys have been used to identify these fault zones (Nelson et al., 2014).

Gravitational anomaly surveys show the scale of deformation in Puget Sound crustal faults (Figure 3). Subsidence in the footwall of the SFZ has created a large sedimentary basin. Relatively low density sediment, estimated to be up to 7 km deep, has filled the Seattle Basin, causing the low gravitational anomaly (Blakely and Brocher, 2000). Conversely, uplift in the hanging wall of the SFZ has brought Tertiary bedrock to the surface, causing the high gravitational anomaly to the south. The steep gradient between these anomalies represents the trace of the frontal fault of the SFZ.

2.2 Glacial history

Deposition and erosion from at least six advances of the Cordilleran Ice Sheet (CIS) into the Puget Lowland during the Quaternary (Booth et al., 2003) make it difficult to locate fault strands in this region. These glacial deposits are common west of the Cascade Range, including lacustrine clay and silt deposits from the dammed proglacial lakes in the Puget Sound basin, advance outwashes, and tills. The deposits often cover surface traces of fault strands. Subglacial scouring, recessional outwash channels, and ice contact have shaped the terrain during the Quaternary (Booth et al., 2003). These erosional processes further obscure evidence of faulting by removing or reworking sediment. Drumlins trend north-south and are formed at the base of the ice sheet parallel to the direction of ice advance. Topographic lineaments trending in this direction can often be explained as glacial fabric. However, faults in this region are often perpendicular or nearly perpendicular to the glacial fabric.

The most recent advance of the CIS is the Fraser Glaciation, and its deposits are common in the region. The following units within the study area were deposited during the Vashon stade of the Fraser Glaciation: Vashon till, advance outwash, recessional outwash, and recessional lacustrine deposits (Troost et al., 2005). Deformation of these units due to faulting would indicate that a fault strand has been active during or since the end of the Fraser Glaciation. Older glacial and non-glacial deposits in the study area include alluvium, lake deposits, beach deposits, glacial drift, and peat deposits (Troost et al., 2005). Quaternary units from different glaciations are difficult to differentiate from one another, particularly in boring logs.

2.3 Unit descriptions

To investigate potential faulting, I focus primarily on the contact between the Oligocene Blakeley Formation and the Quaternary Vashon till within the study area. The unconformity between these units represents a difference in time of at least 20 million years. This is an uncharacteristically long hiatus, so I hypothesize a fault origin. However, erosion is another plausible explanation for this unconformity. The Blakeley Formation is composed of marine sedimentary units. It consists of fresh- to highly-weathered, fossiliferous, massive to well-bedded, medium- or coarse-grained sandstone, conglomerate, and siltstone. It can be distinguished by the presence of marine fossils and by the absence of primary volcanics and breccias (Troost et al., 2005; Weaver, 1916). In Seattle, it can be recognized as a moderately-weathered, reddish to tan siltstone or sandstone with blocky jointing. Vashon till is an ice-contact unit that has been transported and deposited by the ice sheet. It is a compact diamict composed of silt and sand with subrounded to well-rounded gravel (Troost et al., 2005).

3 Methods

Five main tasks used to evaluate the hypothesis included: 1) a literature search and data review, 2) investigation of the scarp and topographic lineaments using digital terrain maps, 3) the preparation and interpretation of lithology cross-sections based on borehole logs, 4) GPR surveys across potential fault strands, and 5) analysis and interpretation of my findings.

3.1 Locating the scarp and lineaments

A bathymetric mosaic obtained from Chamberlin (2010) was used to locate the potential scarp in Lake Washington. These data were compiled using high resolution multibeam National Ocean Service (NOS) surveys made in 2004 and 2005. These surveys were performed at Lake Washington Low Water Datum (LWLWD), an elevation 5.110 m above Mean Lower Low Water (MLLW) of Puget Sound, so no elevation correction was needed (Chamberlin, 2010). He combined the bathymetric grid with a LiDAR topographic grid to create an elevation mosaic.

Because the scarp is a subtle bathymetric lineament that is not visible in the color scale at the range of elevation values, I removed topography above lake level by creating a Boolean raster. The elevation mosaic consists of both bathymetry and topography in an area surrounding Lake Washington, ranging from 67 m below sea level to 180 m above sea level. Values less than or equal to zero were assigned a value of 1, and values greater than zero were assigned a value of 0. I multiplied this Boolean raster by the original raster to constrain the range of elevations to those below lake level, and I converted the values to feet, so units remain consistent with the LiDAR DEM and the borehole logs.

To investigate a continuation of topographic features west of Lake Washington, LiDAR data, obtained from the Puget Sound LiDAR Consortium (PSLC), were used to identify lineaments within the study area. The PSLC is a group of local agencies and scientists comprising participants from Kitsap County, Kitsap PUD, City of Seattle, Puget Sound Regional Council, NASA, and the USGS. The purpose of the consortium is to provide public-domain high-resolution LiDAR data to the public. In this study, I used a 5-ft grid LiDAR raster. This is currently the highest-resolution data available for my study area. High-resolution LiDAR datasets are the most useful for locating surficial evidence of faults, because subtle features in topography are captured.

Urbanization, vegetation, and glacial deposits obscure evidence of faulting at the surface; however, topographic indicators can provide clues to fault location. I denoted lineaments in the topography of southeast Seattle using LiDAR hillshade, slope, and aspect maps. Lineaments oblique to the characteristic north-south-trending glacial fabric were evaluated, and those attributed to human influence were not considered. Lineaments of potential fault origin were mapped. I located four topographic lineaments in my study area near the potential scarp (Figure 4). Lineament L2 generally follows the contact between the Blakeley Formation and Quaternary deposits (Figure 5).

3.2 Borehole Analysis

Information contained within borehole logs may provide insight on faulting. I selected 592 borings from the GeoMapNW database (Troost, written communication, 2014) within my study area (Figure 4) that met the following criteria: location confidence is within 20 feet, depth is greater than or equal to 10 feet, and the logs have distinct layers. These criteria ensured that the subsurface model was spatially accurate and contained sufficient information.

More than 84 thousand borehole logs in the greater Seattle area have been compiled by the GeoMapNW project (Troost and Booth, 2008). These points contain spatial and physical data as a shapefile that can be accessed in ArcGIS. A separate data table contains individual layer data.

In the GeoMapNW database, subsurface layer information is not included in the attribute table of the borehole selection; instead, layer descriptions and metadata are in a separate data table. Spatial data and layer data are connected via unique exploration ID numbers. For my analysis, I combined the subsurface layer table with the attribute table of the spatial data based on the exploration ID numbers to create a comprehensive data table of layer descriptions with spatial information.

Using Rockworks software, I imported the borehole information from GIS, and created lithology profiles across the hypothesized fault location. The data table includes the location of each point, with reference to the State Plane Washington North coordinate system. The data were exported as an Excel template, containing three sheets: location, lithology, and lithology type. The location sheet requires a unique ID number for each borehole; I use the exploration ID from the attribute table. For each borehole, the location sheet requires values for northing, easting, collar elevation, and total depth. The lithology sheet defines the material for each layer. This sheet requires a duplicate of the exploration ID of the borehole point for each distinct layer, top and bottom depths for each layer, and the material classification given in the layer description table. The lithology type sheet creates a symbol for each material classification. With these data extracted in this manner, I created a lithology profile (Figure 6) oblique to lineaments L2 and L3.

3.3 Ground Penetrating Radar

GPR provides the potential to observe the subsurface along transects and can be compared with the lithology profile and discreet data points from borehole logs. Working with colleagues, R. Cesmat and B. Holmes, we ran GPR surveys across the hypothesized fault location, trending west of the scarp in Lake Washington. Equipment was provided by Matthew Benson, of Northwest Geophysics. We used a Mala GroundExplorer shielded HDR 80 MHz shielded antenna with a 300 mm diameter distance measuring wheel and built-in GPS tracking. We were able to view and manipulate raw data in real time with a chest-mounted Mala GX Controller portable display, connected to the antenna. The antenna emits radio waves and receives the reflected signal pulses. Two-way travel time of the radio waves can be converted to depth if the material type is known, and the amplitude of the signal is dependent on the dielectric constant of the material. A sharp change in amplitude or diffraction pattern may indicate a geologic contact or other boundary.

We ran GPR along transects, shown in Figure 4, that cross the expected trace of the proposed fault to check the results of my borehole analysis. The first transect is on 42nd Avenue S. extending from S. Angeline Street to S. Snoqualmie Street. We chose to stop the GPR transect at the bottom of a hill because there has been substantial filling to the north of this location. In the early 1900's the area that is now Genesee Park was dredged to create a slough, but after the level of Lake Washington was lowered in 1917, the area became a marshland and was converted into a landfill in 1947 (City of Seattle, 2014). Anthropogenic alteration to the subsurface has erased evidence of the fault to depths accessible with GPR. The second transect is on 47th Avenue S. from S. Angeline Street to S Genesee Street, with the exception of a stairway on the easement between S. Snoqualmie Street and S. Oregon Street. We were unable to collect data on the stairway, so we resumed data collection at the top of the hill.

In addition to the GPR surveys across the proposed fault trace, we ran a GPR survey on Sqebeqed Trail in Seward Park. Although it does not cross the proposed fault trace, this location was chosen as a control, because the park has not been extensively developed. The trail is gravel rather than asphalt, and there are no buried utilities. The trail also crosses a contact between the Blakeley Formation and Vashon till and a fault mapped by the USGS (2010), which cross Bailey Peninsula (Figure 7). Because the proposed new fault crosses a contact between the same units, the assumption can be made that similar features in the subsurface may be observed.

4 Findings

A scarp is clearly visible north of Bailey Peninsula and west of Mercer Island in both the bathymetric and magnetic data (Figure 8A). The scarp appears to be separate from previously mapped strands in the SFZ to the north and to the south. The aeromagnetic anomaly map (Figure 8B), from Blakely et al. (2002), shows a high magnetic anomaly that follows the trend of the scarp in Lake Washington. This anomaly indicates the presence of a shallow magnetic source, interpreted to be volcanically derived sedimentary bedrock (Blakely et al., 2002). The location, shape, and orientation of the anomaly is coincident with the scarp in the bathymetry, and it follows the trends of the topographic lineaments L1 and L2, west of the lake (Figure 4).

In the borehole cross-section from A-A’, the three boreholes south of lineament L2 terminate in bedrock (Figure 5). North of the lineament, bedrock is not present in boreholes within the depth explored, so an unconformity exists either at the last occurrence of bedrock in the borehole logs or just to the north of that location. As expected, the lithology profile shows sedimentary bedrock in the boreholes south of the proposed fault, and it shows only Quaternary deposits to the north. This relationship is consistent with the Seattle geologic map and confirms the presence of an unconformity, though the boreholes are not deep enough to determine the orientation of the contact. Sedimentary bedrock is absent to the north, so the approximate location of the unconformity is north of the third borehole in the profile and is approximately coincident with lineament L2.

Features observed in the GPR profiles are consistent with the findings of the borehole lithology profile. GPR transect G5 (Figure 9) crosses a fault inferred from a geophysical lineaments at a 1:100,000 scale (USGS, 2010) and a mapped contact between the Blakeley Formation and the Vashon till (Troost et al., 2005). A difference in diffraction pattern can be observed on either side of the mapped fault, suggesting that there is a boundary in the subsurface. North of the fault crossing Seward Park, there are sharp parabolic diffraction patterns, characteristic of glacial till (van Overmeeren, 1997), that mark a material boundary. Also seen in profile of G5 is a reflective surface (B in Figure 9) at the edge of the topographic low Evidence of a similar boundary may be present in transects G2 and G3. They cross a contact between the same geologic units and the hypothesized fault. A north-dipping reflective surface in transect G2 may be a fault surface (Figure 10). On G3, a northerly extension of G2, a difference in diffraction pattern is observed north of the contact (Figure 11); however, the distinction between the two domains is subtle and a clear boundary is not discernable. The dielectric properties of the moderately-weathered Blakeley Formation may be too similar to the properties of the Quaternary deposits to observe the orientation of the boundary.

5 Discussion

Although borehole analysis and GPR surveys were unable to accurately characterize the geometry of the unconformity, my analysis shows that there is a previously unmapped strand of the SFZ in southeast Seattle, extending from the scarp in Lake Washington (Figure 12). The fault trace is mapped on the basis of topographic analysis, subsurface analysis, and geophysical data. The central part of the fault is defined by topographic lineament L2 and borehole profile A-A’, while the eastern and western parts of the fault are defined by the scarp in Lake Washington and by the trace of the aeromagnetic anomaly (Figure 13). Strike and dip measurements made in the field and those published in the geologic map of Seattle (Troost et al., 2005) show beds of the Blakeley Formation dipping to the north. These measurements are consistent with interpretations made by Weaver (1916), who observed an anticlinal structure with a strike of N70E in this area of the Blakeley Formation. North-dipping beds suggest that this strand is antithetic to the south-dipping main thrust.

Seismic reflection surveys by Liberty and Pratt (2008), Stephenson et al. (2007), and ten Brink et al. (2002) interpret fault geometry at depths up to several km. They suggest that one or more back thrusts, antithetic to the south-dipping main strand, deform the crust near the surface. Interpretations of seismic profiles on Mercer Island by Stephenson et al. (2007) (Figure 14), show a fault dipping to the north (Figure 15). Projecting the interpreted fault to the surface, the surface trace is consistent with the identified aeromagnetic anomaly and my mapped fault trace. Additionally, interpretations of seismic profiles in Bellevue (Figure 16), made by Liberty and Pratt (2008), show steep, north-dipping faults rooted in the south-dipping main strand. Their interpretive cross-section (Figure 17) contains a back thrust that could represent the strand identified in this study (highlighted). My observations are consistent with both interpretations, though geometry of the new strand is still uncertain. I recommend that future work include more seismic reflection surveys in this area to more accurately characterize this strand. Deep borings or trenches across the proposed fault trace may also help constrain its geometry.

Geological investigations in the Puget Lowland present significant challenges. Deposits from multiple glacial advances and interglacial periods cover much of the lowland and are often difficult to differentiate from one another. These deposits are draped over topography and are not spatially continuous. Modeling the subsurface is difficult because complex geologic processes have reworked these deposits for thousands to millions of years. There are many sources of sediment, including glacial drift, interglacial alluvial deposits, and localized volcanic deposits (Troost and Booth, 2008). Deposition may have been incomplete or may not have been spatially continuous due to paleotopography or reworking by fluvial processes. It is uncertain whether continuous layers exist in the shallow subsurface. Lenses of material are likely distributed throughout the lowland. Because of these challenges, I focused only on the contact between the contact between Quaternary sediments and Oligocene bedrock.

Development in an urban environment provides a source of data, but it also obstructs observations. The potential seismic hazard to the Seattle metropolitan area has motivated geologic studies in the Puget Lowland, so there is some geophysical data available. Additionally, the extensive development in Seattle necessitates the drilling and logging of thousands of geotechnical boreholes. However, development also presents significant challenges. Seattle is partitioned into north-south and east-west trending city blocks, so GPR work and field observations are often limited to a defined grid. Access to private property is limited. Asphalt, buried utilities, and a shallow water table may interfere with signals produced by reflective surfaces underground, and suspended power lines interfere with GPR quality.

The quality of layer descriptions in the borehole logs is inconsistent. Layer descriptions recorded by some geotechnical companies include detailed descriptions, USCS classifications, and interpreted geologic units, while others include only general layer descriptions. Interpreting these inconsistent logs requires assumptions that may have influenced construction or interpretation of the borehole log profile. These limitations affect the quality of the results. The borehole profile confirms the geologic mapping in this area, but it does not constrain the orientation and depth of a fault strand, because there are too few logs and they are often too shallow. The spatial density of borehole locations and depth of boreholes are not great enough to accurately capture the contact below the surface. Geotechnical borings do not record dip and fracture orientations of bedrock, and drillers often terminate borings when they encounter bedrock. As a result, it is not possible to determine the orientation of the fault with these methods.

6 Conclusion

Surface coverage by glacial deposits, forests, water, and human development makes it particularly difficult to study crustal faults in the Puget Sound region. Aeromagnetic and bathymetric data reveal a fault scarp in southeast Seattle and in southwest Lake Washington, west of Mercer Island. The location of this scarp is coincident with geomorphic evidence of faulting and the mapped contact between the Oligocene Blakeley Formation and unconsolidated Quaternary deposits. The unconformity appears to be a strand of the SFZ. Targeted borehole analysis and shallow geophysics validate previous geologic mapping and indicate the presence of an unconformity, though neither technique was able to sample deep enough to constrain the geometry of the fault. Because of the limitations when working in the Puget Lowland, many sources of data are necessary to form a complete picture of fault characteristics. Analysis of previous geophysical surveys and geologic mapping was necessary to characterize this strand. I conclude that the new strand dips steeply to the north. Fault dip orientation is consistent with surface dip measurements in the Blakeley Formation and with interpretations of previous seismic cross-sections. The presence of this new strand of the SFZ has implications for seismic hazards in the Seattle metropolitan area.

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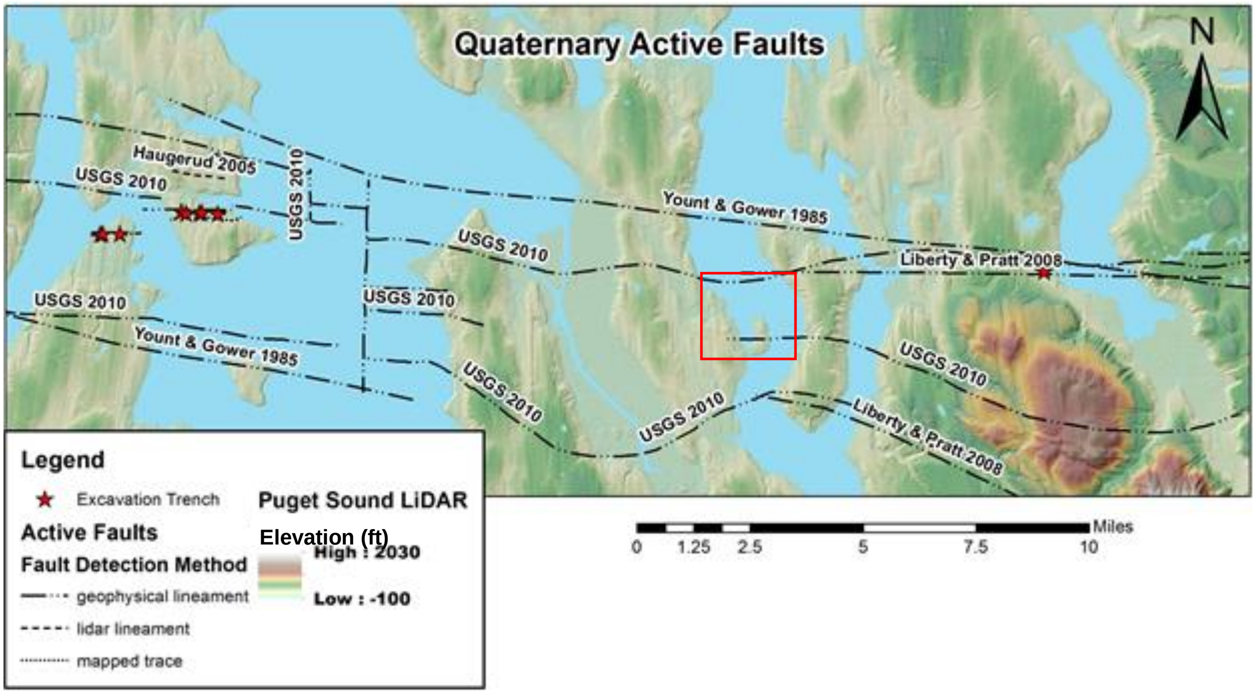

Figure 1. Map of faults active during the Quaternary Period, showing authors, detection methods, and excavation trenches (USGS, 2006) with my study area outlined in red.

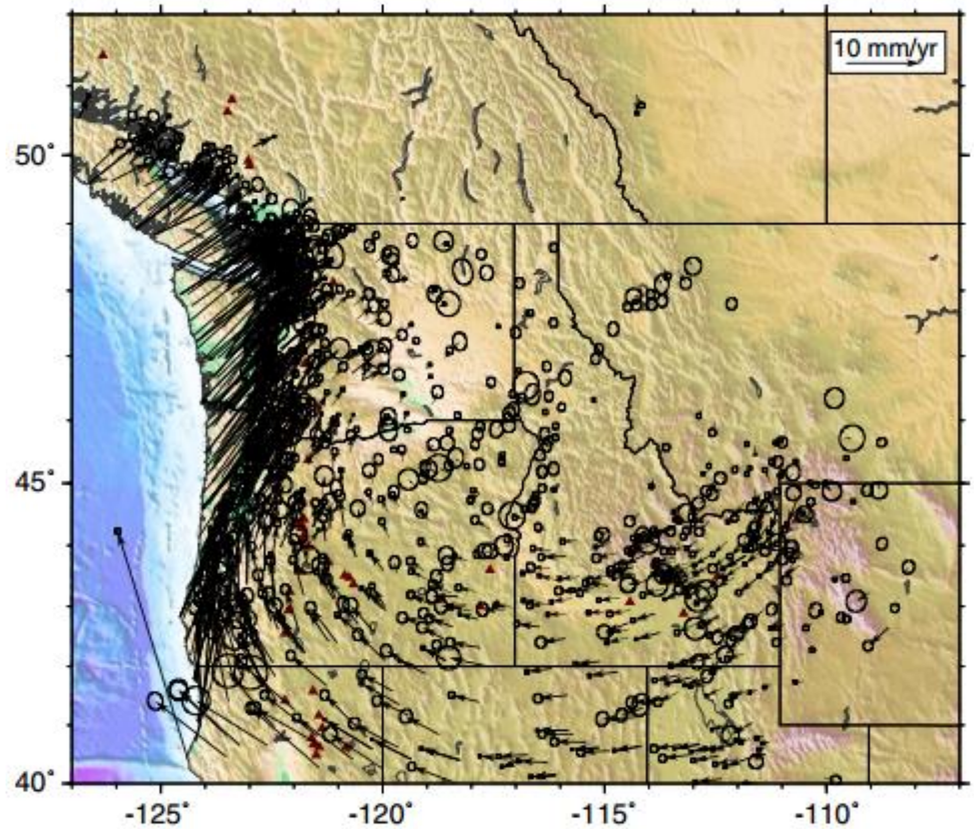

Figure 2. Map of western U.S. and Canada with the 1993-2011 GPS velocity field. Vectors show direction and magnitude of surface motion relative to North America (McCaffrey et al., 2013). Error ellipses show 70% confidence, and red triangles represent volcanoes.

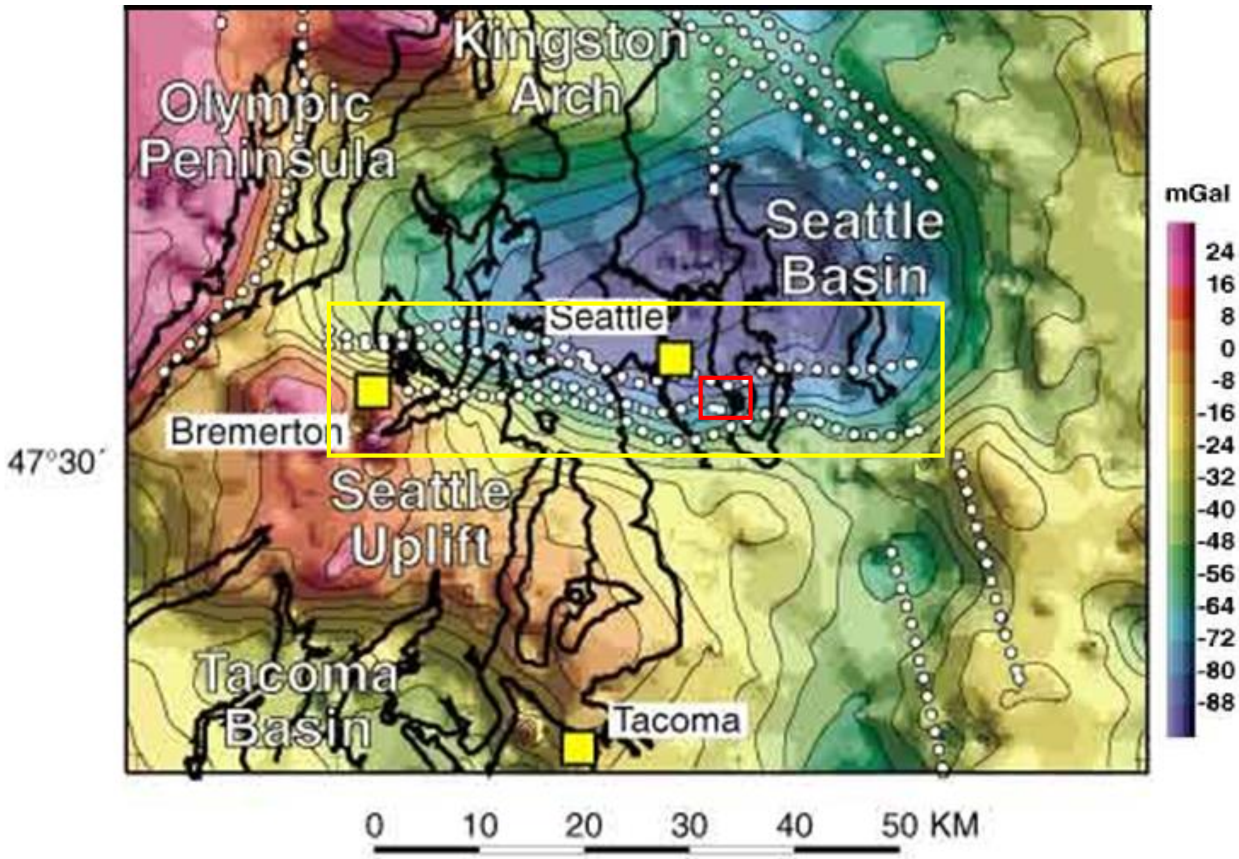

Figure 3. Gravity map of the Puget Lowland. White dotted lines show locations of crustal faults. The general location of the SFZ is shown in the yellow box, and my study area is shown in the red box. Low density sediment, estimated to be up to 7 km thick, fills the Seattle Basin. High density uplifted bedrock shows vertical throw of the SFZ. The steep gravity gradient shows crustal deformation caused by the thrust motion on the SFZ. This margin separates the Seattle Uplift to the south from the Seattle Basin to the north. Adapted from Blakely and Brocher (2000).

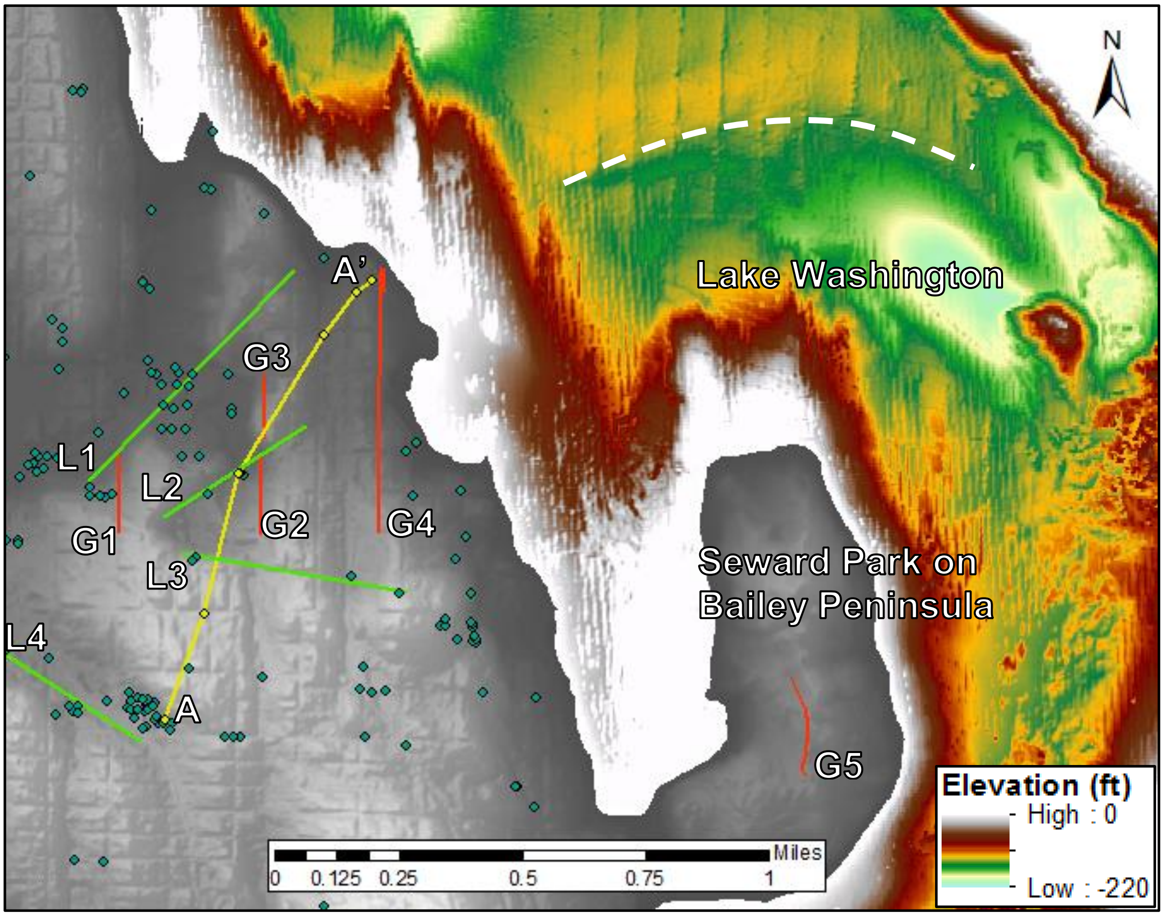

Figure 4. Site map showing borehole locations (blue diamonds) from GeoMapNW database, lineaments L1 – L4 (green lines), borehole profile transect (yellow line), and GPR transects (red lines) over a LiDAR hillshade (Puget Sound LiDAR Consortium). Lake Washington bathymetry displayed as a stretched color scale, and the potential scarp is marked with a white, dashed line.

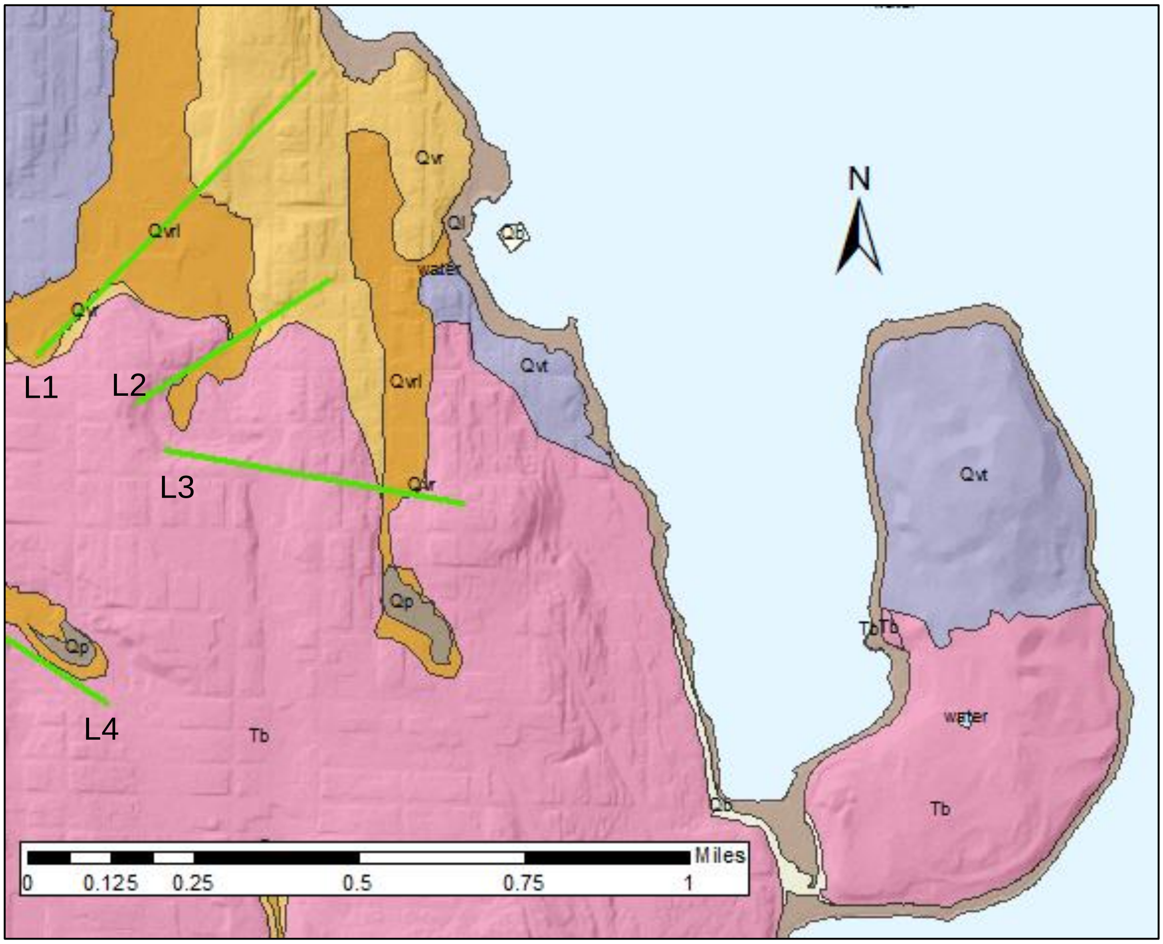

Figure 5. Geologic map of southeast Seattle (Troost et al., 2005). Lineaments (green lines) labeled L1-L4. Tertiary unit: Tb, Oligocene Blakeley Formation. Quaternary units: Qvt, Vashon till; Qvr, Vashon recessional outwash; Qvrl, recessional lacustrine deposits; Ql, lacustrine deposits; Qb, beach deposits; Qp, peat deposits.

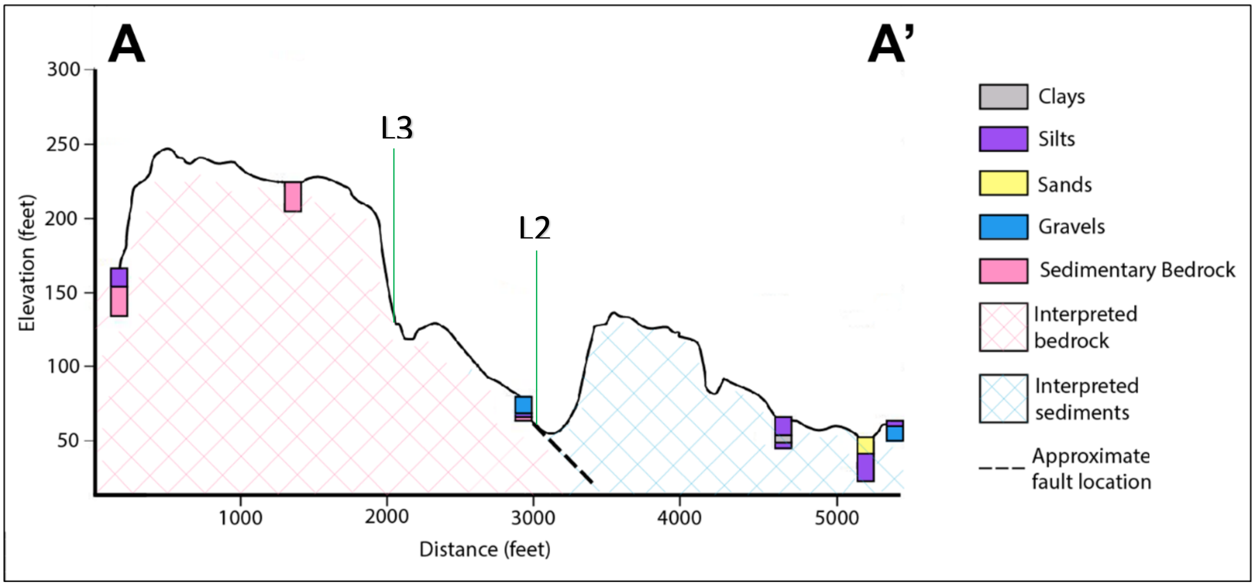

Figure 6. Borehole transect A-A', location shown in Figure 4, with 10x vertical exaggeration. Mapped lineaments (vertical green lines) intersect the profile at the high topographic gradient to the south (L3) and at the terminus of the bedrock to the north (L2). Interpreted fault strand is at the approximate location of L2. Dip direction of the proposed fault strand is uncertain, though the sedimentary bedrock dips approximately 40°-50° to the north along this line (Troost, personal communication, 2014)

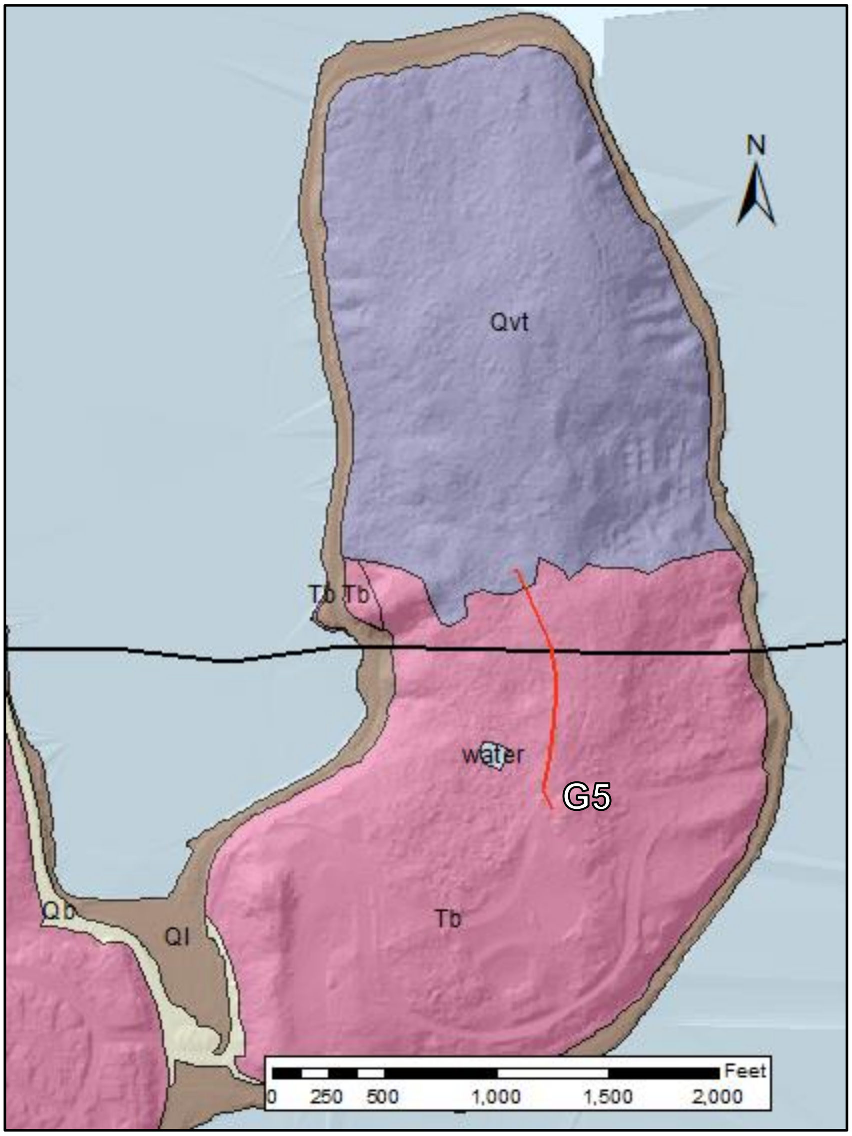

Figure 7. Geologic map, from Troost et al. (2005), of the Bailey Peninsula. Map units: Tb, Oligocene Blakeley Formation; Qvt, Quaternary Vashon till; Ql, Quaternary lacustrine deposits; and Qb, Quaternary beach deposits. A fault (black line), from the USGS Quaternary fault and fold database (2010) lies several hundred ft south of the mapped contact between the Tb and the Qvt. GPR transect G5 crosses the contact and the fault.

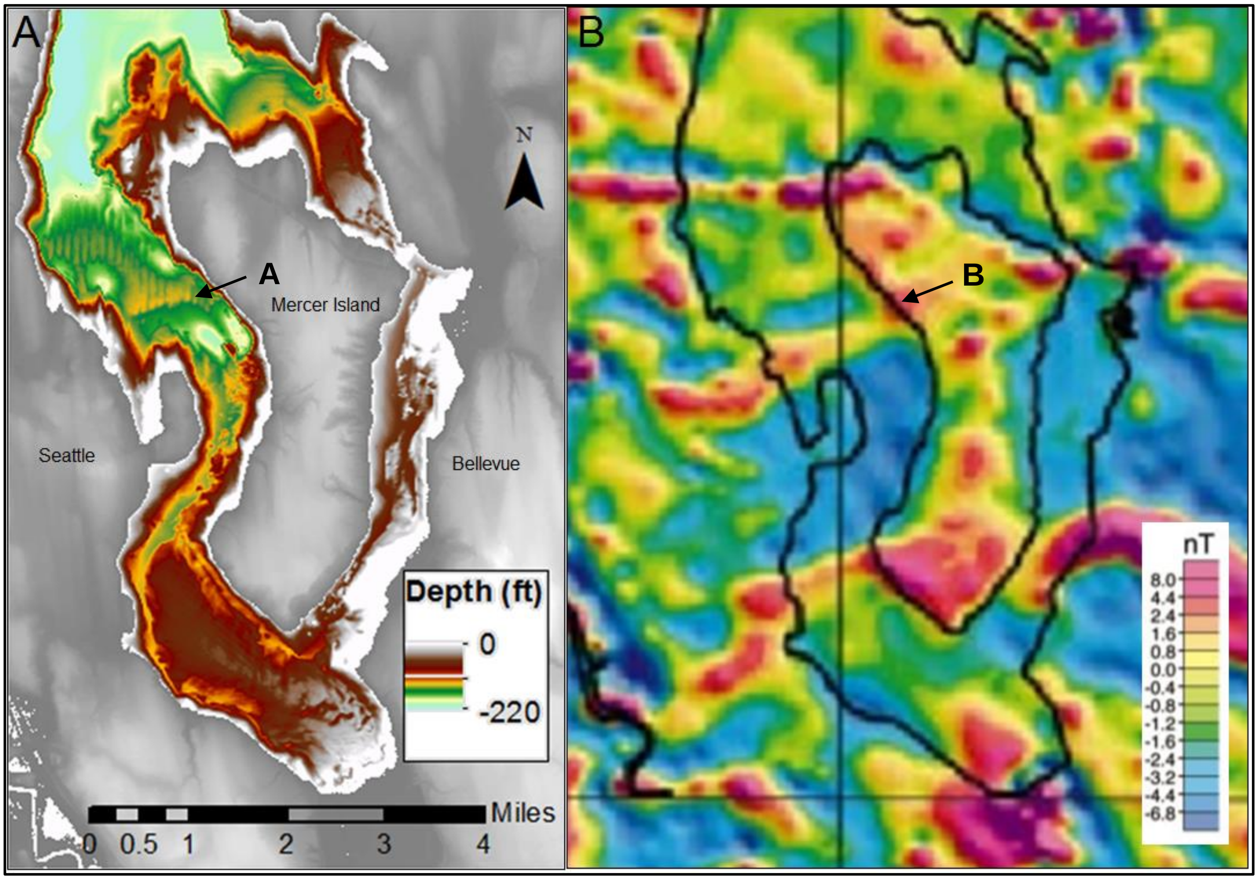

Figure 8. **A)** Map of bathymetric data from NOAA (2010) in southern Lake Washington. A potential scarp, denoted A, trends east-west across the lake between Mercer Island and Seattle, north of the Bailey Peninsula. **B)** Aeromagnetic anomaly map of the same area, to scale. An anomaly coincident with the scarp in the lake is denoted B. Reproduced from Blakely et al. (2002).

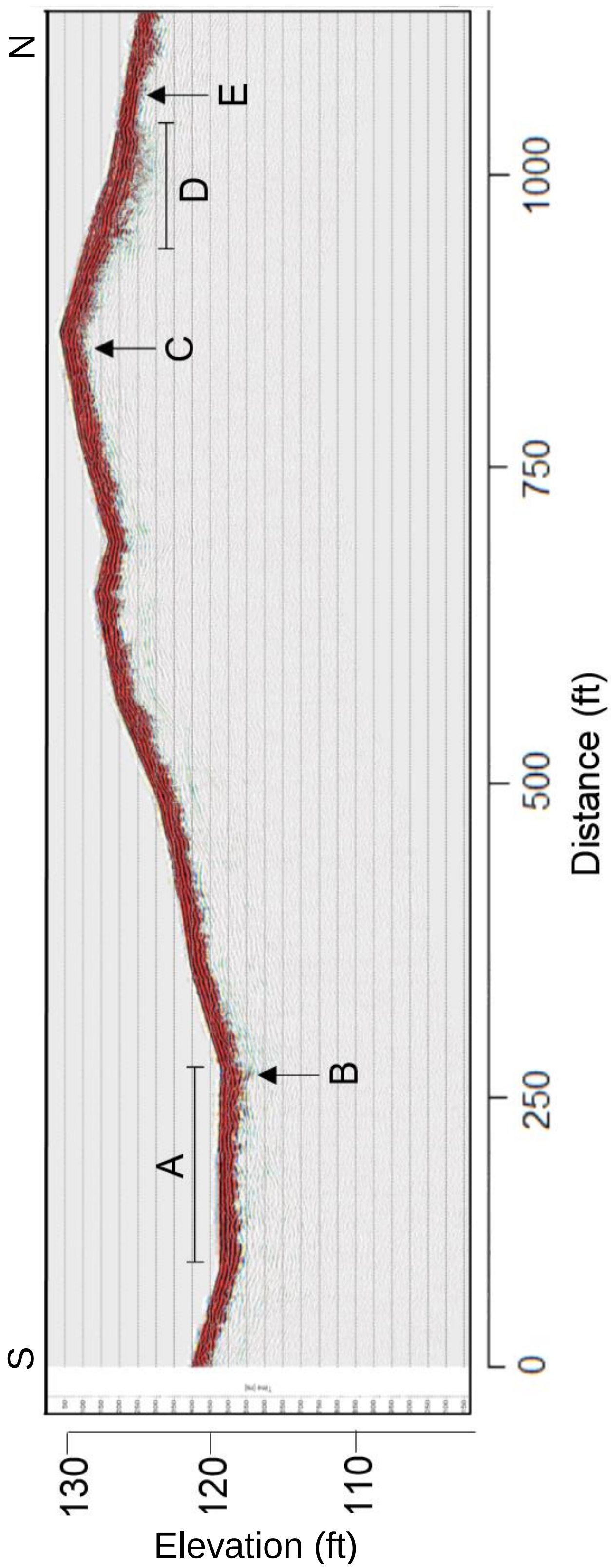

Figure 9. Topographically corrected GPR transect G5 in Seward Park (see Figure 4 for location). **A**, topographic low area; **B**, reflective surface, possibly a recessional outwash surface at the north side edge of the topographic low; **C**, the location of the mapped fault that crosses Bailey Peninsula is at the topographic high in the profile; **D**, the diffraction pattern north of the mapped fault is distinctly different from the diffraction pattern south of the fault, supporting the inference of the mapped fault; **E**, location of the mapped contact between the Blakeley Formation to the south and Vashon till to the north. Surface profile vertically exaggerated by a factor of 5. Two-way travel time (ns) also shown in the vertical scale. Assume 100 ns ≈ 10 ft.

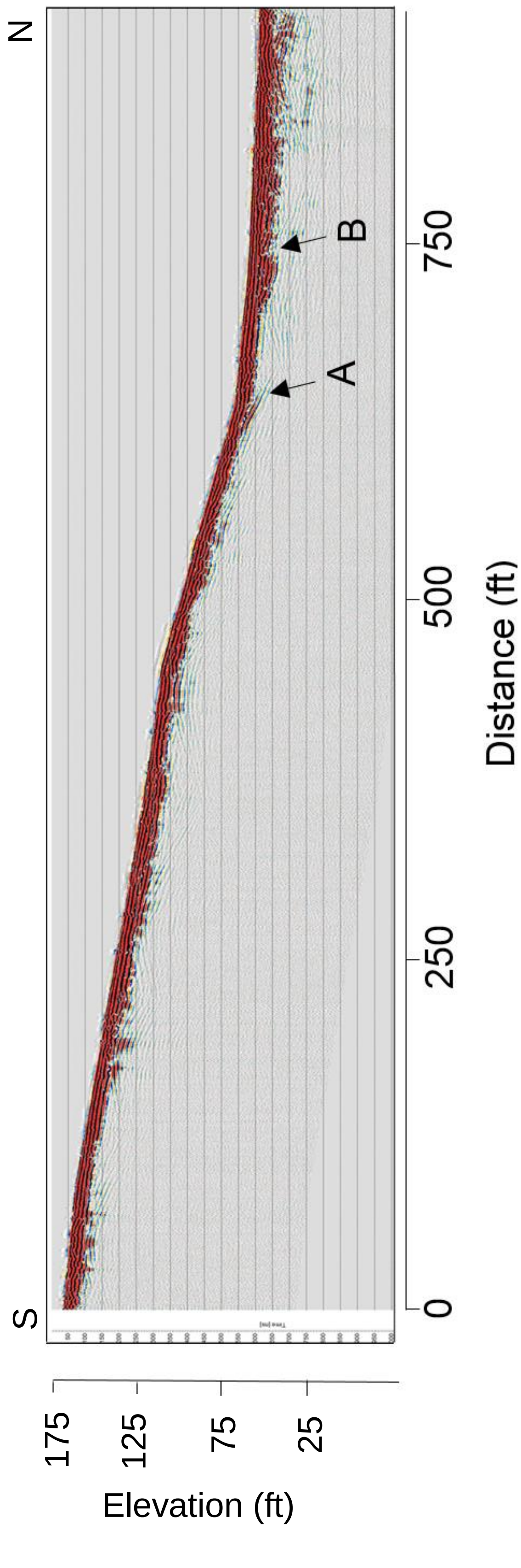

Figure 10. GPR profile of transect G2. **A**, reflective surface that may represent north-dipping bedrock; **B** contact between the Blakeley Formation to the south and the Quaternary deposits to the north. Surface profile vertically exaggerated by a factor of 2. Two-way travel time (ns) also shown in the vertical scale. Assume 100 ns ≈ 10 ft.

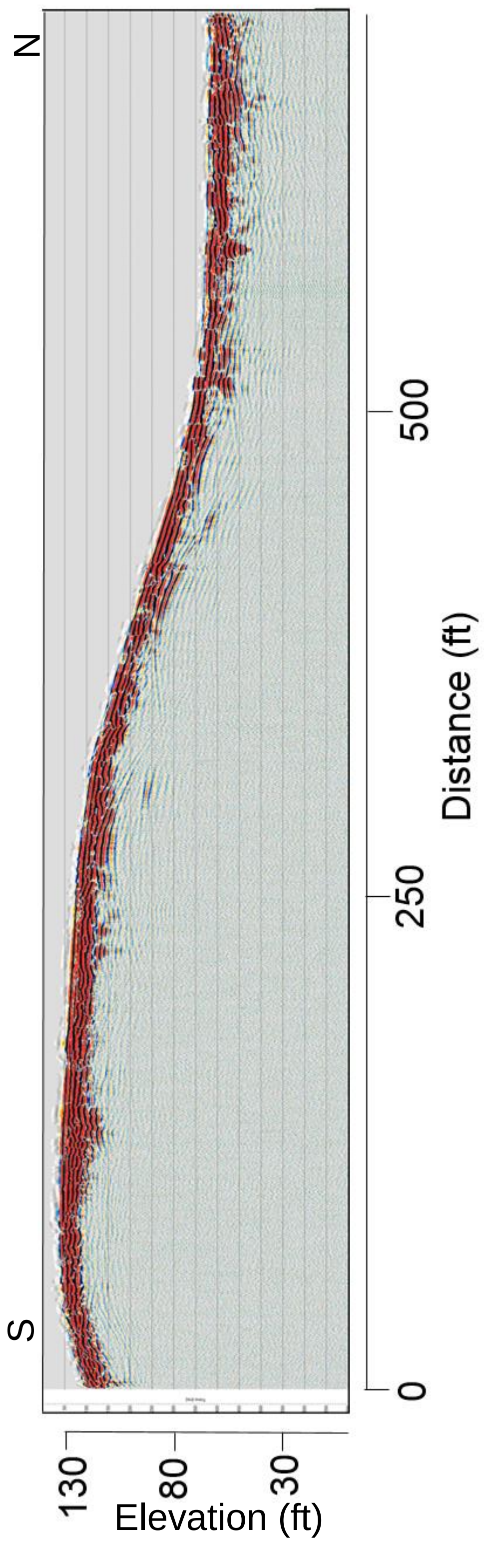

Figure 11. GPR profile of transect G3. The diffraction pattern is consistent with the diffraction pattern in profile G2, north of the contact. Two-way travel time (ns) also shown in the vertical scale. Assume 100 ns ≈ 10 ft.

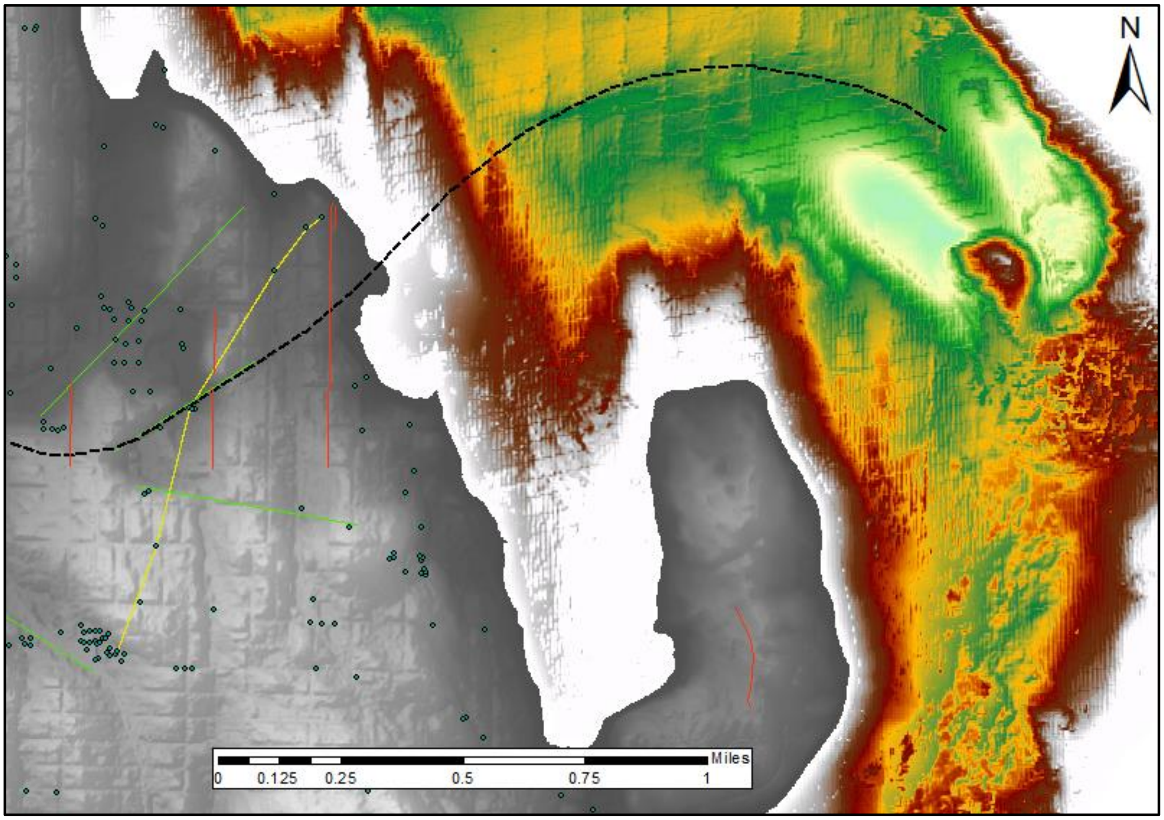

Figure 12. Proposed surface trace of the fault strand (dashed black line) based on topography, bathymetry, aeromagnetics, and borehole analysis. Fault dip direction is uncertain.

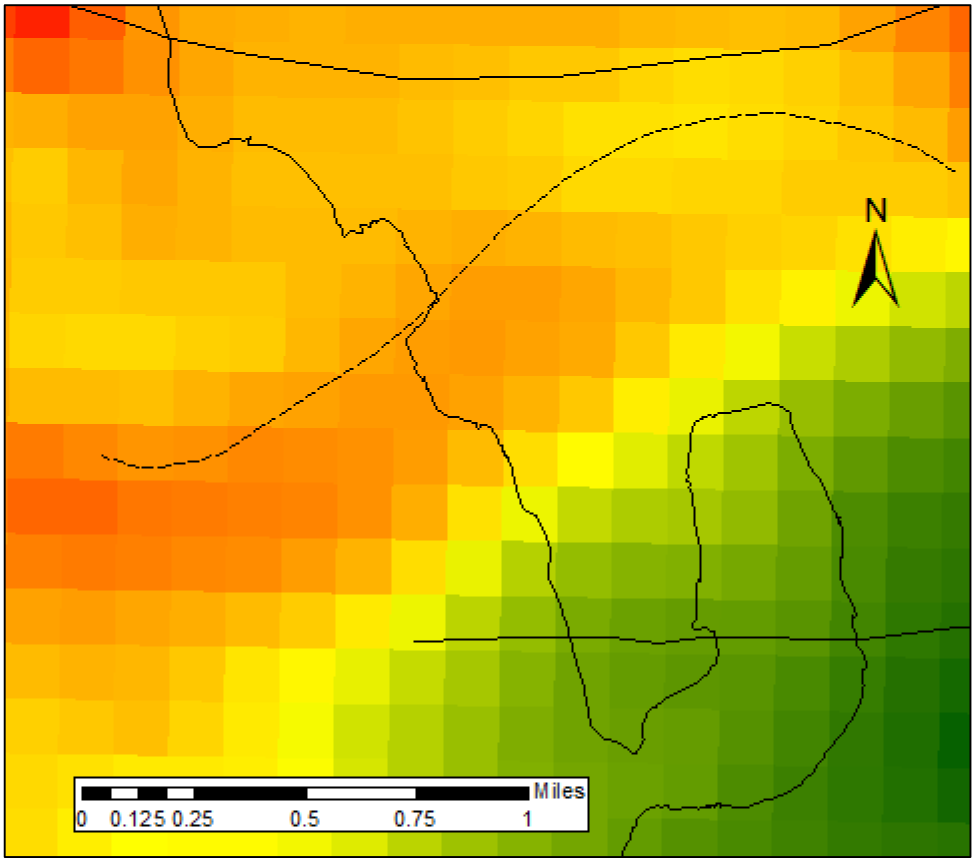

Figure 13. Proposed fault trace (dashed line) and faults previously mapped by the USGS (2010) (solid lines) overlaid on the magnetic anomaly in southeast Seattle (Blakely et al., 2002).

Figure 14. Map of Mercer Island showing P-wave seismic profile locations (orange lines), labeled with avenue numbers, and aeromagnetic lineaments (dashed red lines). Reproduced from Stephenson et al. (2007). The aeromagnetic lineament between 86th Ave and 90th Ave corresponds to the aeromagnetic lineament identified in Figure 8.

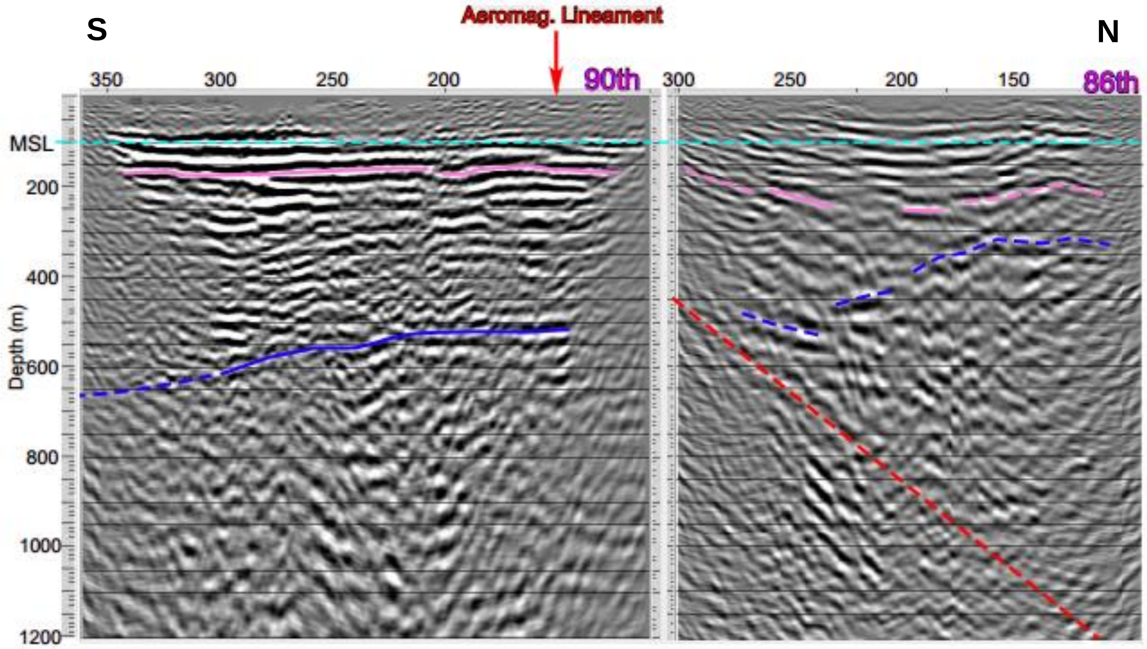

Figure 15. Seismic P-wave profiles for the transects on 90th Ave and 86th Ave. Map symbols: Mean sea level (dashed cyan line), base of Quaternary or weathered, semi-consolidated Tertiary surface (pink lines), high-amplitude bedrock reflector (blue), north-dipping fault (dashed red line), as interpreted by Stephenson et al. (2007).

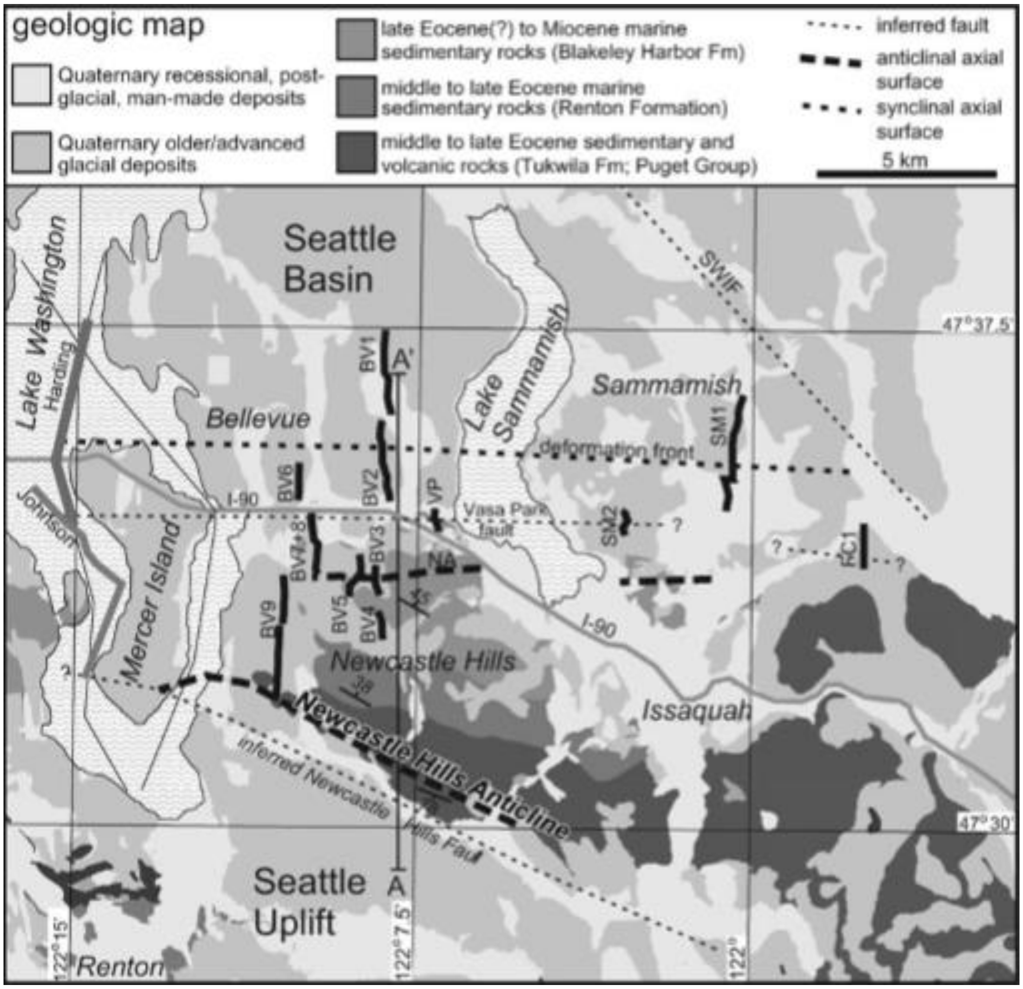

Figure 16. Geologic map of the Bellevue area, showing seismic profile transects. Reproduced from Liberty and Pratt (2008).

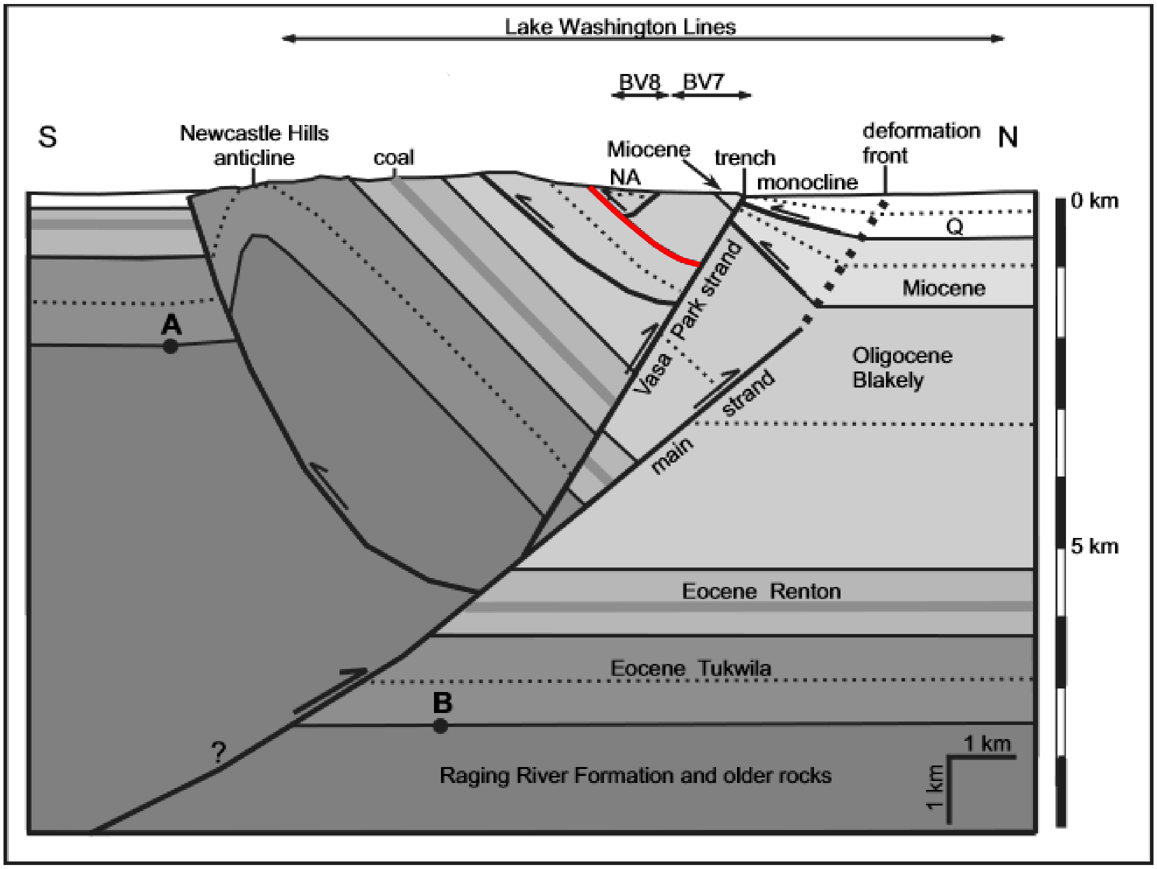

Figure 17. Interpretive cross-section of the SFZ in Bellevue, Washington, based on seismic profiles (see figure 16 for map). Adapted from Liberty and Pratt (2008). Interpreted fault geometry of my proposed strand is consistent with the strand highlighted in red.