MODELS OF BEDROCK ELEVATION AND UNCONSOLIDATED SEDIMENT THICKNESS IN THE PUGET LOWLAND, WASHINGTON

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Models of Bedrock Elevation and Unconsolidated Sediment Thickness in the Puget Lowland, Washington

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INTRODUCTION

The Puget Lowland is part of the Puget–Willamette trough that extends about 200 mi north to south from Vancouver, British Columbia, to 20 mi south of Centralia, Wash., and up to 120 mi from the foot of the Cascade Range westward to the foot of the Olympic Mountains, narrowing southward into the Willapa Hills (Fig. 1). Elevations in this region vary from 14,411 ft at the peak of Mount Rainier to sea level at Puget Sound and the Strait of Juan de Fuca.

The Puget Lowland has accumulated thousands of feet of unconsolidated sediment from several alpine and continental glaciations as well as fluvial sediments from adjacent mountain ranges. This report provides a digital representation of the bedrock topography and thickness of overlying sediment in the Puget Lowland, refining earlier attempts by incorporating additional data and using computer modeling. The study area includes all areas hydrologically connected to Puget Sound and uses modified boundaries from Jones (1996) to more closely represent the extent of Pleistocene glaciation in the southern Puget Lowland.

Figure 1. Study area location map showing physiographic provinces.

This report and associated data also provide an estimate of local uncertainties within the model and a compilation of model input data. With this model, planners, public officials, and researchers will have a better tool for understanding the bedrock topography of the region and guiding larger-scale site-specific studies for infrastructure development, water use, seismic hazards, and many other applications.

Development of bedrock models for the Puget Sound region began as early as the mid-1960s, with local unconsolidated-sediment thickness maps by Hall and Othberg (1974), Yount and others (1985), Yount and Gower (1991), Buchanan-Banks and Collins (1994), Jones (1996), Dethier and others (1996), and Mosher and others (2000). Of these publications, the sediment thickness model of Jones (1996) is the most laterally extensive depth-to-bedrock analysis.

Numerous hydrogeologic studies conducted by the U.S. Geological Survey (USGS) and Washington State Department of Ecology (WSDOE) indirectly address bedrock depths by analyzing aquifers through the use of borehole data. These studies include Drost and others (1998), Woodward and others (1992), Kahle and Olsen (1995), Thomas and others (1997, 1999), Cox and Kahle (1999), Simonds and others (2004), Northwest Land and Water, Inc. (2005), Aspect Consulting (2005), Savoca and others (2009, 2010), and Welch and Savoca (2011).

Marine and land seismic-reflection surveys provide interpretations of bedrock depths for many areas of the Puget Sound, including seismic profiles by Pratt and others (1997), Haug (1998), Johnson and others (1996, 1999,

2001, 2004), Hewitt and Mosher (2001), Kelsey and others (2004, 2009), Liberty (2004), Liberty and Pape (2006), Liberty and Pratt (2008), Mosher and others (2000), Sherrod and others (2008), and Lamb and others (2012).

The Washington State Department of Natural Resources Division of Geology and Earth Resources (WADGER), and USGS mapped bedrock at 1:100,000 scale for the study area and locally at 1:24,000 scale (see Appendix B).

REGIONAL GEOLOGY

The Puget Lowland is a forearc basin formed by the subduction of the Juan de Fuca plate beneath the North American plate that contains accumulated nonglacial sediments shed from adjacent provinces as well as glacial deposits from several late-Pleistocene Cordilleran ice advances. These deposits overlie pre-Quaternary marine sedimentary and volcanic bedrock, locally exposed as a result of uplift and deformation from numerous northwest-trending right-lateral strike-slip faults or east–west-trending reverse faults. These faults bound several deep structural basins filled with unconsolidated deposits to depths as much as 3,000 ft.

Three physiographic provinces surround the Puget Lowland (Fig. 1): the Olympic Mountains, the Cascade Range, and the Willapa Hills. To the west, the Olympic Mountains are a predominantly Tertiary-age uplifted subduction complex composed of deep-marine siliciclastic rocks overlain by basalt flows and breccia. To the east, the Cascade Range is an uplifted forearc/volcanic arc built upon a series of pre-Tertiary fault–separated accreted terranes and Cretaceous to Tertiary metamorphic and plutonic complexes. Tertiary to Holocene dacitic to andesitic volcanic rocks both intrude and overlie these accreted terranes and plutonic complexes in the north. The southern Cascade Range consists of Tertiary to Holocene volcanic flows and thick sequences of volcaniclastic rocks. The Willapa Hills Province bounds the southern limit of the Puget Lowland and consists of low, rolling hills of basaltic volcanic rocks overlain by marine and nearshore sedimentary rocks.

For this model, we regard any consolidated geologic unit in the study area not underlain by any unconsolidated sediments as bedrock. Generally, bedrock closely correlates to any rocks of Miocene age and older, however, we also treated Holocene volcanic rocks as bedrock.

DATA PREPARATION METHODS

To generate elevation and thickness models for the Puget Lowland (Plate 1), we integrated bedrock elevations from geologic maps, geologic cross sections, borehole data, and seismic profiles (Plate 2). Ten-meter DEMs compiled by Gesch and others (2002) merged with 10-m bathymetry data from Finlayson (2000) and 90-m bathymetry from the NOAA National Geophysical Data Center (2014) provide elevations for both the land and seafloor. This study did not utilize lidar-based elevation data, despite its greater elevation precision, due to the scale of the study, incomplete lidar coverage, and file-size limitations. Geographic Information System (GIS) modeling of bedrock elevations from these data sources provided an estimate of bedrock elevation and thickness where little to no bedrock control exists.

Geologic Maps and Cross Sections

Bedrock units mapped at the surface at 1:100,000 scale and, where available, at 1:24,000 scale, provide the best available elevation control; the intersection of geologic contacts for bedrock units and digital elevation models provide the elevation of the surficial extent of bedrock units. To provide a smoother transition between the interpolated bedrock elevation of the model and the true elevation utilized in areas where bedrock exists at the surface, points (capturing elevation data) were generated along the boundary of the bedrock polygons with 328-ft-spacing to ensure that at least one elevation point exists in each raster cell where bedrock was mapped. See Appendix B for a complete list of geologic maps used in this study.

Geologic cross sections produced by geologists for mapped 1:24,000-scale quadrangles provided additional estimates for bedrock depths. Depths to hydrogeologic units representing bedrock were also obtained from cross sections within hydrogeologic studies. While geologic and hydrogeologic cross sections both provide one interpretation of bedrock depth, they provide far better bedrock control in areas of complex structure than point data alone. We retrieved bedrock elevations from the cross sections and converted the bedrock elevations to points at 328-ft intervals along the line of cross sections (Plate 2). The 328-ft resolution used for these points matches the resolution of the final model.

More restricted in availability, seafloor mapping data were incorporated into the bedrock elevation modeling for the Puget Sound. Seafloor mapping using multibeam bathymetry and remotely operated vehicle (ROV) video

analyses is extensive in the area surrounding the San Juan Islands (Picard and others, 2011). Seafloor outcrop polygons designated as sediment-covered bedrock, fractured bedrock, and pinnacle or boulder were included in a single bedrock layer and added to the 1:24,000-scale map compilation. In undersea areas where no bedrock mapping was available, sounding points and nautical maps provided by the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey, and University of Washington (NOAA Ocean Service, Office of Coast Survey, 2001) show the location of potential bedrock outcrops in Puget Sound and the Strait of Juan de Fuca. Locations on nautical maps labeled as 'rocky' or 'rky' and nearby soundings with matching designations were included into the model dataset.

Borehole Data

Water wells, geotechnical boreholes, and oil and gas exploration data provide bedrock control for the depth and lithology of subsurface geologic units. Locations and data for the boreholes originate from three distinct datasets. One of the major distinctions is the precision at which the source agency located the boreholes. The Washington State Department of Ecology (WSDOE, 2013) water well records and locations use township-range coordinates. This method of locating water wells generally places them within the centroid of a quarter-quarter section; the actual location of these wells may be as much as 935 ft away from the reported location. The WADGER Subsurface Database (SSD; unpub. database, 2014) is a compilation of data from agencies such as the Washington State Departments of Transportation (WSDOT) and Health (WSDOH), WSDOE, the USGS, local county and city governments, and geotechnical firms. The SSD and oil and gas well locations generally have a locational precision of 100 feet or better.

Oil and gas well data (WADGER, 2012) provided locations and digital records for a number of permitted oil and gas borings within the Puget Lowland. A review of additional data in the form of geophysical logs, driller reports, and permit documents on file at the WADGER was performed, which provided bedrock depths particularly useful in areas of thick sediment accumulation. However, several boreholes were excluded as: (1) no interpretation of geophysical logs was performed and (2) the documentation on file did not provide any useful lithology information.

The SSD and WSDOE databases produced a number of duplicate records within the model data. Several rounds of quality checks performed on well records identified duplicates and resulted in the removal of numerous boreholes from the WSDOE-sourced part of the model borehole database. (Due to the lack of detail in some of the well records, it is likely that some amount of duplication remains within the model input data.) We then reviewed the well logs, identifying bedrock depths. Wells that had ambiguous logs or questionable descriptions underwent a secondary review for quality control. By comparing the questionable wells to nearby boreholes with definitive bedrock depths, we re-evaluated the reliability of those wells and removed wells with unreliable lithologic descriptions or depths unlike other nearby wells in the model dataset.

When necessary, we used wells that did not penetrate bedrock to provide a minimum estimate of potential bedrock depth in areas where data was sparse. The minimum bedrock elevation for each borehole was determined by subtracting the bedrock depth—or total well depth for 'sediment' wells (wells not encountering bedrock)—from the surface elevation provided through either digital elevation model (DEM) or bathymetry rasters.

Seismic Reflection Data

Both marine- and land-based seismic reflection analyses provided profiles that aided in determining bedrock depths for many areas within Puget Sound, the Strait of Juan de Fuca, and onshore areas near south central Puget Sound and Hood Canal (Plate 2). While numerous seismic profiles exist, this study considered only those with bedrock 'picks' that were also publicly available, excluding the use of proprietary information found with industry profiles. Project constraints also limited the study to using processed seismic data available in scientific literature.

Building a bedrock surface from marine- and land-based seismic profiles used the same methods as employed with the geologic cross sections. The vertical units provided in the source seismic profiles vary in that some provided interpreted depths for the cross section in kilometers, while others provided the depth in terms of two-way travel time (twt) in seconds. In order to convert the profiles given in twt to kilometers, we calculated the distance to bedrock based on the time given and P-wave seismic velocities. Soil and rock velocities range from 1,600 m/sec to 3,500 m/sec. For seismic profiles where the author provided no velocity estimates, we used an average value of 1,800 m/sec. Table A1 provides a list of each seismic section, velocity used in the depth calculations, and vertical exaggeration. We converted all profile depth units from kilometers into feet, and then determined the bedrock elevation for every 328 ft along the line of transect of a given profile (Plate 2).

MODELING METHODS

To create the bedrock elevation model, the elevation data from each data source are first combined to form a global dataset. Final quality checks at this stage ensured that no duplication of data points or missing attribution existed in the data.

Processing the dataset with the kriging interpolation tool provided in the ArcGIS geostatistical analyst toolkit provides an initial estimate for depth to bedrock elevation. Table A2 provides all the parameters used to constrain the model.

To represent bedrock elevation in areas with little bedrock control, refinement of the initial model used a process similar to that of Gao and others (2006), who incorporated select sediment wells that terminate below the modeled bedrock elevation. Sediment wells provide a minimum bedrock estimate in areas where little to no bedrock control exists. We used the deeper sediment wells to modify the bedrock elevation model, iteratively using wells in the upper decile of the sediment well dataset to recalculate the modeled surface. This process went through seven iterations until reaching the point at which any added sediment well would adjust the model by less than 50 ft in a given location. Table A3 summarizes processing results.

The output of the iterative process is a modeled bedrock elevation surface that we consider a minimum estimate for locations lacking surficial outcrop. To better represent the bedrock elevation where surface outcrops exist, we merged the DEM and bathymetry (clipped by outcrop extent) with the bedrock model. Subtraction of the modeled bedrock elevation from the topographic elevation provides a calculated thickness of overlying sediment in the study area and also identifies areas where the model is unreliable by producing negative thickness values (Plate 1).

Certainty in the Model

In addition to the generic determination of reliable versus unreliable for modeled locations as identified above, relative weights (1 – 5) were assigned to data sources according to confidence in their respective accuracy. This confidence assignment allows for a semi-quantitative calculation of model certainty for a given location. Using inverse-distance weighting, this method calculates the certainty of the model for each raster cell (Fig. 2). Locations with or near high-quality data, such as 1:24,000-scale mapping or SSD bedrock boreholes, are given a high confidence whereas areas with interpreted data or data with a large uncertainty, such as seismic track lines and geologic cross sections, are assigned a low confidence (Table A4).

The certainty estimate does not take into account the influence of any 'sediment' wells. As the degree of improvement these wells contributed to the modeled bedrock elevation cannot be assessed, they are disregarded from the certainty estimates. Therefore, modeled certainty estimates are minimums.

DISCUSSION

A comparison between modeled sediment thickness and thickness contours from Jones (1996) shows general agreement for areas less than 900 ft deep (Fig. 3). Major exceptions to this are shallower modeled thicknesses for the northeast Everett and Seattle basins and deeper modeled thicknesses to the northwest of the Tacoma basin. Additionally, the model deviates significantly from Jones (1996) for contours between 1,800 and 3,600 ft; notably, the model greatly extends the limit of the Tacoma basin to the northwest. This is primarily due to inclusion of Lamb and others (2012) and Liberty's (2004) seismic profile data. The Seattle basin is considerably larger in extent north of the Seattle Fault and the Everett basin extends farther to the east than previously mapped.

The greatest advantage of a bedrock elevation model is visualization of structural and geomorphic features that may or may not be apparent from surface topography alone. Many of these prominent features in the bedrock elevation model correspond to major fault zones (Fig. 4), such as the Seattle fault zone, the southern Whidbey Island fault zone, the Darrington–Devils Mountain fault zone, and to structural basins between each of these major fault systems. These faults form three of the largest basins within the Puget Lowland: the Everett basin, the Seattle basin, and the Tacoma basin.

Model Limitations

The bedrock model has some significant limitations in areas with sparse data or adjacent to bedrock exposures. Geologic cross sections provide some improvement to the model, allowing for greater bedrock control where none would otherwise exist. We recognize that cross sections are interpretations based on supporting data, such as

geophysics, structural mapping, and borehole lithology, rather than directly measured data as used in the rest of the bedrock elevation model. Where supporting evidence provided confirmation of a cross section's validity, we opted to include the data in the model.

In thin-sediment areas, we expect the bedrock surface to closely match the topographic profile of the area. Where few subsurface data exist and where topography changes rapidly, the bedrock elevation model is unable to adequately reflect these topographic changes. This results in the bedrock elevation model 'floating' above the topography in these locations. Due to this unreliability in the model, we replaced the erroneous bedrock elevation with 'no data'.
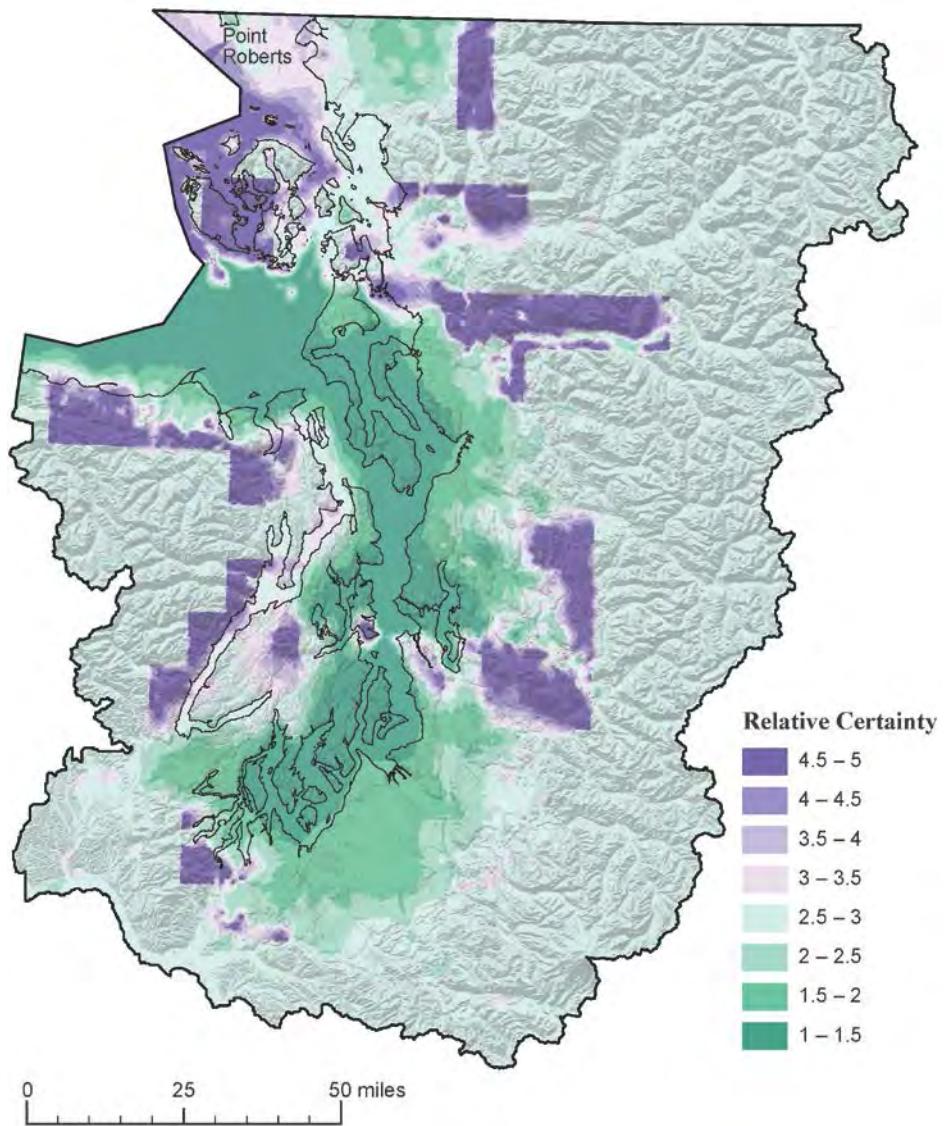
Figure 2. Relative certainty in modeled bedrock elevation. Certainty shown from high (5) to low (1) on the basis of the quality of the data source (Table A4). Note that pronounced edge effects are visible at the boundary between 1:24,000- and 1:100,000-scale mapping, and that certainty is erroneously high in the northwest corner of the map adjacent to Point Roberts. Certainty in bedrock location is lowest in Puget Sound and the Strait of Juan de Fuca where data is sparse and sedimentary cover is exceptionally thick.

Subtraction of the bedrock elevation from the topographic raster determines the reliability of the bedrock elevation model. Negative sediment thickness values resulting from this calculation represent unreliable areas in the sediment thickness model; these areas are shown on Plate 1, map B, and include areas with thickness values of 100 ft or less. In these areas, further work or additional data are required to determine either bedrock elevation or sediment thickness.
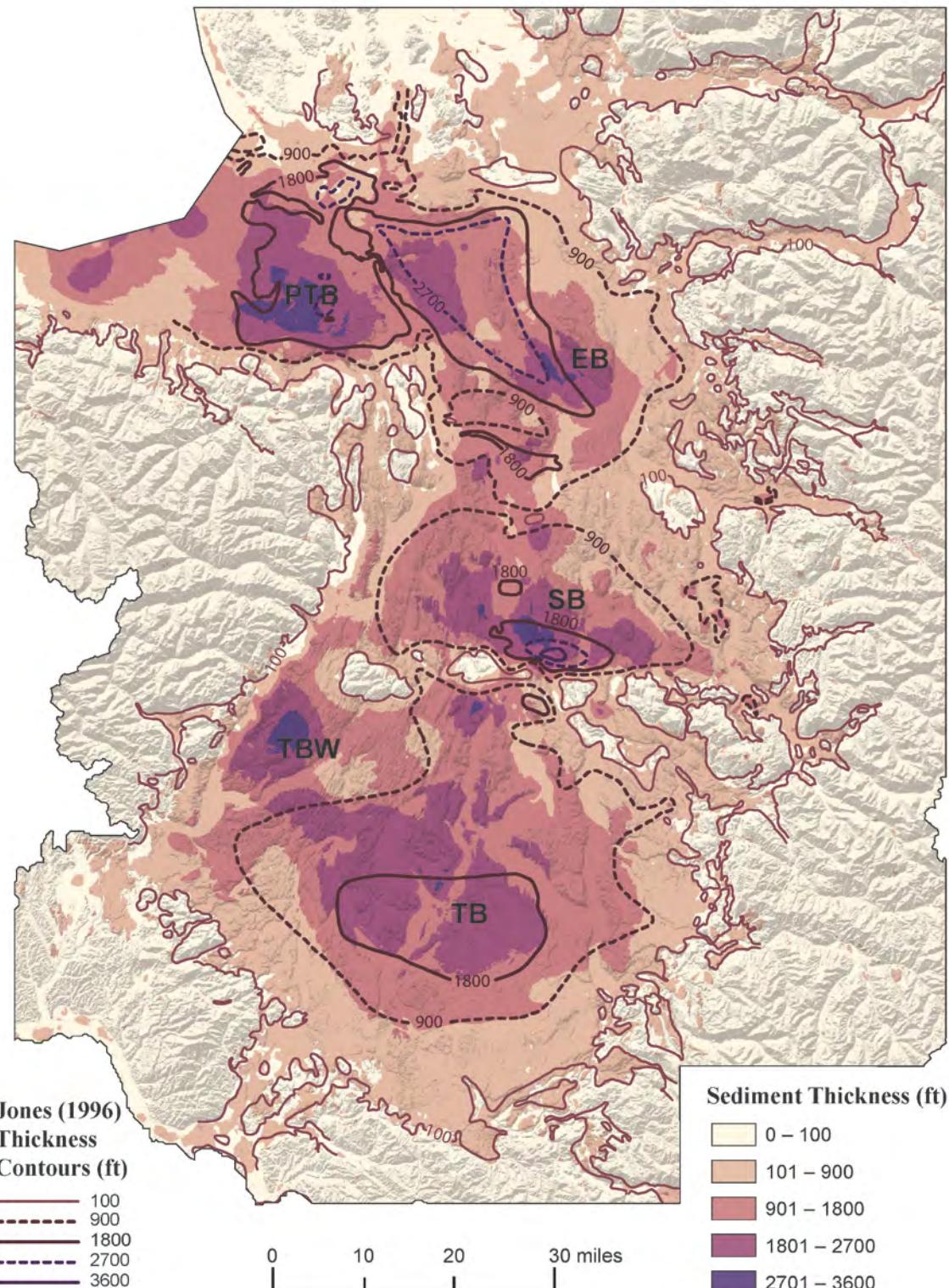
Figure 3. Comparison of modeled sediment thickness to selected thickness contours of Jones (1996) with respect to sediment-filled basins: SB, Seattle basin; EB, Everett basin; TB, Tacoma basin; PTB, Port Townsend basin. Our model includes seismic data from Lamb and others (2012) and Liberty and others (2004) which indicate a westward extension of the Tacoma basin (TBW) not included in Jones (1996).
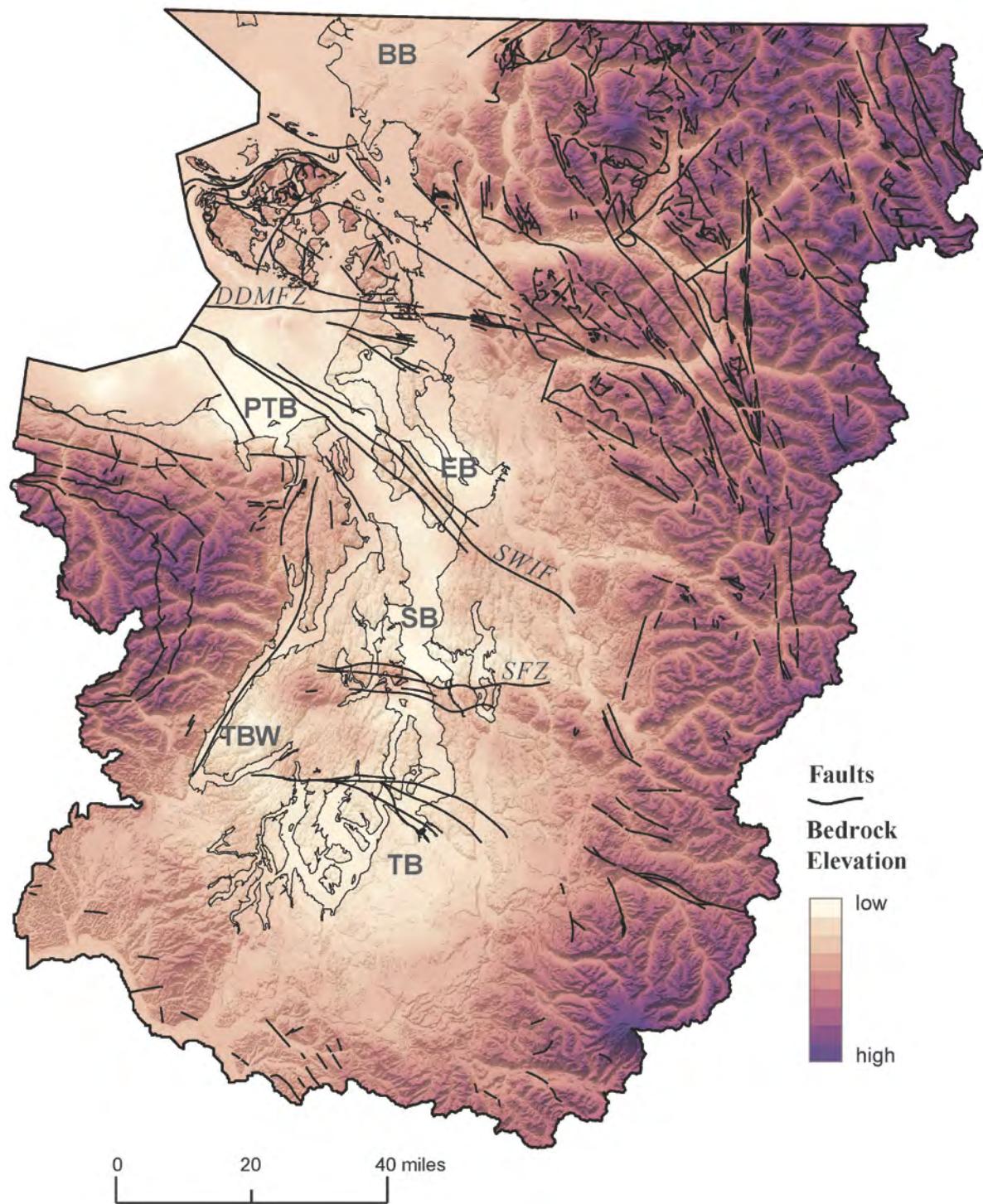
Figure 4. Bedrock elevation model of the Puget Lowland with major fault systems (WADGER, 2010). Significant fault systems: SFZ, Seattle fault zone; SWIF, southern Whidbey Island fault zone; DDMFZ, Darrington–Devils Mountain fault zone. Major structural basins formed from these fault systems: EB, Everett basin; SB, Seattle basin; TB, Tacoma basin; TBW, western Tacoma basin; BB, Bellingham basin; PTB, Port Townsend basin.

Three-Dimensional Bedrock Elevation Model

A 3D bedrock elevation model (Fig. 5), is also available, either with the digital download package, or by clicking on the static image. The model was produced in ArcScene and published in Adobe Acrobat, and includes the modeled bedrock elevation surface, DEM-based surface topography, an elevated topographic surface, cities, major roadways, and significant fault systems. Due to file-size limitations and the scale of the study area, the modeled bedrock elevation and DEM-based surface topography have been resampled to ~3,450-ft raster cells. This produces a coarsening effect on the model and will smooth out smaller undulations in both the bedrock model and topographic surface. In areas with steep terrain, such as the Olympic and Cascade Mountains, the modeled bedrock elevation surface is incorrectly rendered above the true surface topography, producing a patchy appearance in areas where bedrock is near the surface. This is a limitation of the software's drawing capability and in these locations does not accurately reflect the model's appearance. To provide a clearer picture of the underlying model, the PDF includes a topographic surface set to 1,000 ft above its true elevation. Several cross-sectional views highlight significant bedrock features such as uplifted or down-dropped areas related to faulting.
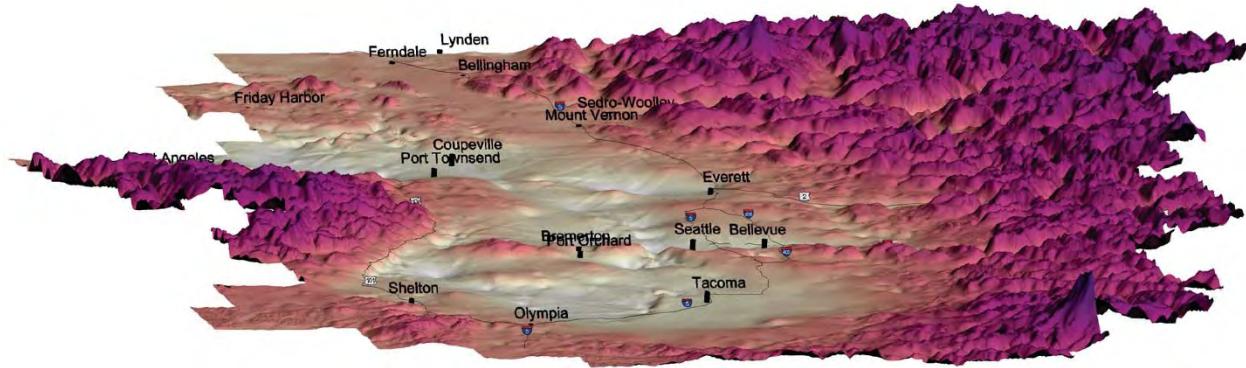
Figure 5. Oblique view of the interactive 3D bedrock elevation model with 3x vertical exaggeration. Click the image to open the model as a 3D PDF

### CONCLUSION

This model represents a significant step forward in understanding bedrock topography in the Puget Lowland. It is the first fully digital representation of bedrock at this scale; it incorporates a wider variety of data sources and a greater volume of data than used in previous bedrock elevation and (or) sediment thickness models. However, significant improvements to the model are possible with additional data and refined methods. For example, study-wide 1:24,000-scale mapping and complete mapping of the sea-floor would greatly improve the resolution of the mapped bedrock extent. This, in conjunction with refined methods of modeling in areas of shallow sediment thickness, would reduce the uncertainty in many areas. Incorporation of additional marine and on-land seismic track lines would greatly improve understanding of bedrock depth in deep structural basins. Though much seismic reflection data exists for the region, it currently has limited usefulness due to the lack of interpretation, its limited public availability, and significant discrepancies in calculated depths.

SUGGESTED READING

Other publications that provide bedrock depth estimates were not used in this model due to the complexity and scale of the data. These include gravity data from Bonini and others (1974), Daneš and Phillips (1983), Dishberger (1983), and bedrock interpreted from aeromagnetic data from Daneš (1985). Finn and others (1998) performed a state-wide aeromagnetic survey; Blakely and others (1999) gathered additional large-scale aeromagnetic data focusing on structures within the Puget Sound region. These data are compiled digitally within Bowman (2013). Gower (1978, 1980), Gower and others (1985), Cheney (1987), and Gordy (1988) produced tectonic and seismic models for select areas in the Puget Lowland.

Numerous authors, including Simonds and others (2004), Dethier and others (1996), and Dragovich and others (2002 2007, 2009), as well as geotechnical firms under contract with city or state agencies completed site-specific

bedrock contour mapping. However, we did not directly use these sources in the production of the model due to the scale and scope of this study.

ACKNOWLEDGMENTS

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Appendix A. Seismic Tracklines, Model Parameters, and Iteration Statistics

Table A1. List of seismic track lines, sources, and processing variables.

Seismic profile name	Source	P-wave velocity (m/sec)	Vertical exaggeration	Length of transect (ft)
Trackline 1	Haug (1998)	depth provided by author	2.6	8,272
Trackline 2	Haug (1998)	depth provided by author	2.6	5,214
Trackline 3	Haug (1998)	depth provided by author	2.6	5,706
Trackline 4	Haug (1998)	depth provided by author	2.6	7,960
Trackline 5	Haug (1998)	depth provided by author	2.6	7,142
Trackline 6	Haug (1998)	depth provided by author	2.6	6,053
Trackline 7	Haug (1998)	depth provided by author	2.6	5,290
Trackline 9	Haug (1998)	depth provided by author	2.6	6,683
Trackline 11	Haug (1998)	depth provided by author	2.6	10,097
Trackline 13	Haug (1998)	depth provided by author	2.6	7,151
Trackline 14	Haug (1998)	depth provided by author	2.6	14,491
Trackline 15	Haug (1998)	depth provided by author	2.6	5,977
Trackline 16	Haug (1998)	depth provided by author	2.6	8,092
Trackline 17	Haug (1998)	depth provided by author	2.6	6,730
Trackline 18	Haug (1998)	depth provided by author	2.6	7,296
Trackline 19	Haug (1998)	depth provided by author	2.6	7,130
Trackline 25	Haug (1998)	depth provided by author	2.6	12,816
Trackline 26	Haug (1998)	depth provided by author	2.6	10,793
Trackline 40	Haug (1998)	depth provided by author	2.6	17,646
Trackline 41	Haug (1998)	depth provided by author	2.6	20,295
Trackline 42	Haug (1998)	depth provided by author	2.6	15,418
Trackline 43	Haug (1998)	depth provided by author	2.6	15,473
Trackline 44	Haug (1998)	depth provided by author	2.6	16,587
Trackline 45	Haug (1998)	depth provided by author	2.6	18,310
Trackline 46	Haug (1998)	depth provided by author	2.6	16,140
Trackline 47	Haug (1998)	depth provided by author	2.6	13,614
Trackline 48	Haug (1998)	depth provided by author	2.6	9,809
Trackline 49	Haug (1998)	depth provided by author	2.6	9,784
unnamed line on figure 11	Johnson and others (1996)	1,800	1	27,241
unnamed line on figure 12	Johnson and others (1996)	1,800	1.5	44,334
unnamed line on figure 6	Johnson and others (1996)	1,800	1.2	133,359
Mobil W70-13	Johnson and others (1996)	1,800	1	19,628
USGS Lines P6, P7, P8, and P14	Johnson and others (1999)	2,000	1.8	51,335
USGS Line P37	Johnson and others (1999)	2,000	1.8	11,958
USGS Lines P350 and P31	Johnson and others (1999)	2,000	1.8	39,539

Seismic profile name	Source	P-wave velocity (m/sec)	Vertical exaggeration	Length of transect (ft)
USGS Line P346	Johnson and others (1999)	2,000	2.5	55,830
USGS Line P16	Johnson and others (1999)	2,000	1.8	43,246
USGS Lines P22 and P23	Johnson and others (1999)	2,000	1.8	35,801
USGS Line P29B	Johnson and others (1999)	2,000	1.6	16,721
Mobil 71-69	Johnson and others (1999)	1,800	1.7	19,267
USGS Line P338	Johnson and others (1999)	2,000	4	36,000
Figure 7C—Industry Profile	Johnson and others (1999)	1,800	2.3	35,721
Figure 7D—Industry Profile	Johnson and others (1999)	1,800	2.3	34,785
USGS Line P332	Johnson and others (1999)	2,000	4	16,692
USGS Line P330	Johnson and others (1999)	2,000	4	28,418
Figure 7G—Industry Profile	Johnson and others (1999)	1,800	1.2	28,603
USGS Line P326	Johnson and others (1999)	2,000	4	27,434
USGS Line P324	Johnson and others (1999)	2,000	4	20,836
USGS Line P323	Johnson and others (1999)	2,000	4	17,345
SHIPS Line JDF-1	Mosher and others (2000)	1,800	2	66,817
SHIPS Line JDF-4	Mosher and others (2000)	1,800	3	174,515
PGC96006 Line 15	Mosher and others (2000)	1,800	3.7	102,806
PGC96006 Line 2	Mosher and others (2000)	1,800	7	199,801
PGC96006 Line 32	Mosher and others (2000)	1,800	4	215,982
PGC96006 Line 35	Mosher and others (2000)	1,800	7	108,474
PGC96006 Line 9A	Mosher and others (2000)	1,800	1.2	13,756
SHIPS Line SG1_2	Mosher and others (2000)	1,800	2.6	181,417
USGS Line P183	Mosher and others (2000)	1,800	2.4	37,146
USGS Line P127	Mosher and others (2000)	1,800	2.4	39,106
Industry Line 2	Mosher and others (2000)	1,800	2.3	65,205
USGS Line 167 and 168	Johnson and others (2001)	1,800	2.7	49,625
USGS Line 166	Johnson and others (2001)	1,800	2.7	40,101
Industry Line 1	Johnson and others (2001)	1,800	2.7	36,021
USGS Line 165	Johnson and others (2001)	1,800	2.7	7,231
USGS Line 164	Johnson and others (2001)	1,800	2.7	33,526
USGS Line 162	Johnson and others (2001)	1,800	2.7	18,446
GSC Line 37	Johnson and others (2001)	1,800	2.7	34,713
USGS Line 176	Johnson and others (2001)	1,800	2.7	54,599
USGS Line 177	Johnson and others (2001)	1,800	2.7	36,941
Mobil M34E	Johnson and others (2004)	1,800	3	70,584
Mobil M34W	Johnson and others (2004)	1,800	3	94,090
SHIPS PS-1	Johnson and others (2004)	1,800	3	49,181
SHIPS PS-2	Johnson and others (2004)	1,800	3	52,325
USGS Line 205	Johnson and others (2004)	1,800	3	50,572
USGS Line 272	Johnson and others (2004)	1,800	3	27,511

Seismic profile name	Source	P-wave velocity (m/sec)	Vertical exaggeration	Length of transect (ft)
USGS Line 284	Johnson and others (2004)	1,800	3	27,486
USGS Line 314	Johnson and others (2004)	1,800	3	14,922
USGS Line 316	Johnson and others (2004)	1,800	3	27,244
Line P183	Kelsey and others (2004)	1,800	2.75	15,160
Sparker	Kelsey and others (2009)	depth provided by author	6	12,657
Big_Beef	Lamb and others (2012)	depth provided by author	2	9,615
Coho	Lamb and others (2012)	depth provided by author	2	5,882
Dewatto	Lamb and others (2012)	depth provided by author	2	25,461
FeatherM	Lamb and others (2012)	depth provided by author	2	18,372
Hite	Lamb and others (2012)	depth provided by author	2	6,693
SR101	Lamb and others (2012)	depth provided by author	2	12,602
Sunset Beach	Liberty (2004)	depth provided by author	1	8,575
Powerline	Liberty (2004)	depth provided by author	1	21,850
Carney Lake	Liberty (2004)	depth provided by author	1	28,774
Bethel–Burley	Liberty (2004)	depth provided by author	1	30,802
Lake Washington	Liberty and Pratt (2008)	2,000	1	20,034
BV1	Liberty and Pratt (2008)	2,000	1	8,000
BV2	Liberty and Pratt (2008)	2,000	1	7,794
SM1	Liberty and Pratt (2008)	2,000	1	11,573
FC1	Liberty and Pratt (2008)	2,000	1	3,959
Snoqualmie Parkway	Liberty and Pape (2006)	depth provided by author	1	15,644
Ames Lake North	Liberty and Pape (2006)	depth provided by author	1	10,833
Ames Lake South	Liberty and Pape (2006)	depth provided by author	1	9,433
River Road North	Liberty and Pape (2006)	depth provided by author	1	16,917
River Road South	Liberty and Pape (2006)	depth provided by author	1	11,287
187th Street	Liberty and Pape (2006)	depth provided by author	1	3,867
Meadowbrook	Liberty and Pape (2006)	depth provided by author	1	14,402
Line PG71-022a	Pratt and others (1997)	3,500	1.5	82,022
Line PG71-022b	Pratt and others (1997)	3,500	1	26,247
195th Street	Sherrod and others (2008)	2,000	1	12,359
Crystal Lake	Sherrod and others (2008)	2,000	1	6,846

Table A2. Parameters for bedrock elevation kriging interpolation. Note that fields followed by (*) denote values calculated using the model optimization tool for the model data. Changes to the input data or running subsections of the model will change these values.

No. of records	304,381
Method	Kriging
Type	Ordinary
Output type	Prediction
Trend type	None
Searching neighborhood	Standard
Type	Standard
Neighbors to include	16
Include at least	5
Sector type	Eight
Angle	0
Major semiaxis	1,180,996*
Minor Semiaxis	1,180,996*
Variogram	Semivariogram
Number of lags	12*
Lag size	98,416*
Measurement error %	100
ShiftON	No
Model type	Stable
Parameter	.893*
Range	1,180,996*
Anisotropy	No
Partial sill	4,948,946*

Table A3. Statistics for inclusion of sediment wells in modeling iterations. Total number of wells represents the number of wells in the sediment dataset that increased the depth to bedrock by greater than 50 ft. Maximum value indicates the greatest improvement, (bedrock depth increase) to the model by a given borehole. Cut-off value represents the minimum improvement to the model for a given borehole included in the model run. Wells included in model are the total number of sediment wells added to the model dataset for each decile run.

Model run no. (decile)	Total number of wells	Maximum value (ft)	Cutoff value (ft)	Number of wells included in model
1	9,483	1,414	210	493
2	7,265	224	132	680
3	6,356	215	97	541
4	4,092	132	80	409
5	3,418	85	67	341
6	2,841	76	55	284
7	2,420	55	46	242

Table A4. Confidence level assigned to data sources for uncertainty estimate. VE, vertical exaggeration. Sediment thickness estimates based on cross sections with vertical exaggerations greater than 5x result in a relatively large amount of error once exaggeration is removed.

Data type	Confidence level
1:24,000-scale geologic maps	5
SSD boreholes	5
geologic cross sections <5x VE	4
seismic track lines with depth provided	3
1:100,000-scale geologic maps	3
WSDOE boreholes	2
geologic cross sections >5x VE	2
seismic track lines with depth calculated	1

Appendix B. Sources of Geologic Mapping

Table B1. List of geologic maps used in construction of the bedrock elevation model not cited in the text.

Map name	Map scale	Citation	Hyperlink
Maple Valley	1:24,000	Booth, D. B., 1995, Surficial geologic map of the Maple Valley quadrangle, King County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2297, 1 sheet, scale 1:24,000.	http://ngmdb.usgs.gov/Prodesc/proddesc_5917.htm
Bellevue South	1:24,000	Booth, D. B.; Walsh, T. J.; Troost, K. G.; Shimel, S. A., 2012, Geologic map of the east half of the Bellevue South 7.5′ x 15′ quadrangle, Issaquah area, King County, Washington: U.S. Geological Survey Scientific Investigations Map 3211, 1 sheet, scale 1:24,000.	http://ngmdb.usgs.gov/prodesc/proddesc_97427.htm
Lilliwaup	1:24,000	Contreras, T. A.; Legorreta Paulin, Gabriel; Czajkowski, J. L.; Polenz, Michael; Logan, R. L.; Carson, R. J.; Mahan, S. A.; Walsh, T. J.; Johnson, C. N.; Skov, R. H., 2010, Geologic map of the Lilliwaup 7.5-minute quadrangle, Mason County, Washington: Washington Division of Geology and Earth Resources Open File Report 2010-4, 1 sheet, scale 1:24,000, with 13 p. text.	http://www.dnr.wa.gov/publications/ger_ofr2010-4_geol_map_lilliwaup_24k.zip
Eldon	1:24,000	Contreras, T. A.; Spangler, Eleanor; Fusso, L. A.; Reioux, D. A.; Legorreta Paulin, Gabriel; Pringle, P. T.; Carson, R. J.; Lindstrum, E. F.; Clark, K. P.; Tepper, J. H.; Pileggi, Domenico; Mahan, S. A., 2012, Geologic map of the Eldon 7.5-minute quadrangle, Jefferson, Kitsap, and Mason Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2012-03, 1 sheet, scale 1:24,000, 60 p. text.	http://www.dnr.wa.gov/publications/ger_ms2012-03_geol_map_ eldon_24k.zip
Lofall	1:24,000	Contreras, T. A.; Stone, K. A.; Legorreta Paulin, Gabriel, 2013, Geologic map of the Lofall 7.5-minute quadrangle, Jefferson and Kitsap Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2013-03, 1 sheet, scale 1:24,000, 19 p. text.	http://www.dnr.wa.gov/publications/ger_ms2013-03_geol_map_lofall_24k.zip
Lake Tapps	1:24,000	Crandell, D. R., 1963, Surficial geology and geomorphology of the Lake Tapps quadrangle [Buckley, Orting, Sumner, and Wilkeson 7.5′ quadrangles] Washington: U.S. Geological Survey Professional Paper 388-A, 84 p., 2 plates, scale 1:24,000.	http://pubs.er.usgs.gov/publication/pp388A
Monroe	1:24,000	Dragovich, J. D.; Anderson, M. L.; Mahan, S. A.; Koger, C. J.; Saltonstall, J. H.; MacDonald, J. H., Jr.; Wessel, G. R.; Stoker, B. A.; Bethel, J. P.; Labadie, J. E.; Cakir, Recep; Bowman, J. D.; DuFrane, S. A., 2011, Geologic map of the Monroe 7.5-minute quadrangle, King County, Washington: Washington Division of Geology and Earth Resources Open File Report 2011-1, 1 sheet, scale 1:24,000, with 24 p. text.	http://www.dnr.wa.gov/publications/ger_ofr2011-1_geol_map_monroe_ 24k.zip
Lake Joy	1:24,000	Dragovich, J. D.; Anderson, M. L.; Mahan, S. A.; MacDonald, J. H., Jr.; McCabe, C. P; Cakir, Recep; Stoker, B. A.; Villeneuve, N. M.; Smith, D. T.; Bethel, J. P., 2012, Geologic map of the Lake Joy 7.5-minute quadrangle, King County, Washington: Washington Division of Geology and Earth Resources Map Series 2012-01, 2 sheets, scale 1:24,000, 79 p. text, 1 Microsoft Excel file.	http://www.dnr.wa.gov/publications/ger_ms2012-01_geol_map_lake_joy_24k.zip
McMurray	1:24,000	Dragovich, J. D.; DeOme, A. J., 2006, Geologic map of the McMurray 7.5-minute quadrangle, Skagit and Snohomish Counties, Washington, with a discussion of the evidence for Holocene activity on the Darrington–Devils Mountain fault zone: Washington Division of Geology and Earth Resources Geologic Map GM-61, 1 sheet, scale 1:24,000, with 18 p. text.	http://www.dnr.wa.gov/publications/ger_gm61_geol_map_mcmurray_24k.zip
Darrington	1:24,000	Dragovich, J. D.; Gilbertson, L. A.; Lingley, W. S., Jr.; Polenz, Michael; Glenn, Jennifer, 2002, Geologic map of the Darrington 7.5-minute quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2002-7, 1 sheet, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_ofr2002-7_geol_map_ darrington_24k.pdf
Carnation	1:24,000	Dragovich, J. D.; Littke, H. A.; Anderson, M. L.; Wessel, G. R.; Koger, C. J.; Saltonstall, J. H.; MacDonald, J. H., Jr.; Mahan, S. A.; DuFrane, S. A., 2010, Geologic map of the Carnation 7.5-minute quadrangle, King County, Washington: Washington Division of Geology and Earth Resources Open File Report 2010-1, 1 sheet, scale 1:24,000, with 21 p. text.	http://www.dnr. wa.gov/publications/ger_ofr2010-1_geol_map_carnation_24k.zip
Sultan	1:24,000	Dragovich, J. D.; Littke, H. A.; Mahan, S. A.; Anderson, M. L.; MacDonald, J. H., Jr.; Cakir, Recep; Stoker, B. A.; Koger, C. J.; DuFrane, S. A.; Bethel, J. P.; Smith, D. T.; Villeneuve, N. M., 2013, Geologic map of the Sultan 7.5-minute quadrangle, Snohomish and King Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2013-01, 1 sheet, scale 1:24,000, plus 52 p. text.	http://www.dnr.wa.gov/publications/ger_ms2013-01_geol_map_sultan_24k.zip
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Map name	Map scale	Citation	Hyperlink
Mount Higgins	1:24,000	Dragovich, J. D.; Stanton, B. W.; Lingley, W. S., Jr.; Griesel, G. A.; Polenz, Michael, 2003a, Geologic map of the Mount Higgins 7.5-minute quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-12, 1 sheet, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_ofr2003-12_geol_map_mount higgins_24k.pdf
Oso	1:24,000	Dragovich, J. D.; Stanton, B. W.; Lingley, W. S., Jr.; Griesel, G. A.; Polenz, Michael, 2003b, Geologic map of the Oso 7.5-minute quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-11, 1 sheet, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_ofr2003-11_geol_map_oso_24k.pdf
Anacortes South and La Conner	1:24,000	Dragovich, J. D.; Troost, M. L.; Norman, D. K.; Anderson, Garth; Cass, Jason; Gilbertson, L. A.; McKay, D. T., Jr., 2000, Geologic map of the Anacortes South and La Conner 7.5-minute quadrangles, Skagit and Island Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2000-6, 4 sheets, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_ofr2000_6_geol_map_anacortess_laconner_24k.zip
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Summit Lake	1:24,000	Logan, R. L.; Walsh, T. J., 2004, Geologic map of the Summit Lake 7.5-minute quadrangle, Thurston and Mason Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2004-10, 1 sheet, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_ofr2004-10_geol_map_summitlake_24k.pdf
Vaughn	1:24,000	Logan, R. L.; Walsh, T. J., 2007, Geologic map of the Vaughn 7.5-minute quadrangle, Pierce and Mason Counties, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-65, 1 sheet, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_gm65_geol_map_vaughn_24k.pdf
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Hoodsport	1:24,000	Polenz, Michael; Miller, B. A.; Davies, Nigel; Perry, B. B.; Clark, K. P.; Walsh, T. J.; Carson, R. J.; Hughes, J. F., 2012a, Geologic map of the Hoodsport 7.5-minute quadrangle, Mason County, Washington: Washington Division of Geology and Earth Resources Open File Report 2011-3, 1 sheet scale 1:24,000, 19 p. text.	http://www.dnr.wa.gov/publications/ger_ofr2011-3_geol_map_hoodsport_24k.zip
Brinnon	1:24,000	Polenz, Michael; Spangler, Eleanor; Fusso, L. A.; Reioux, D. A.; Cole, R. A.; Walsh, T. J.; Cakir, Recep; Clark, K. P.; Tepper, J. H.; Carson, R. J.; Pileggi, Domenico; Mahan, S. A., 2012b, Geologic map of the Brinnon 7.5-minute quadrangle, Jefferson and Kitsap Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2012-02, 1 sheet, scale 1:24,000, with 47 p. text.	http://www.dnr.wa.gov/publications/ger_ms2012-02_geol_map_brinnon_24k.zip
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Sequim	1:24,000	Schasse, H. W.; Logan, R. L., 1998, Geologic map of the Sequim 7.5-minute quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open File Report 98-7, 22 p., 2 plates, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_ofr98-7_geol_map_sequim_24k.zip
Morse Creek	1:24,000	Schasse, H. W.; Polenz, Michael, 2002, Geologic map of the Morse Creek 7.5-minute quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open File Report 2002-8, 18 p., 2 plates, scale 1:24,000.	http://www.dnr.wa.gov/Publications/ger_ofr2002-8_geol_map_morsecreek_24k.zip
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Map name	Map scale	Citation	Hyperlink
East Olympia	1:24,000	Walsh, T. J.; Logan, R. L., 2005, Geologic map of the East Olympia 7.5-minute quadrangle, Thurston County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-56, 1 sheet, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_gm56_geol_map_eastolympia_24k.pdf
Tumwater	1:24,000	Walsh, T. J.; Logan, R. L.; Schasse, H. W.; Polenz, Michael, 2003, Geologic map of the Tumwater 7.5-minute quadrangle, Thurston County, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-25, 1 sheet, scale 1:24,000.	http://www.dnr.wa.gov/publications/ger_ofr2003-25_geol_map_tumwater_24k.pdf
Statewide	1:100,000	Washington Division of Geology and Earth Resources, 2010, Surface geology, 1:100,000 scale—GIS data, June 2010: Washington Division of Geology and Earth Resources, 60.1 MB.	http://www.dnr.wa.gov/Publications/ger_portal_surface_geology_100k.zip