GEOLOGIC MAP OF THE MONROE 7.5-MINUTE QUADRANGLE, KING AND SNOHOMISH COUNTIES, WASHINGTON

by Joe D. Dragovich, Megan L. Anderson,
Shannon A. Mahan, Curtis J. Koger,
Jennifer H. Saltonstall, James H. MacDonald, Jr.,
Gregory R. Wessel, Bruce A. Stoker, John P. Bethel,
Julia E. Labadie, Recep Cakir, Jeffrey D. Bowman,
and S. Andrew DuFrane

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES
Open File Report 2011-1
November 2011

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Peter Goldmark - Commissioner of Public Lands

DISCLAIMER
Neither the State of Washington, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the State of Washington or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the State of Washington or any agency thereof.

INDEMNIFICATION
Research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G10AC00363. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

WASHINGTON STATE DEPARTMENT OF NATURAL RESOURCES
Peter Goldmark—*Commissioner of Public Lands*

DIVISION OF GEOLOGY AND EARTH RESOURCES
David K. Norman—*State Geologist*
John P. Bromley—*Assistant State Geologist*

Washington Department of Natural Resources
Division of Geology and Earth Resources

Mailing Address:	*Street Address:*
MS 47007	Natural Resources Bldg, Rm 148
Olympia, WA 98504-7007	1111 Washington St SE
	Olympia, WA 98501

Phone: 360-902-1450
Fax: 360-902-1785
E-mail: geology@dnr.wa.gov
Website: http://www.dnr.wa.gov/ResearchScience/GeologyEarthSciences/Pages/Home.aspx

Publications List:
http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pubs.aspx

Washington Geology Library Catalog:
http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/washbib.aspx

Washington State Geologic Information Portal:
http://www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/geology_portal.aspx

Suggested Citation: 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 and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2011-1, 1 sheet, scale 1:24,000, with 24 p. text.

Published in the United States of America
© 2011 Washington Division of Geology and Earth Resources

Geologic Map of the Monroe 7.5-minute Quadrangle, King and Snohomish Counties, Washington

by Joe D. Dragovich[1], Megan L. Anderson[2], Shannon A. Mahan[3], Curtis J. Koger[4], Jennifer H. Saltonstall[4], James H. MacDonald Jr.[5], Gregory R. Wessel[6], Bruce A. Stoker[7], John P. Bethel[8], Julia E. Labadie[1], Recep Cakir[1], Jeffrey D. Bowman[1], and S. Andrew DuFrane[9]

[1] Washington Division of Geology and Earth Resources
MS 47007; Olympia, WA 98504-7007

[2] Colorado College
Department of Geology
14 E Cache La Poudre St
Colorado Springs, CO 80903

[3] U.S. Geological Survey
Box 25046, MS 974
Denver Federal Center
Denver, CO 80225-5046

[4] Associated Earth Sciences, Inc.
911 5th Ave, Suite 100
Kirkland, WA 98033

[5] Florida Gulf Coast University
Department of Marine and Ecological Science
Fort Myers, FL 33965

[6] King County Dept of Development and Environmental Services
900 Oakesdale Ave SW
Renton, WA 98057

[7] Earth Systems
19729 207th Ave SE
Monroe, WA 98272

[8] King County Dept of Natural Resources and Parks
Water and Land Resource Division
201 S Jackson St; Seattle, WA 98019

[9] University of Alberta
Dept of Earth and Atmospheric Sciences
1-26 Earth Sciences Building
Edmonton, Alberta, Canada T6G 2E3

INTRODUCTION

The Monroe quadrangle map presented here is the latest of several 7.5-minute scale geologic maps that comprise a years-long mapping effort to document surficial geology and structures in eastern King County and southwestern Snohomish County, a populated region that is seismically active. To further this effort, we have added detailed field observations and several types of geological analyses to existing data, including prior geologic mapping. Major sources of geologic mapping include Tabor and others (1993), Booth (1990), and Associated Earth Sciences (1999, 2002b, 2010). We have also incorporated geotechnical findings from the Washington Department of Transportation, King and Snohomish County Public Works Departments road and bridge engineering studies, and surface and subsurface information obtained by several geotechnical companies for site-specific projects, some of which are referenced below. A data supplement for this study (Dragovich and others, 2011) provides a compilation of radiocarbon, optically stimulated luminescence (OSL), and infrared stimulated luminescence (IRSL) age information for Quaternary deposits and U-Pb age data for a Tertiary tuff. It also includes new geochemical and petrographic data, as well as fault, neotectonic, potential field geophysical, and earthquake hypocenter information and further interpretation of the sedimentary provenance, stratigraphy, sedimentology, igneous petrogenesis, and tectonics of the area. To aid our geographic descriptions, we informally name the uplands covering the southeastern part of the map area the 'southeast highlands' (SE highlands)(see Fig. 3 on map sheet)—an extensive rocky upland from 'High Rock' on the northwest to Cherry Creek on the southeast. Also the finger-like upland north of the Skykomish River, southeast of Woods Creek, and area surrounding age sites OW-8 and OW-5 is informally named 'Cougar Ridge'. We follow the nomenclature of Booth (1990) for the naming of glacial features, such as Vashon proglacial lakes. We herein informally name all the faults, folds, and geomorphic features shown on the geologic map, such as the Monroe fan.

TERTIARY TO QUATERNARY DEFORMATION AND SEDIMENTATION ALONG THE RATTLESNAKE MOUNTAIN AND SOUTHERN WHIDBEY ISLAND FAULT ZONES

Fault Nomenclature, Activity, and General Structure

Geologic mapping of the Monroe 7.5-minute quadrangle is a continuation of our efforts to better understand the connection between the Rattlesnake Mountain fault zone (RMFZ), initially mapped by Walsh (1984) in the North

Bend area, with the southern Whidbey Island fault zone (SWIF). The SWIF was recently extended eastward by Sherrod and others (2008) to the Maltby 7.5-minute quadrangle directly west of the Monroe quadrangle. Dragovich and others (2007, 2009a,b,c, 2010a,b) extended the RMFZ through the Fall City, North Bend, Snoqualmie, and Carnation 7.5-minute quadrangles and correlated this broad fault zone with the SWIF of Sherrod and others (2008). Major faults of the RMFZ in the Carnation 7.5-minute quadrangle directly south of the map area include, from northeast to southwest, the Cherry Valley fault, Snoqualmie Valley faults no. 1, 2, and 3 (SVF-1, -2, -3), and Rattlesnake Mountain faults no. 1 and 5 (RMF-1, -5). The Cherry Valley fault, SVF-1, and the Cherry Creek fault zone are extended into the Monroe quadrangle. (See Dragovich and others [2007, 2009a,b,c, 2010a,b] for earlier mapping of the SVF-1 to -3, and RMF-1 through RMF-11 in the Fall City, Snoqualmie, and North Bend areas.) The northeast-trending Cherry Valley fault zone is conjugate to the northwest-trending RMFZ and likely merges with this major fault zone in the Carnation quadrangle (Dragovich and others, 2010a,b). RMF-1 is the main strand of the RMFZ and was correlated by Dragovich and others (2010a,b) with the Cottage Lake lineament of the SWIF of Sherrod and others (2008), mapped directly southwest of the map area. For the remainder of this document the correlated RMFZ and SWIF composite structure is called the SWIF.

The SWIF from Monroe to the south is likely a strike-slip fault zone and has some active or potentially active fault segments (Dragovich and others, 2007, 2009a,b,c, 2010a,b), some of which align with probable active fault strands mapped by Sherrod and others (2008) in the Maltby area west of this study area. (See Dragovich and others (2010a) for a detailed discussion of individual fault strands, including fault-strand geophysics, structure, certainty, and activity directly south of the map area.) Not all faults in the SWIF are northwest-trending strike-slip faults; reverse faults in the Carnation and Monroe quadrangles include (1) the Carnation faults of Dragovich and others (2010a,b), and (2) the informally named Monroe and Fontal Road faults (this study). These reverse faults are tentatively interpreted to be strike-slip duplex structures and are associated with flexural slip anticlines and synclines that parallel these east- to east-northeast-trending faults. This interpretation is made on the basis of (1) parallelism of these structures, (2) current north–south compression of the Puget Lowland, (3) geophysical data, and (4) limited kinematic data in subsidiary fault zones. The northerly vergence of these reverse faults in the Monroe quadrangle is opposite to the vergence of the Carnation faults to the south. This opposite vergence *may* demark a pop-up or positive flower structure within the SWIF. It is noteworthy that this pop-up occurs where bedrock is shallow or at the surface, such as along the SE highlands. Active uplift of the SE highlands via transpressional reverse faulting may explain the vertical and lateral distribution and structure of ancient Pleistocene alluvial deposits as discussed briefly below.

Current seismicity and outcrop structures indicate that the Cherry Valley fault and the Cherry Creek fault zone are probable active or potentially active structures in the Monroe quadrangle; the remaining mapped faults in the map area are potentially active or not active as discussed further in Dragovich and others (2011). For example, deformation observed in Pleistocene deposits near the Cherry Valley fault differs from the ice-shear soft-sediment deformation noted in advance lake deposits and is interpreted to be of likely tectonic origin. This northwest-trending fault was previously interpreted to be the northeastern boundary of the SWIF in the Carnation area by Dragovich and others (2010a,b). However, our more current mapping suggests that the SWIF is bounded on the north by a fault or faults that control the west-northwest trending Snohomish valley near Monroe. The 1996 Duvall earthquake epicenters (max. M_L=5.3) occurred in the southeastern corner of the Monroe quadrangle and originated at a shallow depth (~2–8 km) along the Cherry Creek fault zone (Dragovich and others, 2010a,b, 2011). This fault zone is an apparent northeast-trending conjugate fault to the SWIF, similar to the northeast-trending Tokul Creek fault in the Snoqualmie 7.5-minute quadrangle (Dragovich and others, 2009a,b).

Some Pleistocene deposits are have distinct liquefaction sedimentary features, particularly pre-Vashon nonglacial deposits but locally including some Vashon deposits. Liquefaction is widespread and also occurs in all ancient alluvial sediments of at least three nonglacial intervals. (See ‘SP’ below.) The extent and intensity of bed liquefaction suggests that Quaternary tectonism is the primary disturbance mechanism, rather than landsliding or glacial ice shear, similar to conclusions of Dragovich and others (2007, 2009a,b,c, 2010a,b, 2011). Liquefaction features include sand dikes, flames, destroyed or chaotic bedding, (rootless) tight to isoclinal folding, and rare dish structures. Some of the best-exposed areas of intense liquefaction are located at significant sites 1G, 37D, 46A, 46W, 49H, and 56B (Dragovich and others, 2011). This liquefaction probably records seismic shaking in saturated ancient alluvial environments.

Pull-Apart and Inverted Basins and Ancient Snoqualmie and Skykomish River Alluvium in Pleistocene Nonglacial Units

Throughout the Snoqualmie valley, ancient Snoqualmie River alluvium representing several nonglacial intervals is pervasive, mappable, and has a vertical and lateral distribution and internal structure that imply significant tectonic control of these old river deposits within the broad SWIF. The distinct Snoqualmie River provenance (SP) of these deposits is discussed in Dragovich (2007) and Dragovich and others (2007, 2009a,b,c; 2010a,b, 2011). SP strata that are similar to modern Snoqualmie alluvium dominate older nonglacial deposits such as Olympia beds (unit Qco) and the Whidbey Formation (unit Qcws). During this study we discovered that Pleistocene nonglacial units in the northern part of the map area are ancient Skykomish River alluvium, which has a provenance very similar to the ancient SP alluvium. 'SP' below refers to ancient and modern alluvium with a Skykomish and Snoqualmie provenance. SP has a distinct granodiorite to granite Tertiary batholith and volcanic provenance signature with significant monocrystalline quartz (~10–20%), plagioclase, volcanic and sedimentary lithic clasts, granitic lithic clasts, and potassium feldspar and lesser, but significant, green pleochroic hornblende and biotite. The ratio of monocrystalline quartz to polycrystalline quartz is distinctly high and comparable to SP nonglacial (units Qco, Qcws, Qch, Qcpf) and modern Skykomish and Snoqualmie River alluvium (unit Qa). Geochemically, SP is very similar to modern alluvium and can be distinguished from glacially derived samples because: (1) nonglacial samples have higher average major element values yet lower average SiO_2 than glacial samples; (2) nonglacial samples have higher abundances of low field strength elements (for example, Pb, Ba, and Sr); and (3) nonglacial samples have higher chondrite-normalized La/Lu ratios (Dragovich, 2007; Dragovich and others, 2010a, 2011). Both the petrography and geochemistry show that nonglacial sands are predominantly derived from an arc source, whereas glacial sands are from arc sources and older accreted sedimentary and metamorphic terranes.

We apply the growth folding, pull-apart, and inverted basin models to the structures and stratigraphic relations we observe within the SWIF and extend these structural-stratigraphic concepts to Quaternary strata. For example, a SWIF pull-apart basin is hypothesized south of the present map area where the Miocene volcanic rocks of Snoqualmie Falls of Dragovich and others (2009a,b) are likely the result of intrusion of the Snoqualmie batholith along RMF-1 around Snoqualmie, synchronous with fault-controlled basin deposition for the volcanic rocks of Snoqualmie Falls within the RMFZ strands. Much younger inversion of sub-basins was hypothesized along the length of the SWIF in the Snoqualmie valley (Dragovich and others, 2007, 2009a,b,c, 2010a,b, 2011; Littke and others, 2009) whereby the Snoqualmie River has been structurally trapped within the SWIF basins during the Pleistocene. Some of this ancient SP alluvium is anomalously thick. It is commonly tilted or broadly folded and is observed at many stratigraphic levels and variable elevated positions along the Snoqualmie and Skykomish valleys. The thickness and structural style of nonglacial SP strata suggest that they are entrained in SWIF pull-apart basins and were locally uplifted to form shortened (formerly extensional) inverted basins. The transition from transtensional to transpressional basins is indirectly evidenced by the exceptional thickness of some of the alluvial basin sediments that are now tilted, folded, and (or) uplifted in blocks between apparent subparallel faults. In this hypothesis, formerly extensional pull-apart basins are uplifted as a result of kinematic changes along the fault zone. We previously postulated that ancient SP sequences up to ~800 ft (~250 m) thick south of the quadrangle formed in fault-controlled transpressional or transtensional basins along the SWIF. In the present study area, geotechnical borings in several locations across the Snoqualmie and Skykomish valleys indicate that micaceous SP Pleistocene sands and silts with peat are 100 to 200+ ft (30–61+ m) thick (for example, Snohomish Co. Dept. of Public Works, 2002). Observations such as these beg the question: To what degree can active SWIF tectonism control the thickness, deformation, and stratigraphic geometry of ancient alluvial sediments in the area. Also, does normal river aggradation allow for alluvial deposits with thicknesses in excess of ~100 ft? Although further work is required, there seems to be a link between the activity of the SWIF strands that bound the inferred basins and the exceptional thicknesses of ancient SP alluvium. Also, our new Quaternary age information combined with outcrop structural data suggest that SP strata, such as the Olympia beds, Whidbey Formation, and Hamm Creek formation of Troost and others (2005), have been uplifted along the Monroe fault inferred along the Skykomish valley and perhaps down-dropped along the inferred Monroe syncline (Cross Section B). For example, the southerly tilt of ancient alluvium in units Qco, Qcws, and Qcpf north of the Skykomish River is tentatively interpreted to be the result of folding along the northern limb of the proposed Monroe syncline. The age, structure, and distribution of ancient SP alluvium suggest that the Skykomish River has migrated southward since the late Pleistocene, possibly as a result of tightening of the Monroe syncline. In this model, the amount of tilting of ancient SP alluvium increases with age, and younger alluvium, such as Olympia beds (unit Qco), are inset against older units, such as the Whidbey

Formation (unit Qc_{ws}). Offset along the Monroe fault may be actively uplifting the SE highlands. Active uplift is suggested by the distribution and internal structure of ancient SP alluvium, the shape of the highlands and surrounding gravity isopachs, and outcrop-scale structures observed in both bedrock and Quaternary deposits. Some uplift of Olympia and Whidbey Formation SP deposits seems likely given the distribution, elevation, age and structure of these SP beds across the map area.

ISOSTATIC GRAVITY AND AEROMAGNETIC ANALYSES FOR THE MONROE QUADRANGLE

Aeromagnetic data come from a project contracted by the U.S. Geological Survey in 1997 (Blakely and others, 1999). An unpublished regional database constrains the isostatic gravity anomalies for this region. (See Anderson and others [2006] for an overview of this database.). Information on data reduction is included in the data supplement (Dragovich and others, 2011). Cross sections produce predictable magnetic and gravity anomalies, constrained by physical property measurements for units in the region (Dragovich and others, 2011). Though all of the andesitic flows of the volcanic rocks of Mount Persis are moderately to highly magnetic (Dragovich and others, 2011), the most magnetic geologic unit of the quadrangle is associated with basaltic flows in the volcanic rocks of Mount Persis (unit Evb_p). These basalts are exposed coincident with one of the strongest magnetic anomalies on the map (BA on aeromagnetic map, Fig. 1 on map sheet) and predominantly control the magnetic anomalies on the map and in the models. We have interpreted that another strong anomaly in the southwest corner of the map (BF, Fig. 1) may be due to large percentages (~50%) of basalts included in the buried Mount Persis units within the Seattle basin. Based on the spatial limitation of the flows within basin accommodation spaces, we interpret the source to be generally east of the map area; flows therefore traveled long distances to be preserved in the ancient lowlands. This interpretation is consistent with the linear shape of magnetic anomaly BC (Fig. 1). This linear geophysical anomaly may reflect an Eocene tributary channel feeding these flows into the basin. Isostatic gravity anomalies largely reflect the Seattle basin deepening westward, thus the overall gradient with decreasing anomaly values to the west. Other smaller amplitude magnetic highs on the quadrangle are likely related to lithologic variations within the Mount Persis between more strongly magnetic andesitic flows and other volcaniclastic and tuffaceous components with low magnetization values. Gravity anomalies strongly support the position of the Cherry Valley fault and its role in producing a large offset on the basement rock with west side down (geophysical model A–A′, Fig. 2 on map sheet), as well as the large vertical offset on the Monroe and High Rock faults (geophysical model B–B′, Fig. 2). Discrete basalt flows modeled at depth on B–B′ may connect to exposed unit Evb_p just to the west of the line (magnetic anomaly BA, Fig. 1). Magnetic anomalies produced by offset of these units by the Monroe and associated reverse faults match our model and strengthen our interpretation of the position and offset along these faults. These large fault offsets imply that the SE highlands are a long-lived geologic feature.

DESCRIPTION OF MAP UNITS

We used the Udden-Wentworth scale (Pettijohn, 1957) to classify unconsolidated sediments, Dickinson's (1970) terminology for sandstones, and Le Maitre and others' (2002) terminology for volcanic rocks. Clinopyroxenes are collectively described as 'augite' but may include other petrographically similar varieties. We use the time scales of the U.S. Geological Survey (USGS Geologic Names Committee, 2007) and Wolfe and others (1998). Description of weathering rinds on basaltic clasts follows the methodology of Colman and Pierce (1981). Thin-section point-count data on the sand-size fractions aids differentiation of several glacial and nonglacial units. An important compositional discriminator for Quaternary strata found in these studies is the average percentage of monocrystalline quartz (Qm) versus quartz-mica tectonite / polycrystalline quartz / chert (Qp) versus potassium feldspar normalized to just the three-component system and shown as $Qm_xQp_xPF_x$ (Dragovich, 2007; Dragovich and others, 2009b, 2010a,b). $Qm_xQp_xPF_x$ provided below were obtained from these previous studies to the south as well as petrographic examination of 41 sand samples from the present map area (Dragovich and others, 2011). Percentages given for individual mineral or lithic grains in the unit descriptions are not normalized and represent the whole clast population.

Quaternary Sedimentary Deposits

HOLOCENE NONGLACIAL DEPOSITS

Qf **Artificial fill and modified land (Holocene)**—Mixed earth materials, including sand and gravel fill and natural deposits that have been disturbed at major construction sites where the original strata have been significantly obscured; includes artificial fill and modified land along parts of State Routes 2 and 203.

Qp **Peat (Holocene)**—Peat, muck, and organic silt and clay, with local thin beds of tephra; loose or soft. Mazama ash is locally interstratified with Holocene peat (Knoll, 1967). Peat occurs in abandoned channels in the Snoqualmie and Skykomish River valleys, as well as in the Cherry Valley alluvial plain and in upland depressions, hummocks, and kettles over low-permeability glacial deposits. These bogs are mapped mostly using LiDAR (Light Detection and Ranging), topographic maps, aerial photographs, and previous mapping of Booth (1990).

Qa **Alluvium (Holocene)**—Sand, silt, (cobble) gravel, gravelly sand, sandy pebble gravel, peat, and organic sediments; sands are gray to yellowish green-gray, weathering orange-gray to yellowish brown; subrounded to rounded clasts; loose; well stratified and sorted; plane-bedded sands, wood debris, and detrital wood are common. The lower-energy Snoqualmie River alluvium consists mostly of sand and silt, with some clay, organic mud, and peat —typical of a meandering river depositional style. The higher-gradient Skykomish River is dominated by cobble gravel deposits—typical of a higher energy, braided river depositional style. Snoqualmie River sand ($Qm_{59\text{-}65}Qp_{12\text{-}29}PF_{12\text{-}26}$) contains distinct monocrystalline quartz, plagioclase, and potassium feldspar, and minor but significant mica and hornblende, and has fewer metamorphic lithic clasts, chert, and polycrystalline quartz than northern-sourced glacial deposits. These sands are compositionally similar to ancient SP alluvium in pre-Fraser nonglacial alluvium (units Qc_o, Qc_{ws}, Qc_h, and Qc_{pf}) and have a Snoqualmie batholith and Tertiary volcanic igneous signature and an intermediate, continental-arc geochemistry (Dragovich, 2007; Dragovich and others, 2007, 2009a,b,c, 2010a,b, 2011). Skykomish River alluvium is compositionally very similar to Snoqualmie River alluvium, due to the similar basin geology, and contains distinct monocrystalline quartz, plagioclase, and potassium feldspar, and minor but significant mica and hornblende. Granitic lithic clasts are significant and the provenance is strongly influenced by the Tertiary granitic to granodioritic bodies, such as the Index and Grotto batholiths (Dragovich and others, 2011). Similar to Snoqualmie River sands, the geochemistry of Skykomish River sands suggests they were derived from an intermediate, continental-arc source (Dragovich and others, 2011). Woods Creek alluvium channel deposits located in the northern part of the study area are mostly pebble gravel and gravelly sand derived from local sources. Subsurface information suggests that modern alluvium is typically thin (~10–50 ft; ~3–4.5 m thick) over much of the map area (Cross Sections A and B). Associated Earth Sciences (2001b) obtained a radiocarbon age of 1,760 ±70 yr B.P. from wood in Snoqualmie River alluvium directly south of the quadrangle near the intersection of Novelty Hill Road and Snoqualmie Valley Road (Dragovich and others, 2010a). Locally divided into:

Qa_l **Levee deposits (Holocene)**—Sand, silt, and mud; brownish gray to yellowish brown; subrounded to rounded clasts; loose; well stratified and sorted; plane bedded to ripple cross stratification common, with local bioturbation. Levees are mapped only along the current margins of Snoqualmie and Skykomish River channels where wedge-shaped accumulations of overbank flood sediments are observable on topographic and contoured lidar-based maps. Levees form at the edges of channels where floodwaters lose much sediment-carrying ability as rising floodwaters decelerate. The contact with the broad valley floodplain is inferred from the contoured lidar data where the wedge grades into the flatter floodplain.

Qoa **Older Alluvium (Holocene to latest Pleistocene)**—Cobble gravel to pebble gravel, sand and silt with minor peat, and organic sediments; sands are gray to brown; subrounded to rounded clasts; loose; well stratified and sorted; plane-bedded sands common. Older alluvium is mapped along the margins of the Skykomish valley as terraced bodies that are elevated 10 or more feet (several meters) above the floodplain and are inset against Pleistocene glacial and nonglacial deposits. Contacts are the result of field mapping, lidar elevation information, and previous mapping by Booth (1990), who also mapped several unit Qoa bodies north of the Skykomish River in the adjacent Sultan quadrangle. We cannot distinguish between Skykomish River fluvial incision due to changes in base level or sediment input and (or) incision due to tectonic uplift as the cause of the isolation of these elevated terraces (Dragovich and others, 2011).

Qls **Landslide deposits (Holocene to latest Pleistocene)**—Diamicton or boulder gravel; contains minor sand or gravel beds where locally modified by stream processes; includes a few areas of thick colluvium; loose or soft; typically poorly sorted and nonstratified. Clasts are angular to subangular where derived from bedrock, but may contain mostly rounded clasts where landslides originate in Quaternary deposits. Landslides include rock falls, slump-earthflows, debris slumps, and debris flows. (See Varnes, 1978a,b, landslide classification system.) This unit may include chaotic, stratified slump blocks or debris-flow aprons originating from unstable recessional deposits perched on hillsides, particularly kames and recessional deltas. Not shown are the numerous thin debris-flow chutes evident on some steep slopes by lidar. Some landslides may be seismically induced or initiated during late Pleistocene deglaciation.

Qaf **Alluvial fan deposits (Holocene to latest Pleistocene)**—Debris-flow diamicton, alluvial sand and gravel, and local boulder gravel; loose; mostly poorly to moderately sorted; massive to moderately stratified. The reduced gradient where streams emerge from confining valleys causes some of the sediment load to be deposited as a fan. Deposits mapped as unit Qaf were distinguished from those in unit Qls by location and the regular lobate geomorphology of alluvial fans. Fans were partly distinguished using lidar elevation data. Some fans may have initiated as fan deltas that graded to glacial lake Snoqualmie or Skykomish at the close of the last glaciation. (See ‘Monroe fan’ discussed in unit Qgod.)

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Recessional Deposits of the Vashon Stade of the Fraser Glaciation

Recessional sands have a mixed local (Cascade Range) and northern metamorphic-granitic provenance. For example, most recessional sediments contain more local Cascade-provenance mélange belt and Tertiary volcanic provenance clasts, such as metasandstone, meta-argillite, metachert, greenstone, volcanic lithic clasts, amphibolite, and serpentinite, with low monocrystalline-quartz grain content and polycrystalline quartz greater than monocrystalline quartz (Dragovich, 2007; Dragovich and others, 2009b; 2010a,b, 2011). As compared to average SP strata (for example, units Qc_o and Qa; $Qm_{56\text{-}59}Qp_{26\text{-}31}PF_{13\text{-}14}$), average recessional sands contain little potassium feldspar ($Qm_{\sim41}Qp_{\sim56}PF_{\sim3}$) due to the scarcity of this mineral in metamorphic and plutonic rocks of the Cascades directly north and east of the map area. Their geochemistry also suggests a mixed arc and sedimentary source (Dragovich and others, 2011). Vashon deglaciation in the map area commenced about 14,000 yr B.P. along the Cascade Range foothills directly to the east, and the map area was fully deglaciated by about 13,500 yr B.P. (Porter and Swanson, 1998). The Puget lobe ice front receded across the map area in a northwesterly direction, depositing recessional ice-contact, fluvial, deltaic, and lacustrine sediments. Many of these facies are laterally and vertically gradational and commonly interfinger. During ice recession, a series of ice-marginal lakes and connecting glaciofluvial channels formed behind the retreating ice lobe; the geometry, inset relations, and elevation of these deposits reflect a general lowering of base level as lower valleys successively became deglaciated and new spillways emerged during ice recession. These spillways controlled the level of glaciolacustrine lakes and connecting channels that migrated westward and northward during deglaciation (Knoll, 1967; Booth, 1990; Porter and Swanson, 1998). Booth (1990) subdivided recessional outwash deposits into five stages of deglaciation and emphasized the importance of both ice-marginal and subglacial meltwater paths. For example, some of the small southwest-trending valleys traversing the glacial uplands may have originated as channels in subglacial tunnels. Our mapping also shows that ice-marginal meltwater followed several elevated pathways during glacial recession, depositing kame and lake sediments. Inset recessional outwash bodies are graded to a local base level that lowered over time and resulted in younger inset recessional deposits. Glacial lake Snoqualmie was an ice-dammed lake that covered Snoqualmie valley during deglaciation (Mackin, 1941; Booth, 1990; Dragovich and others, 2007, 2009a,c, 2010a,b). Glacial lakes Snoqualmie and Skykomish of Booth (1990) were two separate proglacial lakes that likely merged as ice tongues receded down the Snoqualmie and Skykomish valleys to the area near the City of Monroe.

Qgl_r **Recessional glaciolacustrine (glacial lake) deposits (Pleistocene)**—Silt, clayey or sandy silt, and silty sand, typically with scattered dropstones (stones dropped from melting icebergs); may contain lenses and beds of sand or gravel; loose or soft; massive, laminated to thinly bedded with some varve-like rhythmites; kame lake deposits may contain some soft-sediment deformational features. Sediments mostly deposited in relatively small proglacial lakes formed in kames or other upland ice-marginal settings. Upward-coarsening sequences may begin as glacial-lake deposits (units Qgl_r and Qgos) and grade into overlying terrestrial deposits (unit Qgof) as a result of progradation of fluvial-deltaic complexes. Upward-fining sequences record waning lake sedimentation during ice recession.

Qgos **Outwash sand (Pleistocene)**—Sand and pebbly sand, with some interbeds of silty sand, silt, or gravel; sands typically dark blue-gray; loose or soft; varies from nonbedded to weakly stratified to plane bedded, laminated, and rarely crossbedded. Vertical and horizontal fining trends indicate deposition mostly as shallow-water glaciolacustrine deposits. Unit Qgos complexly interfingers with recessional lake deposits (unit Qgl_r), fluvial deposits (unit Qgof), and deltaic deposits or kame deltaic deposits (unit Qgod). Some unit Qgos sands coarsen upward into unit Qgod sands and gravels, and often fine downward to unit Qgl_r silty lake deposits due to deltaic progradation.

Qgod **Deltaic outwash and kame deltas (Pleistocene)**—Sandy cobble gravel, gravel, pebbly sand, and minor sand; sands are typically dark blue-gray, weathering to yellowish brown; loose; moderately to well sorted; thin to very thickly bedded and well stratified. Deltas have high-amplitude planar foreset beds graded to temporary ice-dammed lake levels. This unit includes either deltaic front portions of kames or ice-free deltas graded to varying glacial levels. Delta sediments have a distinct Cascade or local provenance similar to unit Qgof (for example, Dragovich and others, 2010a). It is common for deltaic deposits to grade laterally to bottomset beds of glaciolacustrine sand (unit Qgos) and silt or clay (unit Qgl_r). Gravels (unit Qgof) that cap deltas were fed by upland braided rivers, which vigorously incised the newly exposed and unstable upland surfaces. Non-kame deltas lack evidence for near-ice deposition and are thus mostly younger than nearby ice-contact deposits. The Woods Creek delta-front beds dip west to south as determined from measurements in past sand and gravel pits within Monroe (this study and Booth, 1990), and the delta is a large complex of glaciofluvial, deltaic, and glacial-lake deposits that was sourced by the early outwash channels on the Woods Creek outwash plain (unit Qgof). The complex likely prograded significantly into glacial lake Skykomish, forming a lobate delta front. Fluvial terraces on the delta top record incision as glacial lakes dropped during glacial recession. The delta complex has a persistent glaciofluvial-delta front interface at about 180 to 200 ft (55–61 m) in elevation, similar to the front interface to parts of the nearby High Rock kame complex on the SE highlands. Although conjectural, this similarity in delta tops suggests a similar age. The Woods Creek delta and High Rock kame complex might have formed a compound deltaic system that followed an ice margin occupying the northwestern portion of the Monroe quadrangle prior to glacial lake Snoqualmie merging with glacial lake Skykomish—thus the High Rock kame complex might have formed an ice-contact meltwater pathway between glacial lakes Snoqualmie and Skykomish. The varying elevation of these proglacial lakes controlled the altitude of many delta tops, recessional channels, and the distribution of most glaciolacustrine deposits. For example, it is apparent that delta tops are graded to lowering glacial lakes Snoqualmie and Skykomish during deglaciation as ice receded in a north-northwesterly direction, with delta deposits at successively lower elevations, such as in the High Rock kame complex. We suggest that the Monroe fan (~60–70 ft apsl elevation) is a subtle low-elevation deposit that graded to the final glacial lake episode in the Snohomish, Skykomish, and Snoqualmie valleys and represents the youngest Vashon glacial deposits in the quadrangle. This fan is (1) graded to a glacial lake level of about 60 to 70 ft (18–21 m)(Cross Section B), and (2) evident on lidar. The elevated Woods Creek delta is likely partially preserved as a result of the southern deflection of the Skykomish River by the lower elevation latest Pleistocene Monroe fan. This fan has been defended against Holocene Skykomish River erosion by dense Olympia beds that underlie the Monroe fan and are presently exposed along the terminus of Woods Creek. Borings and test pit observations indicate that the Monroe fan forms a coarsening upwards sequence from sands to cobble gravel as a result of latest glacial deltaic progradation into the emergent Skykomish valley. Sands along the subtle western portion of the delta front are overlain by Holocene Skykomish River overbank sediments (Associated Earth Sciences, 2000).

Qgof **Fluvial outwash deposits (Pleistocene)**—Bouldery cobble gravel, gravel, pebbly sand, sand, and rare silt; loose; moderately to well stratified; commonly contains medium to very thick subhorizontal beds, local bar or ripple crossbedding, and rip-up clasts. This unit lacks ice-contact sedimentary structures and other geomorphic and stratigraphic evidence for nearby ice deposition, although unit Qgof in the High Rock kame complex was likely ice-proximal. Unit Qgof was deposited as broad braided-river outwash sediments along valley trains (Woods Creek outwash plain) or as topset beds on deltas (unit Qgod), including the Woods Creek delta. Valley trains are typically southwest-trending recessional meltwater pathways incised into older glacial deposits. Outwash terraces and meltwater channels generally decrease in elevation to the west and southwest. Fluvial outwash terraces above deltas are due to fluvial incision as glacial lake Skykomish or Snoqualmie levels dropped. The incision, dropping lake levels, and migrating delta fronts results in compound nested deltas.

Qgic **Ice-contact deposits, undivided (Pleistocene)**—Bouldery cobble gravel with lesser diamicton, silty pebbly gravel, and (pebbly) sand and silt; loose; mostly moderately stratified and medium to very thickly bedded; variably sorted with abrupt grain-size changes common. Ice-contact primary structures include oversteepened and contorted bedding and other ice-shear or slump features producing variably dipping strata. Soft melt-out, flow, and water-laid diamictons are interstratified with granular supraglacial, englacial, and subglacial meltwater deposits observed rarely (see subglacial depositional model of Booth, 1984, 1986, 1990). The upper surface is typically hummocky and contains numerous kettle depressions, indicating sedimentation in, around, and on stagnant or active ice in moraine and pitted outwash-plain settings. Active ice recession in the Monroe quadrangle is evidenced by the general lack of ice-contact deposits with kettled and hummocky dead-ice geomorphology. Locally divided into:

Qgik **Ice-contact kames (Pleistocene)**—Sand and gravel, pebbly sand, sand, and cobble gravel, with rare lenses of diamicton (mostly flow till or melt-out till from buried sediment-laden ice blocks); sands are typically dark yellowish gray to gray; loose; moderately to well stratified and commonly medium to very thickly bedded; contains till or silt rip-up clasts, crossbedding, cut-and-fill structures, and localized oversteepened or slumped bedding. Receding ice tongues likely occupied the Snoqualmie and Skykomish valleys during recession (this study; Dragovich and others, 2010b; Minard, 1985; Minard and Booth, 1988; Booth, 1990). These elevated fluvial deposits were mapped where sedimentary structures, geomorphology, and (or) geologic setting imply lateral ice-buttressing. A wasting ice tongue impinged upon the SE highlands during ice recession, resulting in perched ice-contact deposits, such as the High Rock kame complex, veneering parts of the valley walls. Unit Qgik may include some undivided kame delta deposits. In some kames, the fluvial deposits grade laterally into or overlie divided kame deltas (unit Qgod) and (or) proglacial lake deposits (units Qgos and Qgl_r), forming coarsening-upward deposits.

Qgog **Outwash gravel deposits, undivided (Pleistocene)**—Bouldery pebble cobble gravel to pebbly sand; loose; massive to crudely bedded; deposited mostly as ice-contact deposits, including kame outwash bodies, but may include any of the gravelly Vashon recessional facies, including fluvial outwash. We were were unable to assign a depositional environment to these gravelly recessional deposits because of their generally poor exposure. Similar to the Carnation quadrangle directly to the south (Dragovich and others, 2010b), the current map area apparently lacks the late-glacial strandlines and associated glacial lake beach deposits (unit Qgog) mapped in the Fall City and North Bend quadrangles by Dragovich and others (2007, 2009a,c).

Advance Proglacial and Subglacial Deposits of the Vashon Stade of the Fraser Glaciation

Deposits related to the Vashon Stade of the Fraser Glaciation of Armstrong and others (1965) occur widely across the study area. Glacial ice and meltwater deposited drift and carved extensive areas of the southern Puget Lowland into a complex geomorphology that provides insight into latest Pleistocene glacial processes. Throughout the map area, numerous drumlins and flutes reveal that Puget lobe ice advanced over the map area from northwest to southeast (azimuth ~140–150°). Ice advance occurred about 14,500 yr B.P. and blocked ancient rivers, creating extensive temporary ice-dammed lakes across much of the area (Mackin, 1941; Booth, 1990). The resulting glacial lake deposits (unit Qgl_v) are widespread and complexly interlayered with proglacial river and delta sediments (unit Qga_v). Facies relations between units Qga_v and Qgl_v, as well as thickness and areal distribution, indicate that one or more large proglacial lakes progressively occupied significant portions of the map area during ice advance, similar to findings south of the map area (Knoll, 1967; Dragovich and others, 2007, 2009a,c, 2010b). Advance outwash (average ~$Qm_{40}Qp_{54}PF_6$) and lake deposits are similar to other glacial outwash deposits, are a mixture of northern and local Cascade detritus, and have a predominantly intermediate igneous provenance geochemistry with contributions from accreted sedimentary or metamorphic material (Dragovich, 2007; Dragovich and others, 2009b, 2010a,b, 2011). Sands are polycrystalline quartz-rich, polymictic sediments, typically containing significant volcanic and granitic lithic clasts, plagioclase, and metamorphic and sedimentary lithic clasts. Advance outwash contains lower amounts of monocrystalline quartz and potassium feldspar than SP deposits such as the Olympia beds (unit Qc_o, average $Qm_{59}Qp_{26}PF_{14}$). Bedding is common in Vashon deposits. Beds in advance outwash and lake deposits commonly have a primary dip to the east, southeast and south as a result of glaciofluvial or deltaic deposition away from the advancing ice and into temporary glacially dammed lakes or onto steep-gradient and high-energy braided streams sloping away from the advancing ice front. Thus dips of Vashon strata shown on the geologic map record subtle paleocurrent directions and primary bedding sloping away from the ice as foreset beds on deltas or the lee side of fluvial bar deposits and probably do not indicate significant tectonic tilting. This differs from the ancient alluvial nonglacial deposits (for example, unit Qc_o) which are dominated by overbank (flood) sediments having originally sub-horizontal primary bedding deposited along flat alluvial floodplains.

Qgt_v **Vashon lodgment till (Pleistocene)**—Mixture of clay, silt, sand, and gravel (diamicton) with rare lenses of sand and gravel; grayish blue to very dark gray; locally slightly weathered to mottled yellow-brown; dense; matrix-supported; unsorted with disseminated cobbles and boulders in a silt-sand matrix; unstratified; locally contains a friable shear fabric as a result of ice shear. Clast types include both northern-source and local rounded to subangular clasts. Till on the uplands unconformably overlies advance deposits, older Quaternary deposits, and bedrock. This unit may contain angular clasts where directly overlying local bedrock. Basalt-clast weathering rinds are less than 0.5 mm. Till is generally about 5 to 50 ft thick (Cross Sections A and B) and was accreted at the base of Vashon ice.

Qga_v **Vashon advance outwash (Pleistocene)**—Sandy (pebble) gravel, sand, and cobble gravel, with local silt interbeds; sands are typically dark green-gray, weathering to (light) yellowish brown; dense; mostly well sorted and stratified; thinly to very thickly bedded; local laminated silt interbeds and (or) rip-up clasts; contains deltaic and bar foreset beds, cut-and-fill structures, and rare ice-shear structures in some outcrops. Basalt clast weathering rinds are less than 1.0 mm. Unit Qga_v was deposited by streams emanating from the advancing ice front and is complexly interlayered with, conformably overlies, or may locally underlie glacial-lake deposits (unit Qgl_v). Advance outwash deltas occupied parts of Skykomish and Snoqualmie valleys and prograded into smaller proglacial lakes along the southeastern part of the SE highlands with distinct deltaic foreset beds mapped in the area northwest of Johnson Swamp and Lake Fontal. Advance outwash may include some fluvial-deltic kame sediments deposited between advancing ice and restrictive highlands and is overlain by Vashon lodgment till (unit Qgt_v) along a sharp contact. Composite sections of fluvial-deltaic advance outwash and glacial-lake deposits are fairly thick in the Snoqualmie and Skykomish valleys where fluvial-deltaic deposits prograded into proglacial lakes during ice advance. Radiocarbon ages from south to southwest of the map area are 14,500 ±130 yr B.P. (Associated Earth Sciences, 2003; Dragovich and others, 2007) and 14,450 to 14,560 yr B.P. (Porter and Swanson, 1998). Local and regional radiocarbon ages for the older Olympia beds (unit Qc_o and Qc_{ol}) provide additional age constraints (for example, Dragovich and others, 2010a, 2011).

Qgl_v **Vashon advance glaciolacustrine deposits (Pleistocene)**—Silt, clayey silt, pebbly silt, and diamicton; typically contains scattered dropstones and beds or lenses of massive diamicton that may be iceberg melt-out till or flow till; stiff or dense; stratification and sorting variable; varies from massive to thinly bedded, laminated, or varved. Some lenticular diamicton beds in unit Qgl_v have a till-like appearance. Several exposures are mostly diamicton with thin, wispy interbeds of silt or laminated silt and fine sand. Some outcrops contain contorted or folded bedding and rare sand dikes. Folded sand and silt beds at significant sites 25M and 27C are likely the result of glacial ice shear. Conversely, distinct sand dikes that intrude unit Qgl_v beds of diamicton, pebbly silt, and gravel observed at significant site 3C may be the result of earthquake liquefaction. Basalt clast weathering rinds are less than 0.5 mm. Unit Qga_v typically overlies unit Qgl_v regionally, but unit Qga_v underlies thick successions of unit Qgl_v in some areas; in other areas the two units are complexly interbedded. Unit Qgl_v includes some of the transitional beds of Booth (1990) and correlates with the Lawton Clay mapped elsewhere in the Puget Lowland.

Deposits of the Olympia Nonglacial Interval

Qc_o **Olympia beds of Minard and Booth (1988), Snoqualmie and Skykomish River provenance (Pleistocene)**—Sand, sandy silt, silty sand, and silt, with some clay, organic silt-clay, and minor peat; gravel beds are more common in ancient Skykomish alluvium (see below); typically yellowish brown-gray to grayish brown with distinctive orange-gray oxidation; dense; laminated to very thickly bedded and well stratified. Unit Qc_o contains charcoal, disseminated detrital organic matter, trough and ripple crossbedding, graded beds, sand dikes, chaotic or folded bedding, and flutes with rare dish structures. Thick exposures of orangish well-bedded sand and silt (fluvial overbank deposits) that form thick, upward-fining pebbly sand–sand–silt sequences typical of meandering river systems are the norm. Lenticular beds of sand and gravel represent channel deposits; some exceptionally thick beds of sand are probably fluvial levee or splay overbank deposits. Unit Qc_o is the “ancient Snoqualmie River alluvium” ($Qm_{40\text{-}82}Qp_{10\text{-}46}PF_{8\text{-}26}$) of Dragovich (2007) and Dragovich and others (2007, 2009a,b,c, 2010a,b, 2011). Ancient Skykomish River alluvium is mapped in the Skykomish valley around the city of Monroe and areas to the east, and is compositionally and geochemically very similar to ancient Snoqualmie River alluvium (Dragovich and others, 2011). Compared to glacial deposits, ancient river deposits of the Snoqualmie and Skykomish Rivers alluvium contain more potassium feldspar (up to ~10%) and limited amounts of polycrystalline quartz, and have the same SP signature as units Qc_{pf}, Qc_{ws}, and Qc_h. Sands from this unit are geochemically dacitic to rhyolitic and were predominantly derived from an intermediate to slightly primitive arc source with minor mixing from older accreted sedimentary and metamorphic sources (Dragovich and others, 2010a,b, 2011). Olympia bed sands at age site 24D on the northeastern part of the SE highlands contain a higher percentage of more diverse lithic grain types and slightly more serpentinite, metasedimentary lithic clasts, and polycrystalline quartz, suggestive of mixing of ancient Skykomish River alluvium with alluvium derived from the Western mélange belt to the east. We suspect these beds incorporated older Quaternary sediment as the ancient Skykomish River incorporated emerging local highlands detritus. Other beds at this site contain the distinctive ancient Skykomish River composition, with significant monocrystalline quartz, potassium feldspar, and minor but significant hornblende and mica. Multiple Olympia bed ages from 17,150 yr B.P. to >44,020 yr B.P. were obtained previously by Associated Earth Sciences (2001a, 2002a, 2004, 2007) and Dragovich and others (2007, 2009a,b,c, 2010a,b) in quadrangles south of the map area, including the Carnation 7.5-minute quadrangle directly south of the quadrangle. These beds have a distinct SP composition and were assigned to the Olympia nonglacial interval (~15–60 ka). We have obtained several new radiocarbon ages in the present quadrangle, including ages of 17,500 ±80 yr B.P. and 19,920 ±130 yr B.P. from age site 56A. We also obtained radiocarbon ages of 18,703 ±110 yr B.P., 24,790 ±170 yr B.P., and >43,500 yr B.P. from age sites 50H, 49E, and 24D, respectively. Finally, we obtained two infrared-stimulated luminescence (IRSL) ages of ~50,500 and 51,500 yr B.P. (50.5 ±3.53 and 51.5±3.84 ka) from age sites 24A and 24D near Monroe and along the northeastern slope of the SE uplands. Unit Qc_o within the SWIF to the south of the area is locally folded and uplifted into ‘inverted basins’(Dragovich and others, 2010a; Littke and others, 2009). Similarly, the distribution of Olympia bed ages around the Skykomish River, combined with the structural geometry and elevation of these beds, suggests uplift of unit Qc_o along the proposed Monroe fault. In this scenario, the elevation difference between ancient Skykomish River alluvium (unit Qc_o), exposed along the present river and perched along the northeastern slopes of the SE highlands, is at least partially the probable result of folding and uplift across the tentatively mapped Monroe fault, suggesting a potentially active structure. The orientation of bedding in pre-Fraser SP deposits in the area north of the Skykomish River indicates that these units are tilted to the south, perhaps as a result of folding around the proposed Monroe syncline. Bedding in these ancient alluvial sediments was originally horizontal, likely deposited on the floodplain as overbank material during floods. We believe the measured southerly tilt is the result of tectonism. (See persistent southerly dipping strata in units Qc_o, Qc_{ws}, and Qc_{pf} north of the Skykomish River on the geologic map.) Olympia beds include some of the transitional beds of Booth

(1990) and correlate with the deposits of the Olympia nonglacial interval of Pessl and others (1989). (See “Pull-Apart and Inverted Basins and Ancient Snoqualmie and Skykomish River Alluvium in Pleistocene Nonglacial Units” above and Dragovich and others [2007, 2009a,b,c, 2010a,b, 2011] for more information.) Locally divided into:

Qc_{ol} **Olympia beds of Minard and Booth (1988), local provenance (Pleistocene)**—Silt, sand, and (pebble) gravel, with some peat and organic sediments, including paleosols; dense; thickly to thinly bedded and well stratified and sorted. Unit Qc_{ol} sediments were mapped only on Cougar Ridge in the northern part of the map area, but this thin unit may be present in the subsurface in other parts of the quadrangle. Sands encountered in boreholes on Cougar Ridge contain significant numbers of lithic mélange belt grains of metamorphic and Tertiary volcanic provenance, including metasandstone, meta-argillite, and greenstone. This detritus is eroded and recycled from nearby older glacial and nonglacial units and bedrock, and has a provenance that is petrographically distinct from the SP provenance described for unit Qc_{o}. The geochemistry of unit Qc_{ol} sediments in the Carnation quadrangle (Dragovich and others, 2010a) is consistent with our local-source interpretation for these lithic-rich deposits. Unit Qc_{ol} sediments were deposited in alluvial, alluvial fan, and swamp settings, and likely represent small ancient-tributary basin deposits of limited extent. A similar local geologic setting was envisioned for Redmond Ridge southwest of the Monroe quadrangle in the westernmost part of the Carnation quadrangle and the easternmost part of the Redmond 7.5-minute quadrangle where several finite radiocarbon ages (n = 11) were derived from similar unit Qc_{ol} strata. Radiocarbon ages in that area ranged from 29,730 ±260 B.P. to 45,540 ±1,930 B.P., but also include several infinite radiocarbon ages (n = 19)(Saltonstall and others, 2003; Associated Earth Sciences, 2001a,b, 2002a, 2004, 2007; Dragovich and others, 2010a,b). In the present study area, a thin (~10 ft; 3 m) sequence of unit Qc_{ol} strata underlies recessional and advance outwash (units Qgof and Qga_{v}) and overlies probable Possession glacial deposits (unit Qgl_{p}) on Cougar Ridge (Associated Earth Sciences, 1999). We obtained radiocarbon ages of 23,090 ±110 yr B.P. and 38,660 ±390 yr B.P., respectively, from age site samples OW-8 and OW-5 at respective geotechnical drill hole sample depths of 75 and 35 ft (23 and 11 m)(Dragovich and others, 2011). The contact between the Olympia beds and Possession glacial deposits appears to dip to the south as a result of either original paleogeography and (or) tectonic tilting on Cougar Ridge.

Deposits of the Possession Glaciation

Qgl_{p} **Glaciomarine and glaciolacustrine deposits (Pleistocene)**—Silt, silty clay, and silt with scattered gravel (dropstones) and lesser sand and diamicton; hard or dense; moderately to well sorted and typically massive or moderately stratified, with laminations common (Associated Earth Sciences, 1999). Diamictons and silts with scattered gravels encountered in boreholes on Cougar Ridge are probable glaciomarine drift (reacts with HCl). These deposits are probable ice-distal marine deposits with dropstones. Unit Qgl_{p} lies below Olympia beds dated in the subsurface at 23,090 ±110 and 38,660 ±390 yr B.P. (See unit Qc_{ol} above.) Possession glacial deposits were also mapped in the Carnation quadrangle directly south of the present map area by Dragovich and others (2010a,b) and Associated Earth Sciences (2004 and 2007).

Whidbey Formation

Qc_{ws} **Whidbey Formation, Snoqualmie and Skykomish River provenance (Pleistocene)**—Sand, silt, and silty sands with lesser pebbly sand, clay, gravel, organic sediments including peat, and lesser lenses of (cobble) gravel; sands are yellow-gray or brown and weather to a distinctive orange-gray; dense or hard; well sorted and stratified; mostly occurs as laminated to thickly bedded sands and silts with thin beds or laminae of clay locally; commonly plane bedded; may contain charcoal, disseminated organic matter, trough and ripple crossbedding, graded beds, flutes, flames, sand dikes, and dish structures; folds and chaotic bedding are evident in liquefied areas. These SP sands are generally lithic poor and contain abundant monocrystalline quartz (~20%) with lesser but significant potassium feldspar, granitic lithic clasts, hornblende, and mica similar to units Qa, Qc_o, Qc_h, and Qc_{pf}. Geochemically, they were predominantly derived from an intermediate arc source with minor sedimentary or metamorphic input (Dragovich and others, 2010a,b, 2011). Sands microscopically appear to be more weathered at some sites (for example, age site 24E) than the younger nonglacial sands. We obtained an IRSL age of 123 ± 8.24 ka (~123,000 yrs B.P.) at age site 24E north of Monroe. The position of the unit along the northern limb of the Monroe syncline, combined with outcrop structure and distribution of the nonglacial SP, suggests that the younger Olympia beds are inset against the Whidbey Formation along the northern limb of this syncline (Cross Section B). We also obtained OSL ages of 101 ± 4.47 ka and 107 ± 9.87 ka at age sites 25A and 25B, as well as radiocarbon ages of 40,000 ±350 yr B.P. and >43,500 yr B.P. at age sites 22A and 25A from thick, crossbedded ancient SP sands and pebbly sands that underlie advance outwash in the Cadman quarry on the western SE highlands (Dragovich and others, 2011). The finite age of 40,000 ±350 yr B.P. is interpreted to be the result of contamination by modern organics. We correlate these strata with the Whidbey Formation (~80,000–130,000 yr B.P.) on the basis of age, composition, and stratigraphic position. This ancient Snoqualmie River alluvium is elevated (410 ft or 125 m apsl) and likely has been uplifted by offset along the Cherry Valley and (or) Monroe faults. Ages of ~122 to 128 ka were obtained from unit Qc_{ws} in the Carnation quadrangle. (See Dragovich and others [2007, 2009a,c, 2010a,b] for previous mapping and dating of the Whidbey Formation south of the Monroe area and Capps and others [1973] for mapping of the Whidbey Formation directly west of the Monroe map area.)

Deposits of the Double Bluff Glaciation

Qgt_d **Double Bluff till (Pleistocene)**—Dominantly diamicton; very dense and massive. Basaltic clasts have distinct 1 to 2 mm weathering rinds. This older till is overlain by probable Whidbey Formation sands and silts with a distinct southerly tilt in a steep ravine north of Woods Creek in the northernmost part of the map area. We obtained an age of 123 ± 8.24 ka at age site 24E for the overlying unit Qc_{ws} sediments west of the ravine. A correlation with the Double Bluff Drift (~130-180? ka) of Easterbrook and others (1967) is made on the basis of this age and the moderate weathering characteristics of the till, analogous to the probable Double Bluff Drift in the Carnation area where Dragovich and others (2010a,b) dated similar overlying unit Qc_{ws} strata to 122 to 128 ka. Unit Qgt_d tills are distinctly less weathered than some older glacial tills in the Snoqualmie valley south of the map area, such as unit Qgd_{pd} of Dragovich and others (2010b), tills in unit Qgn_{pf} of Dragovich and others (2009a,b), or old glacial deposits described in Booth (1990).

Deposits of the Hamm Creek Formation of Troost and Others (2005)

Qc_h **Hamm Creek formation, Snoqualmie and Skykomish River provenance (Pleistocene)**—Sand, silt, and silty sands, with lesser pebbly sand, clay, organic sediments including peat, and lenses or beds of gravel; sands are weathered to a distinctive orange-brown; dense or hard; well sorted and stratified; mostly occurs as laminated to thinly bedded sands and silts; may contain charcoal, disseminated organic matter, crossbedding, and graded beds; beds are disrupted, folded, and extended, as a result of moderate to intense liquefaction similar to other ancient SP units in the map area. Sands are lithic poor and contain abundant monocrystalline quartz (~20%) with lesser plagioclase and potassium feldspar and some polycrystalline quartz and lithic clasts. Fine sands and silty fine sands contain minor but significant hornblende and mica similar to other ancient (units Qc_o, Qc_{ws}, and Qc_{pf}) and modern (unit Qa) SP sands. Unit Qc_h sand geochemistry suggests they were predominantly derived from an intermediate to slightly primitive arc source (Dragovich and others, 2011). Sedimentary structures, stratification style, and provenance indicate that the unit was deposited as ancient alluvium. Unit Qc_h is exposed in the core of a syncline on the northwestern edge of the SE highlands south of the Monroe fault, where the unit is inferred to be about 100 ft (30 m) thick (Cross Section B). In this case, the unit may represent another inverted basin within the broad SWIF (Dragovich and others, 2007, 2009a,b, 2010a,b). We obtained an IRSL age of 233 ±10.9 ka (~233,000 yrs B.P.) at age site 24B. Sands and silts at this site are intensely liquefied and display rootless isoclinal folds. Similar intensely liquefied nonglacial beds to the southeast of age site 24B at significant site 46A are also assigned to unit Qc_h, suggesting that the unit is tilted to the north and likely broadly folded south of the Monroe fault (Dragovich and others, 2011). We also obtained an OSL age of >155 ka from age site 24C, which is directly south of the Monroe fault and which we tentatively correlate with unit Qc_h. We correlate these nonglacial strata with the Hamm Creek formation of Troost and others (2005) on the basis of age and their nonglacial sedimentary character. The Hamm Creek formation is presently mapped by Troost and others (2005) southwest and west of the Monroe area in southwest Seattle, Redondo, and in Snohomish County. They indicate that the formation was deposited during the marine isotope stage 7 interglacial episode, which spans 188 to 243 ka (~188,00–243,000 yrs before present) (Morrison, 1991), although this warmer interval might have a short glacial or cooler interval from ~219 to 233 ka (~219,00–233,000 yrs before present).

PRE-FRASER GLACIAL AND NONGLACIAL DEPOSITS

Qc_{pf} **Pre-Fraser continental nonglacial deposits, Snoqualmie and Skykomish River provenance (Pleistocene)**—Sand, silt, clay with some organic silt-clay and peat, lesser pebbly sand and gravel, and rare cobble gravel deposited prior to the Fraser Glaciation; sands typically yellow-brown-gray, weathering to a distinctive orange-gray or light yellowish brown; dense; laminated to very thickly bedded and mostly well stratified; may contain charcoal, disseminated organic matter, trough and ripple crossbedding, and graded beds; liquefaction features are observed in most outcrops and include sand dikes and flames; distorted or destroyed bedding is evident in liquefied areas (Dragovich and others, 2011). Petrographic inspection of several sand samples reveals that the deposits contain significant monocrystalline quartz (20–25%), potassium feldspar, and lesser but significant hornblende, mica, and granitic lithics similar to the other SP units, including modern Skykomish and Snoqualmie alluvium (Dragovich and others, 2011). Geochemically, they were predominantly derived from an intermediate arc source with minor sedimentary or metamorphic input (Dragovich and others, 2010a,b, 2011). Similar to the Carnation quadrangle directly south of the map area (Dragovich and others, 2010a,b), unit Qc_{pf} is tentatively inferred to be up to ~500 ft (~150 m) thick on Cross Section A where thick successions of sand and silt with some clay and a few beds of gravel are tentatively correlated with unit Qc_{pf}. Exploration borings penetrated peat, wood, sticks, and logs, indicative of nonglacial deposition, and generally lack reports of the diamicton, hardpan, or thick beds of coarse (cemented) gravels that are commonly correlated with glacial intervals. Similar to modern Snoqualmie River deposits, stratigraphic style and the dominance of sands and silts suggest deposition as thick fining-upward gravel-sand-silt sequences typical of meandering river systems, where thick successions of thinly bedded sand and silt likely represent overbank deposits. Unit Qc_{pf} deposits compositionally match ancient SP alluvial units and thus are likely correlative with units such as the Olympia beds (unit Qc_o), Whidbey Formation (unit Qc_{ws}), or the Hamm Creek formation (unit Qc_h). We obtained a radiocarbon age of >43,500 yr B.P. from unit Qc_{pf} strata on the Snoqualmie River (sample site 690 ft west of age site 28D in the Maltby quadrangle) (Dragovich and others, 2011). The silts and sands at this site are intensely liquefied as well as fractured (Dragovich and others, 2011). We suspect these deposits were deformed by Quaternary offset along the Cherry Creek fault, which projects to near this site and appears to align with fault scarps and lineaments mapped by Sherrod and others (2008) along the southwestern slopes of Lords Hill in the western Maltby 7.5-minute quadrangle.

Qgn_{pf} **Pre-Fraser glacial and nonglacial deposits, undivided (Pleistocene to Pliocene?)(cross sections only)**—Mostly (boulder) gravel, sand and gravel, sand, silt, clay, diamicton, and some wood or peat; dense to very dense. The few wells or boreholes that penetrated this undivided geologic unit encountered diamicton or hardpan suggestive of significant glacial strata. However, available data are limited and can only be used to suggest undivided glacial or nonglacial deposits with limiting ages depending upon the inferred local stratigraphic arrangement. For example, unit Qgn_{pf} is locally overlain by unit Qc_o on Cross Section B and thus is demonstrably older than the Olympia nonglacial interval below much of the city of Monroe. Dragovich and others (2007, 2009c, 2010a,b), Booth (1990), and Knoll (1967) also describe older glacial and nonglacial deposits elsewhere in the Snoqualmie valley area, including the highly weathered tills and outwash in unit Qgn_{pf} of Dragovich and others (2009a,b) south of the map area.

Tertiary Volcanic and Sedimentary Rocks

₥vc **Volcanic and sedimentary rocks (Miocene)(cross sections only)**—Nonmarine volcanic to tuffaceous sandstone, pebbly sandstone, volcanic to polymictic conglomerate, tuff, claystone, siltstone, and lignite; may locally contain volcanic breccia or agglomerate with some petrified logs. Pebbly sandstones and lithic vitric lapilli tuff are exposed on High Bridge Road directly west of the quadrangle. The dark gray-green lapilli tuff is composed of andesite and dacite, plagioclase, pumice, and a few scattered exotic grains of polycrystalline quartz and sedimentary lithic grains set in a matrix of volcanic glass. The poor sorting, angularity of most grains, high proportion of volcanic grains, and glassy matrix suggest deposition as a pyroclastic flow. Dragovich and others (2010a,b) obtained a ^{206}Pb/^{238}U zircon age of ~18 Ma from a lapilli tuff sample (located 800 ft [244 m] west of age site 09-54Z) in the Maltby quadrangle. The age indicates the sample is Miocene and, given the pyroclastic nature of the deposit, is likely a distal equivalent of the volcanic rocks of Snoqualmie Falls (18–23 Ma) of Dragovich and others (2009a,b) mapped southeast of the sample site. Very thickly bedded pebbly sandstones that crop out near the lapilli tuff contain about 95 to 98 percent subrounded andesitic clasts with a few grains of plagioclase, polycrystalline quartz, and greenstone. The bedding style suggests deposition in a fluvial setting. We petrographically examined other fluvial volcanic sandstones cropping out in the easternmost part of the adjoining Maltby quadrangle. These deposits are similarly volcanic-clast-rich (20–90%) with some plagioclase, monocrystalline quartz, and sedimentary lithic grains. Minard (1985) tentatively assigned these fluvial deposits to the Blakeley Formation (see unit ΦEc below). However, given the similar stratigraphy and composition to the fluvial sandstones near the 18-Ma tuff site, we suspect that some of the sedimentary rocks along the eastern part of the Maltby quadrangle are Miocene and not correlative with the Blakeley Formation. Because stratigraphic relations are similar to those in the Carnation area (Dragovich and others, 2010a,b), we infer that: (1) unit ₥vc overlies the Blakeley Formation on Cross Section A and is preserved in a SWIF synclinal basin in the Snoqualmie valley between the Cherry Valley fault and Snoqualmie Valley fault no. 1; (2) distal Miocene volcanic and volcaniclastic deposits are preserved in other restricted strike-slip basins of the SWIF; and (3) Miocene deposits exposed along the eastern part of the Seattle basin are predominantly fluvial volcanic sedimentary deposits with interbedded volcanic rocks related to nearby volcanic centers (Dragovich and others, 2009a,c; Littke and others, 2009). Unit ₥vc may be chronostratigraphically equivalent to the volcanic rocks of Snoqualmie Falls of Dragovich and others (2009a,b) directly south of the map area and the nonmarine Blakely Harbor Formation of Fulmer (1975) near Seattle. Some of the Miocene ages southwest of the map area include hornblende K-Ar ages of 9.3 to 14.7 Ma (Yount and Gower, 1991) and an Ar-Ar laser fusion age of 11.40 ±0.61 Ma (Dragovich and others, 2002). (For a more regional context of similar Miocene rocks south and southwest of the present map area, see Dragovich and others [2002, 2007, 2009a,b,c, 2010a,b]).

ΦEn, ΦEc **Blakeley Formation (Oligocene to latest Eocene?)(cross sections only)**—These two subunits are inferred to be separate depositional facies in the subsurface. Unit ΦEn includes (tuffaceous) sandstone, pebble conglomerate, tuff, and minor siltstone and shale deposited in a nearshore marine environment. Unit ΦEc includes fluvial-deltaic lithofeldspathic to volcanic lithic volcanic sandstone or conglomerate, tuffaceous siltstone, siltstone, tuff, lapilli tuff, claystone, and coal (Yount and Gower, 1991). Both units are predominately well stratified, and laminated to thickly bedded. We infer that the nearshore marine-deltaic-fluvial transition between these units occurs in the subsurface on Cross Sections A and B. The Blakeley Formation in the eastern part of the Seattle basin is rich in volcanic lithic sedimentary and tuffaceous rocks derived from Cascade volcanic arc to the east, and generally contains quartz, feldspar, and lithic volcanic grains in varying amounts. Our examination of outcrops directly west of the study area previously correlated with the Blakeley Formation shows that these crossbedded fluvial deposits contain abundant volcanic lithics and plagioclase, with some sedimentary lithics and monocrystalline quartz grains similar to both the Blakeley Formation and nearby Miocene rocks. (See unit ₥vc above.) Although some of these rocks may be Miocene, directly west of the map area in the Maltby quadrangle, Minard (1985), Capps and others (1973), and Yount and Gower (1991) correlate sedimentary rocks locally with tuff and coal to the Blakeley Formation and (or) rocks of Bulson Creek of Marcus (1981). Four miles (6.4 km) directly west of the northwest corner of the Monroe quadrangle, in the Fiddlers Bluff area of the Maltby quadrangle, Lindquist (1957) convincingly correlated siltstones and sandstones containing middle to upper Oligocene shallow-marine (0–120 ft; 0–37 m) pelecypods and other marine fossils to the Blakeley Formation. Although turbidites and other deep-water depositional facies are common in the marine part of the section farther to the west, Lindquist's (1957) work shows that nearshore deposits likely underlie at least part of the Monroe area. The Blakeley Formation was also mapped in the subsurface south of the map area by Dragovich and others (2007, 2009a,b,, 2010a,b). On the basis of geophysical modeling and local field relations, we infer on Cross Sections A and B that the Seattle basin is locally truncated by the Cherry Valley fault and conjecture that the Blakeley Formation occurs under the city of Monroe, thus defining the southeastern-most portion of the Everett basin. The thick (3000+ ft; 910+ m) sedimentary rocks ~2 to 3 mi (3–5 km) NNW of the quadrangle (McFarland, 1981) are likely Eocene to Oligocene (Dragovich and others, 2002) and part of the Everett basin. The Johnsons Swamp fault zone may extend north of the quadrangle and structurally separate exposed mélange belt basement rocks directly north of the Monroe quadrangle from thick Eocene to Oligocene sedimentary rocks (units ΦEc and ΦEn) ~2 to 3 mi NNW of the quadrangle. (See gas and oil wells Sh-3, Sh-4, Sh-8, and 74 in McFarland [1981].) Regionally, late Eocene to middle or late Oligocene ages are typical for the Blakeley Formation (Fulmer, 1975; Walsh, 1984; Yount and Gower, 1991; Rau and Johnson, 1999). However, the Restoration Point Member of the Blakeley Formation on Bainbridge Island may span only the latest Oligocene to earliest Miocene (Prothero and Nesbitt, 2008).

Evs$_{p}$ **Volcanic rocks of Mount Persis of Tabor and others (1993), undivided (Eocene)**—Interbedded andesitic flows, dacitic lithic to crystal lithic breccia and tuff breccia, and dacitic to rhyolitic crystal lithic to lithic to vitric tuff, volcanic lithic sandstone, tuffaceous siltstone, and lahar and volcanic (boulder) conglomerate, with minor silty shale, claystone, and rare coal; tuffs and breccias vary from andesitic to rhyolitic; clasts in breccias are commonly dacitic (Tabor and others, 1993; Dragovich and others, 2009b, 2010a,b, 2011). Flows vary from andesite to basaltic andesite with some dacite and basalt. Rocks are locally strongly altered, particularly near tectonic zones (units tz and tz$_{h}$). The geochemistry of this unit suggests that it originated from a calc-alkaline arc that had an enriched mafic source that underwent assimilation as the magma evolved (Dragovich and others, 2011). Volcaniclastic sections are mostly moderately to well stratified and typically contain interbedded flows, tuffs, and breccias. The dominance of tuffs and volcanic-rich sedimentary rocks over coarse volcanic breccias and flows suggests a more distal volcanic depositional setting for areas south of the map area (Dragovich and others, 2009a,c, 2010a,b). Conversely, the dominance of flows and coarse breccia mapped by Tabor and others (1993) around Mount Persis and Youngs Creek headwaters and a possible intrusive center along the eastern part of the map area (unit Ei$_{p}$) point to a volcanic center or centers along the eastern edge and (or) east of the present study area. Mount Persis rocks unconformably overlie the Western mélange belt across a broad area east of the Cherry Valley fault (Tabor and others, 1993; Danner, 1957), but underlie a thick section of younger Tertiary sedimentary rocks along the eastern part of the Seattle basin (Dragovich and others, 2009a,b, 2010a,b; Sherrod and others, 2008). For example, west of Cherry Valley fault and north of the proposed Monroe fault on Cross Sections A and B, respectively, Mount Persis rocks likely underlie the Blakeley Formation (units ΦEn and ΦEc) and, locally, Miocene rocks (unit Mvc). Tabor and others (1993) assigned a late Eocene age to the volcanic rocks of Mount Persis on the basis of a poor apatite fission-track age (47.4 Ma), a hornblende K-Ar age (38.1 Ma), and the observation that the Mount Persis unit is intruded by the Index batholith (34 Ma) and mafic dikes (33 Ma) east of the map area. Dragovich and others (2009a,b) obtained a U-Pb zircon age of 36 ±2.3 Ma (late Eocene) from a thick felsic tuff bed in the Snoqualmie quadrangle southeast of the map area. The Mount Persis volcanism may span several million years (~36–47 Ma) and thus may involve several intrusive centers. Like Dragovich and others (2010b), we suspect that the Mount Persis unit thins to the west where it is dominated by distal volcaniclastic and tuffaceous strata with interbedded basalt and basaltic andesite flows in the subsurface. We suggest that the distal Mount Persis rocks interfinger with the undivided Puget Group (unit Evs$_{pg}$) in the western part of the area on Cross Sections A and B. We note here that although the Mount Persis likely originally thinned to the west, it currently may actually thin to the east because of uplift and subaerial erosion of the volcanic rocks in the SE highlands. Locally divided into:

Eva$_{p}$ **Volcanic rocks of Mount Persis, andesite flows (Eocene)**—Medium-K calc-alkaline andesite flows (~56–63% SiO_2) with minor dacite flows (~67% SiO_2); greenish gray, dark green, or (dark) gray, weathered or altered to dark reddish (brown)-gray, maroon-gray or yellow-brown-gray; flows typically massive but locally exhibit flow structure, including aligned phenocrysts, microlites, amygdules, or vesicles; flow breccia, altered flow tops, and well-formed columns are rarely observed. These two-pyroxene flows contain phenocrysts of plagioclase, augite ± hypersthene, and rare chloritized hornblende. Glomerophyric textures and oscillatory-zoned plagioclase are common and they locally contain quartz microphenocrysts. Geochemically, these flows most likely originated from a continental arc source (Dragovich and others, 2010a, 2011). Flows are ~30 to 100+ ft (~9–30+ m) thick, but are most typically 40 to 75 ft (12–23 m) thick (SubTerra, 1999), with thick flows likely the result of compound lava flows. Flows in the area are mostly lenticular canyon flows traversing ancient volcanic highlands. Magnetic highs in the map area east of SVF-1 likely reflect a greater percentage of unit Eva_p, Evb_p, and Eva_{pd} flows in the shallow subsurface. Cross Sections A and B show a greater concentration of andesite flows to the east, consistent with (1) magnetic susceptibility data, and (2) regional field information indicating an overall greater amount of proximal volcanic rocks to the east (this study; Danner, 1957; Tabor and others, 1993; Dragovich and others, 2010a,b). We suspect that the volcanic center(s) for the Mount Persis unit is (are) towards Youngs Creek east of the study area or along the easternmost part of the study area as discussed in units Ei_p and $Evbx_{pb}$.

Eva_{pd} **Volcanic rocks of Mount Persis, dark basaltic andesite flows (Eocene)**—Medium-K calc-alkaline basaltic andesite to andesite flows (~54–61% SiO_2); typically dark gray to very dark gray, weathering to reddish gray; typically fine-grained and massive; commonly show flow structure defined by aligned phenocrysts or microlites, amygdules or vesicles. Well-formed columns are observed in Cadman quarry. Thick compound flows are common. Unit Eva_{pd} contains microphenocrysts of plagioclase (<0.5 mm) and augite ± hypersthene with significant disseminated magnetite grains (≤15%) coloring the rock dark gray. Some flows have altered hornblende and biotite, and a few flows have blocky plagioclase (1–3 mm). Unit Eva_{pd} is typically holocrystalline with patches of glomerophyric microphenocrysts. If present, minor interstitial glass is typically chloritized or sericitized or is replaced by secondary carbonate. Geochemistry indicates that these flows most likely originated from a continental arc source (Dragovich and others, 2011). Outcroppings of the mafic flows and tuffs (units Eva_{pd} and Evt_{pd}, respectively) are megascopically similar, dark, fine-grained rocks that are typically difficult to classify in the field; thus, many unit Eva_{pd} exposures had to be confirmed petrographically. Also, although most of these dark volcanic rocks are demonstrably volcanic flows, we cannot exclude the possibility that some of these rocks are dikes or sills.

Evb_p **Volcanic rocks of Mount Persis, basalt flows (Eocene)**—Medium-K calc-alkaline basalt (~51.3% SiO_2); massive and dark gray; contains phenocrysts of plagioclase and augite ± hypersthene or hornblende. Although dark volcanic rocks are common in the study area (for example, unit Eva_{pd}), true basalts are relatively rare and could only be confidently identified (using geochemical analyses) near the State Reformatory and along the center of the map area on the SE highlands (Dragovich and others, 2011). Geochemically, the basalt is primitive and most likely originated from a continental arc source (Dragovich and others, 2011). We suspect that basalts are common in the distal subsurface on the western and northwestern parts of Cross Sections A and B. This is supported by geophysical modeling that suggests that mafic flows (units Eva_{pd} and Evb_p) with a high magnetic susceptibility flowed into these more distal volcanic environments because of their low viscosity, perhaps pooling on flatter plains bordering volcanic highlands.

Evt_p **Volcanic rocks of Mount Persis, tuffs (Eocene)**—Medium-K calc-alkaline dacitic to rhyolitic tuffs, mostly lithic dacitic tuffs with lesser vitric dacitic to rhyolitic tuffs; typically light to dark gray to light yellowish brown and massive. Limited petrographic information indicates that the more felsic tuffs are composed of euhedral to anhedral quartz and plagioclase phenocrysts in yellowish glass and locally contain plagioclase microlites and (or) ash-sized pumice fragments.

Geochemistry indicates that the tuffs most likely originated from a continental arc source (Dragovich and others, 2011).

Evt_{pc} **Volcanic rocks of Mount Persis, cream-colored lapilli tuffs (Eocene)**—Medium-K calc-alkaline dacitic crystal vitric, vitric crystal, and (lithic) vitric lapilli tuffs, locally with some tuff breccia; typically pale brown, weathering to a distinctive yellowish brown (cream); pumice clasts are white and lithic clasts are variable in color from green to gray. Lapilli tuff with scattered pumice lapilli and lapilli or breccia clasts of andesite or dacite in a cream-colored glassy matrix is typical. Pumice lapilli are flattened and lithic grains are somewhat aligned to form a crude primary bedding structure in most outcrops. Some lithic clasts are tuffs. Rocks microscopically contain angular grains of broken plagioclase, quartz, and fragments of pumice with variable volcanic lithic grains. The yellowish-brown glassy matrix between the large blocky plagioclase grains contains microlitic plagioclase, and in some samples, the glass is extensively replaced by carbonate. This very thick unit occurs on the SE highlands and is likely a composite of many beds (Cross Sections A and B). Pumice grains microscopically appear welded, suggestive of deposition as a hot pyroclastic flow. In the present study area, we obtained a single $^{206}Pb/^{238}U$ zircon age of 43.7 ±1.0 Ma from age site 40Y on the central part of the SE highlands (Dragovich and others, 2011). This age is from the weighted average of the $^{206}Pb/^{238}U$ zircon age data as presented in Dragovich and others (2011). These felsic tuffs are compositionally dissimilar to the dark felsic tuffs (unit Evt_{pd}) mapped in the Monroe quadrangle and were also extensively mapped in the Snoqualmie quadrangle southeast of the map area by Dragovich and others (2009a,b), who obtained a U-Pb single zircon age of 36 ±2.3 Ma (late Eocene). However, the accidental detrital zircon histogram ages in both Mount Persis age samples are similar, suggesting a similar magmatic source and magmatic basement environment (Dragovich and others, 2011). In other words, the uniformity of older zircons in the two tuffs suggests that they assimilated similar rock types during magmatic ascent. Geochemistry indicates that these tuffs underwent a high degree of assimilation, which is in agreement with the large number of zircon xenocrysts found (Dragovich and others, 2011).

Evt_{pd} **Volcanic rocks of Mount Persis, dark tuffs (Eocene)**—Dark medium-K calc-alkaline dacitic to rhyolitic crystal vitric and vitric tuffs; typically dark gray, weathered or altered to a brownish yellow to very pale brown. Very thick beds of aphanitic dark volcanic rock are the norm. Petrographically unit Evt_{pd} consists of scattered blocky and broken plagioclase in a clear glass matrix containing disseminated grains of opaque minerals that color the rock dark gray. Samples from a few sites also contain minor augite (rimmed by biotite), sparse lithic grains, and small fragments of pumice. Although unit Evt_{pd} is mostly massive, aligned plagioclase microlites form a subtle flow or flattening fabric in some outcrops. Outcrops of the dark mafic flows and tuffs (units Eva_{pd} and Evt_{pd}, respectively) are similar fine-grained rocks that are typically difficult to classify in the field and apparently occur widely across the SE highlands. Subsequent petrographic examination revealed that many dark tuffs classified in the field are flows. Unit samples were devoid of zircons and efforts to date the unit were unsuccessful.

$Evbx_p$ **Volcanic rocks of Mount Persis, volcanic breccia (Eocene)**—Medium-K calc-alkaline dacitic lithic tuff breccia, agglomerate, and lapilli tuff; multicolored but generally gray-brown to dark green-gray to gray with brownish weathering. Volcanic clasts vary from subrounded to subangular to locally angular, with rounding of some clasts likely due to airborne emplacement, mutual interaction, and bouncing of hot, ductile pyroclastic fragments (not water erosion). Although many outcrops are limited in exposure, breccia beds are generally very thick, massive, and moderately to poorly sorted. A few of the breccia beds we observed were thinner and interbedded with either volcanic sedimentary rocks or bedded pyroclastic surge deposits. Unit $Evbx_p$ clasts to the south are mostly two-pyroxene andesites that are petrographically and geochemically similar to the andesite flows (unit Eva_p) in the complex and probably represent flow breccia; elsewhere pyroclastic breccias also contain clasts of semivesicular light green dacite (~66% SiO_2) set in a clear glassy matrix with scattered small grains of augite (Dragovich and others, 2009a,b, 2010a,b). In the present study area, breccia clasts appear to be mostly hornblende dacite (~68% SiO_2) surrounded by a chaotic matrix containing variable smaller lapilli clasts, plagioclase, and quartz in a brownish glass matrix (≤20%) lacking augite and hypersthene. Some breccia may also contain exotic clasts of greenstone, metasandstone, and metachert (Danner, 1957). Breccia is typically poorly exposed, but likely represents pyroclastic flow deposits, including dome collapse breccia. The occurrence of thin interbeds of epiclastic volcanic sandstones in a few outcrops suggests that the substantial thickness of some of the breccia units is the result of emplacement of stacked pyroclastic deposits into a restricted basin or area. The dacitic composition of the clasts in the Carnation and Monroe map areas (Dragovich and others, 2010a,b, 2011) suggests that part of the unit may correlate with the hornblende dacite breccia unit mapped extensively by Tabor and others (1993) east of the map area. Our finding in the Monroe quadrangle that dacite dominates the breccia clasts and that many are hornblende-phyric supports this correlation and the model that many of the breccias are the result of a nearby dacite dome collapse. (See unit $Evbx_{pb}$.)

$Evbx_{pb}$ **Volcanic rocks of Mount Persis, volcanic bomb breccia (Eocene)**—Medium-K calc-alkaline dacitic lithic bomb breccia; typically with reddish gray or dark gray clasts. Bombs are mostly subrounded to subangular and are locally up to 7 ft (2 m) in diameter, but average ~2.6 ft (~80 cm). Deposits appear to be relatively homogeneous and almost clast-supported in most outcrops. Beds are very thick, massive to subtly graded (coarse fraction), and moderately to poorly sorted. A few outcrops contain thin lenticular volcaniclastic interbeds, demonstrating that at least locally the breccia is a composite of several pyroclastic flows. Clasts are dominated by dacite (~68–70% SiO_2) as in unit $Evbx_p$, and they most likely originated from a continental arc source (Dragovich and others, 2011). They also contain subhedral to euhedral phenocrysts to 1 mm with a glassy matrix containing plagioclase microlites and altered mafic minerals, including euhedral hornblende. Many of the clasts have holocrystalline volcanic flow textures, including aligned microlites. Bomb breccias are well-exposed along the northern part of the SE highlands, where they tend to form subvertical cliffs. These breccias were likely deposited as dome collapse breccias near an edifice, as in unit $Evbx_p$. Given the impressive size of some of the bombs (up to 2 m), it seems likely that the volcanic source of the breccias is in or near the map area. (See unit Ei_p.) The dacitic composition of the breccia clasts in the Carnation and Monroe map areas (Dragovich and others, 2010a,b, 2011), along with our finding that many are hornblende-phyric, suggests that part of the unit may correlate with the hornblende dacite breccia mapped extensively by Tabor and others (1993) in the volcanic rocks of Mount Persis east of the map area. (See unit $Evbx_p$ above.)

Evc_p **Volcanic rocks of Mount Persis, volcaniclastic rocks (Eocene)**—Lithic and feldspatholithic volcanic to tuffaceous sandstone and siltstone; may include interbeds of volcanic conglomerate, shale, tuff and lapilli tuff, and rare beds of coal or shale; color variable but mostly light yellowish brown to very pale brown to light bluish gray with some dark red volcanic siltstone; volcanic sediments are mostly well sorted and stratified and contain angular to subrounded grains; strata vary from massive to medium to thickly bedded, with plane and ripple crossbedding typical of fluvial environments commonly observed; rare antidune crossbedding typical of pyroclastic surge deposits rarely observed. Fossil leaves, stems, and fragments of black carbonized or brown petrified wood are common and consist mostly of fragments of broadleaf trees as well as stems of rushes similar to modern *Equisetum* (Dragovich and others, 2010b; Danner, 1957). Most volcaniclastic rocks are rich in volcanic lithics; for example, volcanic sandstones contain abundant andesite to dacite clasts, but also locally contain altered volcanic glass, plagioclase, and a few grains of polycrystalline quartz and sandstone-siltstone. However, there is a spectrum of compositional volcaniclastic rock types. For example, crystal-rich sediments with significant subangular to angular plagioclase, volcanic quartz, and variable amounts of fragmental pumice are probably fluvially reworked crystal-vitric ash flow tuffs. Sandstones rarely have a mixed volcanic and Western mélange belt (unit KJm) provenance (Dragovich and others, 2009a). Conglomerate mostly contains subrounded clasts dominated by andesite and dacite. Danner (1957) describes andesitic boulder conglomerates with shale lenses, which are likely fluvial deposits, directly east of the map area. Because these volcanic sediments are generally more erodible than volcanic deposits, such as lava flows, these rocks tend to be recessive or covered with colluvium and other Quaternary deposits, and thus rarely form prominent outcrops. This is supported by subsurface drilling information that suggests that volcaniclastic rocks, such as volcanic sandstone and shale, are more common in the subsurface. Unit Evc_p was deposited mostly as fluvial stream deposits within a dissected volcanic highland setting. As a result of this moderately proximal volcanic setting, unit Evc_p forms lenticular beds surrounded by flows, tuffs, and breccias. In more distal settings, such as the inferred depositional environment for the western part of the study area (Cross Sections A and B), volcanic sediments might have been deposited in a lower energy plain setting, mostly with tuffs and basaltic andesite and basalt flows.

Evl_p **Volcanic rocks of Mount Persis, lahars (Eocene)**—Cohesive to noncohesive lahar and lesser volcanic (boulder) conglomerate; clasts dark gray, commonly weathered or altered to gray-green; contains subrounded to subangular pebbles, cobbles, and boulders of andesite (~60% SiO_2) up to ~3 ft (~1 m) in diameter, with petrified wood, log or stick casts, and a few clasts of opal and volcanic sandstone and siltstone. Weathering masks some original textures, but the lahar matrix generally varies from volcanic sand to ashy, silty, clayey sand, and is locally semi-cohesive. Unit Evl_p occurs as very thick massive beds with possible subtle overall grading. Clast composition (~95–100% andesite), matrix texture, and overall moderate to poor sorting suggest deposition mostly as lahars. Contacts are generally poorly exposed, but the spatial association with volcaniclastic fluvial sedimentary rocks, including clast-supported cobble-boulder conglomerate with thin interbeds of volcanic siltstone, suggests deposition as lenticular beds within valleys emanating from a volcanic highland to the east of the map area. In the Carnation and Monroe quadrangles, deposits vary from matrix-supported lahar to clast-supported hyperconcentrated flood deposits or volcanic alluvium (this study, Dragovich and others, 2010b). Geochemically, one medium-K calc-alkaline clast from unit Evl_p sampled directly south of the current study area has a higher aluminum saturation index and is more chemically altered than other Mount Persis samples (Dragovich and others, 2010b, 2011). Geochemical and petrographic analyses of lahar clasts indicate that the original flows were sourced by andesitic lavas exhibiting pervasive silica, K-feldspar, and clay alteration (Dragovich and others, 2010a,b). Zones of alteration around andesitic stratovolcanoes can lead to edifice instability, collapse, and to the generation of high-volume cohesive mudflows (lahars) or hyperconcentrated flood deposits (lahar runouts) similar to the mapped deposits. However, given the preponderance of dacitic breccias in the Monroe area and areas to the east (Tabor and others, 1993), and the restricted lahar clast chemical data, some of the lahars might have been a sourced by dacitic pyroclastic deposits. (See units Ei_p and $Evbx_p$.)

Ei_p **Volcanic rocks of Mount Persis, intrusive complex (Eocene)**—Uniquely textured medium-K calc-alkaline dacite flows (~68% SiO_2) with lesser andesite flows and pumiceous crystal-lithic to vitric lapilli tuff and dacitic bomb breccia; rocks are bluish gray to gray. These flows, fragmental volcanic rocks, and possible hypabyssal intrusive rocks are exposed in logging road cutbanks north of Lake Fontal on the SE highlands in the east-central part of the map area. The flows or possible hypabyssal intrusives in this complex all contain glomerophyric mafic ellipsoids or “knots” that define a subvertical mafic mineral lineation suggestive of vertical flow; however, this lineation is very limited in spatial extent and thus its causation requires further study. The flows are mostly holocrystalline and contain blocks of euhedral to microlitic plagioclase and augite, with lesser altered hornblende. Nearby lapilli tuffs contain a variety of clasts, including pumice, basalt, hornblende-augite dacite, and hypidiomorphic intrusive rocks, as well as clasts of the Western mélange belt basement (prehnite- and pumpellyite-bearing metasandstone and meta-argillite). Geochemically, unit Ei_p most likely originated from a continental arc source (Dragovich and others, 2011). We tentatively hypothesize that the subvertical flow lineation, along with the apparent glomerophyric hypabyssal(?) rocks and the unusual composition of the tuffs, may be due to intrusion, necking, or doming at a volcanic plug. (Compare with unit $Evbx_{pb}$.) In addition, the unusual high percentage of mélange belt fragments in the lapilli tuffs suggests plucking of basement rocks during ascent and, along with the gravity signature of the easternmost part of the map area (Dragovich and others, 2011), suggests magmatic erosion of basement that is only 500 to 900 ft (150–275 m) below the present surface.

Evs_{pg} **Puget Group, undivided (Eocene)(cross sections only)**—Continental feldspathic to volcanic lithic subquartzose sandstone, siltstone, claystone, and lesser lapilli tuff, tuff, carbonaceous shale, pebble conglomerate, and coal, and rare or absent andesitic flows and breccia. The Puget Group is exposed to the south and southwest of the map area and includes the Renton, Tukwila, and Tiger Mountain Formations. The middle to late Eocene Renton and older middle Eocene Tiger Mountain Formations were deposited as meandering-river fluvial-deltaic sediments on a coastal plain. The andesitic volcanic deposits of the Tukwila Formation erupted onto this coastal plain south of the map area and interrupted the fluvial deposition of the Renton and Tiger Mountain Formations southwest of the Monroe area. The distance to the andesitic volcanic center(s) of the Tukwila Formation suggests that flows and breccias are not part of the Puget Group shown on Cross Sections A and B. Rau and Johnson (1999) showed the Puget Group to be locally at least 4,000 ft (1,220 m) thick in the Seattle basin west of the map area. This thickness is similar to that given by ten Brink and others (2002), who showed the undivided Eocene sediments in the basin to be about 3,500 to 4,200 ft (1,060 to 1,280 m) thick. We infer on Cross Sections A and B that the middle and late Eocene Puget Group (1) thins or is truncated by faulting to the east, and (2) interfingers with moderately distal rocks of the Eocene volcanic rocks of Mount Persis. (See Mount Persis age information in units Evs_{p} and Evt_{pd}.)

Mesozoic Low-Grade Metamorphic Rocks (Prehnite–Pumpellyite Facies)

KJm **Western mélange belt of Tabor and others (1993)(Cretaceous to Jurassic)(cross sections only)**—Dominantly metamorphosed argillite, sandstone, greenstone, metagabbro, and diabase, with minor metachert, metatonalite, slate, phyllite, marble, and rare ultramafite (Dragovich and others, 2007, 2009a,b,c, 2010b). Most metasedimentary rocks were deposited as turbidites along an accretionary wedge. The Western mélange belt is inferred to underlie the map area (Cross Sections A and B). Geophysical modeling suggests that the volcanic rocks of Mount Persis unconformably overlie the mélange belt over much of the map area (Dragovich and others, 2010a,b, 2011). Danner (1957), Tabor and others (1993), and Dragovich and others (2009a, c) also mapped this unconformity to the east and south of the Monroe map area.

Tertiary to Holocene Tectonic Zones

tz, tz_{h}, Qtz **Tectonic zone (Tertiary to Holocene)**—Cataclasite, fault breccia, clay-rich fault gouge, protomylonite, and strongly slickensided and fractured rocks in fault zones; variously colored, mottled, and veined as a result of local hydrothermal alteration or strong weathering. Dragovich and others (2007, 2009a,b,c, 2010a,b) map tectonic zones along faults south of the map area. Sherrod and others (2008) map many strands of the SWIF west of the map area. Most kinematic indicators, such as shallow slickenlines on steep shear planes and (or) en echelon vein arrays, suggest right-lateral strike-slip or oblique-slip offset along strands of the SWIF. Wide zones of cataclasis are common in the Cherry Creek fault zone, parts of the Johnsons Swamp fault zone, and the Fontal Road reverse fault. **Hydrothermally altered tectonic zones** (unit tz_{h}) are mapped where tectonic zones host broad mappable zones of hydrothermal alteration. Unit tz_{h} contains principally low-temperature carbonate (calcite) mineralization with local silicification producing a widespread whitish rock. **Quaternary tectonic zones** (unit Qtz) are mapped only in the subsurface on Cross Sections A and B adjacent to active or potentially active faults. This tectonic deformation is characterized by high-angle fractures and (or) discrete faults with bedding offsets in Pleistocene deposits near probable active faults, such as the Cherry Valley fault, as discussed more fully in Dragovich and others (2011). More information related to the mapping of faults, fault deformational structures, liquefaction, earthquake hypocenters and focal mechanisms, and geophysical lineaments are provided in Dragovich and others (2011). For example, we describe the numerous (locally intense) liquefaction and tectonic features associated with the Cherry Valley fault, as well as the shallow seismicity associated with the Cherry Creek fault zone.

ACKNOWLEDGMENTS

This geologic map was funded in part by the U.S. Geological Survey (USGS) National Cooperative Geologic Mapping Program under award no. G10AC00363. We thank many people for assistance: Heather Littke and Benjamin Perry for office help with GIS and other data; Dan Smith (King County DNRP/WLRD) for helping with field mapping; the late Lou Lepp (Associated Earth Sciences, Inc.) for unpublished mapping of the Monroe quadrangle; Jeff Jones (Snohomish County Public Works) for geologic mapping information, including subsurface data; Julie Stangell (Hancock Forest Management) for logistical help; Ray Wells (USGS) for laboratory support; Diane Cornelius, Rick Conrey, and Charles Knaack (Wash. State Univ.) for geochemical analyses of samples; and Gabe Morrelli for access to the Cadman mine. We thank Dennis Armstrong (King County Dept. of Transportation), Russ Steele (Wash. State Dept. of Transportation), and Sue Kahle and Myrtle Jones (USGS, Water Resources Division, Tacoma) for subsurface geologic information. We also thank the following Washington Division of Geology and Earth Resources colleagues: Tim Walsh for helping with the lidar data, Robert Berwick for metadata file management, and Lee Walking for assistance with references.

REFERENCES CITED

Anderson, M. L.; Blakely, R. J.; Brocher, T. M.; Pratt, T. L.; Wells, R. E.; Haugerud, R.; Bush, M., 2006, Structure of the Seattle uplift from seismic, gravity, magnetic, geologic, and geomorphic data: Eos (American Geophysics Union Transactions), v. 87, no. 52, Supplement, Abstract T41A-1554.

Armstrong, J. E.; Crandell, D. R.; Easterbrook, D. J.; Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, no. 3, p. 321-330.

Associated Earth Sciences, Inc., 1999, Environmental impact statement—Soils, geology, geologic hazards, and water quality, Cougar Ridge and Old Owen Place, Snohomish County, Washington. *In* Associated Earth Sciences, Inc., 2010, Monroe quadrangle reports: Associated Earth Sciences, Inc., [excerpts].

Associated Earth Sciences, Inc., 2000, Subsurface exploration, geologic hazard and geotechnical engineering report, Monroe Library, Village Way, Monroe, Washington. *In* Associated Earth Sciences, Inc., 2010, Monroe quadrangle reports: Associated Earth Sciences, Inc., [13p]

Associated Earth Sciences, Inc., 2001a, Proposed borrow pit dewatering impact analysis, Trilogy at Redmond Ridge, King County, Washington: Associated Earth Sciences, Inc., 1 v.

Associated Earth Sciences, Inc., 2001b, Subsurface exploration, geologic hazard, and geotechnical engineering report, Trilogy at Redmond Ridge, Project B vault, West Snoqualmie Valley Road NE and Novelty Hill Road, King County, Washington: Associated Earth Sciences, Inc., 1 v.

Associated Earth Sciences, Inc., 2002a, Final hydrogeologic and geotechnical assessment report—Pegasus Thoroughbred Training Center, King County, Washington: Associated Earth Sciences, Inc., 1 v.

Associated Earth Sciences, Inc., 2002b, Hydrogeologic assessment—Plat of Cromwell Plateau, Snohomish County, Washington. *In* Associated Earth Sciences, Inc., 2010, Monroe quadrangle reports: Associated Earth Sciences, Inc., 10 p.

Associated Earth Sciences, Inc., 2003, Proposed Snoqualmie Ridge II project—Environmental impact statement—Technical report on geology, soils, and groundwater: Associated Earth Sciences, Inc., [Kirkland, Wash., under contract to] Quadrant Corporation, 1 v.

Associated Earth Sciences, Inc., 2004, Environmental impact statement—Technical report on geology, soils and ground water, Redmond Ridge East UPD/FCC and Panhandle preliminary plat, King County, Washington: Associated Earth Sciences, Inc., 1 v.

Associated Earth Sciences, Inc., 2007, Summary of SRS-1 No. 1 infiltration pond, general geologic hazard, and geotechnical engineering recommendations, recreation complex, Redmond Ridge East, King County, Washington: Associated Earth Sciences, Inc., 1 v.

Associated Earth Sciences, Inc., 2010, Monroe quadrangle reports: Associated Earth Sciences, Inc., 1 v., 3 plates.

Blakely, R. J.; Wells, R. E.; Weaver, C. S., 1999, Puget Sound aeromagnetic maps and data: U.S. Geological Survey Open-File Report 99-514, version 1.0. [http://geopubs.wr.usgs.gov/open-file/of99-514/]

Booth, D. B., 1984, Glacier dynamics and the development of glacial landforms in the eastern Puget Lowland, Washington: University of Washington Doctor of Philosophy thesis, 217 p., 1 plate.

Booth, D. B., 1986, The formation of ice-marginal embankments into ice-dammed lakes in the eastern Puget Lowland, Washington, U.S.A., during the late Pleistocene: Boreas, v. 15, no. 3, p. 209-264.

Booth, D. B., 1990, Surficial geologic map of the Skykomish and Snoqualmie Rivers area, Snohomish and King Counties, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1745, 2 sheets, scale 1:50,000, with 22 p. text.

Capps, Gerald; Simmons, J. D.; Videgar, F. D., 1973, Preliminary report on the geology of southern Snohomish County, Washington: Washington Division of Geology and Earth Resources Open File Report 73-1, 11 p., 8 plates.
[http://www.dnr.wa.gov/publications/ger_ofr73-1_geology_south_snohomish_co_pt1.pdf
http://www.dnr.wa.gov/publications/ger_ofr73-1_geology_south_snohomish_co_pt2.pdf
http://www.dnr.wa.gov/publications/ger_ofr73-1_geology_south_snohomish_co_pt3.pdf
http://www.dnr.wa.gov/publications/ger_ofr73-1_geology_south_snohomish_co_pt4.pdf
http://www.dnr.wa.gov/publications/ger_ofr73-1_geology_south_snohomish_co_pt5.pdf
http://www.dnr.wa.gov/publications/ger_ofr73-1_geology_south_snohomish_co_pt6.pdf
http://www.dnr.wa.gov/publications/ger_ofr73-1_geology_south_snohomish_co_pt7.pdf]

Colman, S. M.; Pierce, K. L., 1981, Weathering rinds on andesitic and basaltic stones as a Quaternary age indicator, western United States: U.S. Geological Survey Professional Paper 1210, 56 p.

Danner, W. R., 1957, A stratigraphic reconnaissance in the northwestern Cascade mountains and San Juan Islands of Washington State: University of Washington Doctor of Philosophy thesis, 3 v. [562 p.], 7 plates.

Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, no. 2, p. 695-707.

Dragovich, J. D., 2007, Sand point count and geochemical data in the Fall City and Carnation 7.5-minute quadrangles, King County, Washington: Washington Division of Geology and Earth Resources Open File Report 2007-3, 2 Microsoft Excel files with 6 p. text. [http://www.dnr.wa.gov/Publications/ger_ofr2007-3_fallcity_supplement.zip]

Dragovich, J. D.; Anderson, M. L.; MacDonald, J. H., Jr.; Mahan, S. A; DuFrane, S. A.; Littke, H. A.; Wessel, G. R.; Saltonstall, J. H.; Koger, C. J.; Cakir, Recep, 2010a Supplement to the geologic map of the Carnation 7.5-minute quadrangle, King County, Washington—Geochronologic, geochemical, point count, geophysical, earthquake, fault, and neotectonic data: Washington Division of Geology and Earth Resources Open File Report 2010-2, 42 p., 8 digital appendices. [http://www.dnr.wa.gov/Publications/ger_ofr2010-2_carnation_supplement.zip]

Dragovich, J. D.; Anderson, M. L.; Walsh, T. J.; Johnson, B. L.; Adams, T. L., 2007, Geologic map of the Fall City 7.5-minute quadrangle, King County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-67, 1 sheet, scale 1:24,000. [http://www.dnr.wa.gov/Publications/ger_gm67_geol_map_fallcity_24k.zip]

Dragovich, J. D.; Littke, H. A.; Anderson, M. L.; Hartog, Renate; Wessel, G. R.; DuFrane, S. A.; Walsh, T. J.; MacDonald, J. H., Jr.; Mangano, J. F.; Cakir, Recep, 2009a, Geologic map of the Snoqualmie 7.5-minute quadrangle, King County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-75, 2 sheets, scale 1:24,000. [http://www.dnr.wa.gov/Publications/ger_gm75_snoqualmie_24k.zip]

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., 2010b, 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, 21 p. text. [http://www.dnr.wa.gov/Publications/ger_ofr2010-1_geol_map_carnation_24k.zip]

Dragovich, J. D.; Littke, H. A.; MacDonald, J. H., Jr.; DuFrane, S. A.; Anderson, M. L.; Wessel, G. R.; Hartog, Renate, 2009b, Geochemistry, geochronology, and sand point count data for the Snoqualmie 7.5-minute quadrangle, King County, Washington: Washington Division of Geology and Earth Resources Open File Report 2009-4, 35 p. text, 3 Microsoft Excel files. [http://www.dnr.wa.gov/Publications/ger_ofr2009-4_snoqualmie_suppl.zip]

Dragovich, J. D.; Logan, R. L.; Schasse, H. W.; Walsh, T. J.; Lingley, W. S., Jr.; Norman, D. K.; Gerstel, W. J.; Lapen, T. J.; Schuster, J. E.; Meyers, K. D., 2002, Geologic map of Washington—Northwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-50, 3 sheets, scale 1:250,000, with 72 p. text. [http://www.dnr.wa.gov/publications/ger_gm50_geol_map_nw_wa_250k.pdf]

Dragovich, J. D.; Mahan, S. A.; Anderson, M. L.; MacDonald, J. H., Jr.; Wessel, G. R.; DuFrane, S. A.; Cakir, Recep; Bowman, J. D.; Littke, H. A., 2011, Analytical data from the Monroe 7.5-minute quadrangle, King and Snohomish Counties, Washington—Supplement to Open File Report 2011-1: Washington Division of Geology and Earth Resources Open File Report 2011-2, 58 p., 2 plates, 2 Microsoft Excel files. [http://www.dnr.wa.gov/Publications/ger_ofr2011-2_monroe_supplement.zip]

Dragovich, J. D.; Walsh, T. J.; Anderson, M. L.; Hartog, Renate; DuFrane, S. A.; Vervoot, Jeff; Williams, S. A.; Cakir, Recep; Stanton, K. D.; Wolff, F. E.; Norman, D. K.; Czajkowski, J. L., 2009c, Geologic map of the North Bend 7.5-minute quadrangle, King County, Washington, with a discussion of major faults, folds, and basins in the map area: Washington Division of Geology and Earth Resources Geologic Map GM-73, 1 sheet, scale 1:24,000. [http://www.dnr.wa.gov/Publications/ger_gm73_geol_map_northbend_24k.zip]

Easterbrook, D. J.; Crandell, D. R.; Leopold, E. B., 1967, Pre-Olympia Pleistocene stratigraphy and chronology in the central Puget Lowland, Washington: Geological Society of America Bulletin, v. 78, no. 1, p. 13-20.

Fulmer, C. V., 1975, Stratigraphy and paleontology of the type Blakeley and Blakely Harbor Formations. *In* Weaver, D. W.; Hornaday, G. R.; Tipton, Ann, editors, Paleogene symposium and selected technical papers—Conference on future energy horizons of the Pacific coast: American Association of Petroleum Geologists Pacific Section, 50th Annual Meeting, p. 210-271.

Knoll, K. M., 1967, Surficial geology of the Tolt River area, Washington: University of Washington Master of Science thesis, 91 p., 1 plate.

Le Maitre, R. W.; Streckeisen, A.; Zanettin, B.; Le Bas, M. J.; Bonin, B.; Bateman, P., eds., 2002, Igneous rocks—A classification and glossary of terms; 2nd ed.: Cambridge University Press [Cambridge, U.K.], 256 p.

Lindquist, J. W., 1957, Molluscan paleontology of Fiddlers Bluff, Washington: University of Washington undergraduate research thesis, 38 p.

Littke, H. A.; Dragovich, J. D.; Anderson, Megan; Hartog, Renate; Wessel, G. R.; Dufrane, S. A.; Walsh, T. J.; MacDonald, J. H., Jr.; Cakir, Recep, 2009, Geologic map of the Snoqualmie 7.5-minute quadrangle, King County, Washington—Active faulting, basin inversion and Miocene volcanic extrusion of the Snoqualmie batholith along the Rattlesnake Mountain fault zone [abstract]: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 457.

Mackin, J. H., 1941, Glacial geology of the Snoqualmie–Cedar area, Washington: Journal of Geology, v. 49, no. 5, p. 449-481.

Marcus, K. L., 1981, The rocks of Bulson Creek—Eocene–Oligocene sedimentation and tectonics in the Lake McMurray area, Washington: Western Washington University Master of Science thesis, 84 p., 1 plate.

McFarland, C. R., 1981, Oil and gas exploration in Washington, 1900-1981: Washington Division of Geology and Earth Resources Information Circular 67R, 119 p. [http://www.dnr.wa.gov/publications/ger_ic67r_oil_gas_exploration_wa_1900-81.pdf]

Minard, J. P., 1985, Geologic map of the Maltby quadrangle, Snohomish and King Counties, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1746, 1 sheet, scale 1:24,000.

Minard, J. P.; Booth, D. B., 1988, Geologic map of the Redmond quadrangle, King County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2016, 1 sheet, scale 1:24,000.

Morrison, R. B., editor, 1991, Quaternary nonglacial geology—Conterminous U.S.: Geological Society of America DNAG Geology of North America, v. K-2, 672 p., 8 plates in accompanying case.

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.

Pettijohn, F. J., 1957, Sedimentary rocks; 2nd ed.: Harper & Row, 718 p.

Porter, S. C.; Swanson, T. W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, no. 3, p. 205-213.

Prothero, D. R., Nesbitt, E. A. 2008, Paleomagnetism and tectonic rotation of the Restoration Point member of the Blakeley Formation (type Blakeley stage), Bainbridge Island, Washington, and the Pacific Coast Oligocene–Miocene boundary: New Mexico Museum of Natural History and Science Bulletin 44, p. 315-322.

Rau, W. W.; Johnson, S. Y., 1999, Well stratigraphy and correlations, western Washington and northwestern Oregon: U.S. Geological Survey Geologic Investigations Series Map I-2621, 3 sheets, with 31 p. text.

Saltonstall, J. H.; Koger, C. J; Sweet, Suzanne; Thompson, S. S., 2003, Olympia age paleotopographic influences on Vashon glaciofluvial sedimentation beneath eastern Bear Creek plateau, King County, Washington [abstract]: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 109.

Sherrod, B. L.; Blakely, R. J.; Weaver, C. S.; Kelsey, H. M.; Barnett, Elizabeth; Liberty, Lee; Meagher, K. L.; Pape, Kristin, 2008, Finding concealed active faults—Extending the southern Whidbey Island fault across the Puget Lowland, Washington: Journal of Geophysical Research, v. 113, B05313, doi:10.1029/2007JB005060, 2008.

Snohomish County Department of Public Works, 2002, Geologic investigation and geotechnical engineering report—Woods Creek Bridge #6 replacement: Snohomish County Department of Public Works, 13 p., excerpts.

SubTerra, Inc., 1999, Report on the soils, geology, hydrogeology and geologic hazards for the proposed Mile Five andesite quarry, south Snohomish County, Washington: SubTerra, Inc., 1 v.

Tabor, R. W.; Frizzell, V. A., Jr.; Booth, D. B.; Waitt, R. B.; Whetten, J. T.; Zartman, R. E., 1993, Geologic map of the Skykomish River 30- by 60-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1963, 1 sheet, scale 1:100,000, with 42 p. text. [http://pubs.usgs.gov/imap/i1963/]

ten Brink, U. S.; Molzer, P. C.; Fisher, M. A.; Blakely, R. J.; Bucknam, R. C.; Parsons, T. E.; Crosson, R. S.; Creager, K. C., 2002, Subsurface geometry and evolution of the Seattle fault zone and the Seattle basin, Washington: Seismological Society of America Bulletin, v. 92, no. 5, p. 1737-1753.

Troost, K. G.; Booth, D. B.; Wisher, A. P.; Shimel, S. A., 2005, The geologic map of Seattle—A progress report: U.S. Geological Survey Open-File Report 2005-1252, version 1.0, 1 sheet, scale 1:24,000. [http://pubs.usgs.gov/of/2005/1252/]

U.S. Geological Survey Geologic Names Committee, 2007, Divisions of geologic time—Major chronostratigraphic and geochronologic units: U.S. Geological Survey Fact Sheet 2007-3015, 2 p. [http://pubs.usgs.gov/fs/2007/3015/]

Varnes, D. J., 1978a, repr. 1995, Landslide classification system. *In* Dragovich, J. D.; Brunengo, M. J., Landslide map and inventory, Tilton River–Mineral Creek area, Lewis County, Washington: Washington Division of Geology and Earth Resources Open File Report 95-1, 165 p., Plate 3. [http://www.dnr.wa.gov/publications/ger_ofr95-1_lewis_co_landslides_plates.pdf and http://www.dnr.wa.gov/publications/ger_ofr95-1_lewis_co_landslides_text.pdf]

Varnes, D. J., 1978b, Slope movement types and processes. *In* Schuster, R. L.; Krizek, R. J., editors, Landslides—Analysis and control: National Academy of Sciences Transportation Research Board Special Report 176, p. 11-33, 1 plate.

Walsh, T. J., 1984, Geology and coal resources of central King County, Washington: Washington Division of Geology and Earth Resources Open File Report 84-3, 24 p., 2 plates. [http://www.dnr.wa.gov/publications/ger_ofr84-3_central_king_co_coal_24k.pdf]

Wolfe, J. A.; Forest, C. E.; Molnar, Peter, 1998, Paleobotanical evidence of Eocene and Oligocene paleoaltitudes in midlatitude western North America: Geological Society of America Bulletin, v. 110, no. 5, p. 664-678.

Yount, J. C.; Gower, H. D., 1991, Bedrock geologic map of the Seattle 30' by 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 91-147, 37 p., 4 plates. [http://pubs.er.usgs.gov/usgspubs/ofr/ofr91147]