GEOLOGIC MAP OF THE FALL CITY 7.5-MINUTE QUADRANGLE, KING COUNTY, WASHINGTON

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Geologic Map of the Fall City 7.5-minute Quadrangle, King County, Washington

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DESCRIPTION OF MAP UNITS

Information for the unit descriptions was compiled from the sources listed at the end of each description. Unconsolidated sediments are classified according to the Udden-Wentworth scale (Pettijohn, 1957). Classification of sandstones follows the terminology of Dickinson (1970), except for volcanic sandstones (lithic sandstones). Assignment of volcanic rock names was made on the basis of whole-rock geochemistry and the total alkali-silica (TAS) diagram (Le Maitre, 1989). We use the new time scale of the U.S. Geological Survey (USGS Geologic Names Committee, 2007). Lidar topographic data from the Puget Sound Lidar Consortium (http://pugetsoundlidar.ess.washington.edu/) facilitated our mapping.

Quaternary Sedimentary Deposits

Point-count data on the sand-size fractions aids differentiation of several glacial and nonglacial units in the map area. One important compositional discriminator for various Quaternary geologic units is the average percentage of monocrystalline quartz (Qm) *versus* quartz mica tectonite/polycrystalline quartz/chert (Qp) *versus* potassium feldspar (PF) (see $Qm_xQp_xPF_x$ data below). (See Dragovich [2007] for point count data and geochemistry.)

HOLOCENE NONGLACIAL DEPOSITS

af **Artificial fill and modified land (Holocene)**—Mixed earth materials, including engineered and nonengineered fill at major construction sites, that obscure the original geologic deposit. Includes sand and gravel fill or extensively graded natural deposits.

Qa **Alluvium (Holocene)**—Sand and silt with lesser gravelly sand, sandy pebble gravel, peat, and organic sediments; subrounded to rounded clasts; loose, mostly well stratified and sorted; plane-bedded sands common. Snoqualmie River alluvium also contains much sand, clay, organic mud, and peat deposited in overbank (flood) and abandoned channel settings (see unit Qp). Raging River alluvium is mostly gravel with volcanic boulders from the Puget Group common (see units Qaf and Qgog). Snoqualmie River sands (site 1, Plate) contain monocrystalline quartz (19–23%), plagioclase (14–15%), volcanic lithic clasts (13–16%), granitic lithic clasts (7–10%), and potassium feldspar (~4%), similar to ancient Snoqualmie River alluvium found in the Olympia beds (Dragovich, 2007). The Snoqualmie River sands have a Snoqualmie batholith and Tertiary volcanic igneous signature and contain fewer metamorphic lithic clasts (4–5%), chert and polycrystalline quartz (6–7%) than northerly derived glacial deposits ($Qm_{54}Qp_{38}PF_8$ vs. $Qm_{37\text{-}43}Qp_{54\text{-}59}PF_{4\text{-}6}$, respectively). (See unit Qc_o.)

Qp **Peat (Holocene)**—Peat, muck, and organic silt and clay, with some thin beds of tephra; loose or soft; poorly stratified. Peat occurs in flood plains and marshy upland depressions. Many of the flood plain depressions consist of abandoned channels of the Snoqualmie River or hummocks and kettles in ice-contact glacial deposits. Much of the Patterson Creek alluvial plain is composed of low-energy, moderately stratified peat, sand, gravel, and organic sediment interstratified with basin-margin alluvial fan deposits. (this study; Anderson, 1965; Booth, 1990; Associated Earth Sciences, 2000a,b)

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 rounded clasts where landslides originate in Quaternary deposits. Landslides include slump-earthflow, debris slump, debris flow, and rock avalanches. May include chaotic, stratified slump blocks or debris-flow aprons originating from unstable recessional deposits perched on hillsides. The Tiger Mountain landslide is a large slump-earthflow in the southwest corner of the map area. It originates in clay-rich alteration zones common in the Puget Group (Vine, 1969). Some landslides may be seismically induced and (or) initiated during late Pleistocene deglaciation. (See unit Qaf.) (this study; Walsh, 1984; Booth, 1990; Powell, 1999; Sarikhan and Walsh, written commun.[1], 2007)

Qaf **Alluvial fan deposits (Holocene to latest Pleistocene)**—Debris-flow diamicton and alluvial sand, gravel, and boulder gravel; loose; mostly poorly to moderately sorted; massive to weakly stratified. The reduced gradients where streams emerge from confining valleys cause some of the sediment load to be deposited as a fan. Deposits mapped as unit Qaf were distinguished from those in unit Qls by the regular lobate geomorphology of alluvial fans. The Raging River alluvial fan and many smaller fans were partly mapped using lidar elevation data. Some fans may have been initiated as fan deltas that graded to glacial Lake Snoqualmie at the close of the last glaciation (see unit Qgog). Several of the fans emanating from the Seattle uplift (such as the Raging River fan)

[1] Map by I. Y. Sarikhan and T. J. Walsh, currently in review, tentatively titled "Issaquah Creek Watershed, Priority 3, Mass Wasting Assessment, Landslide Hazard Inventory Project, Washington Department of Natural Resources, Olympia, Washington".

may have been influenced by high sediment fluxes following tectonic events. (this study; Booth, 1990)

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Deposits of the Fraser Glaciation

Vashon Stade Recessional Deposits

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 thus contacts are typically gradational and interfingering. 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 (Anderson, 1965; 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. Glacial Lake Snoqualmie was a long-lived, ice-dammed lake that covered a substantial part of the map area during deglaciation (Mackin, 1941; Booth, 1990). The varying elevation of this lake controlled the altitude of many delta tops, strandlines, and recessional channels, as well as the distribution of most glaciolacustrine deposits. Many of these features indicate a persistent lake surface elevation of 320 to 400 ft. Inset recessional outwash bodies are graded to a local base level that lowered over time and resulted in younger kame and delta deposits being deposited at lower successive elevations. For example, it is apparent that delta tops are graded to a lowering glacial Lake Snoqualmie during deglaciation.

Our mapping shows that ice marginal meltwater followed several elevated pathways during the initial stages of glacial recession, depositing kame and lake sediments. Recessional sands have a mixed local “Cascade” provenance and northern metamorphic-granitic provenance, with recessional sediments fed by the Griffin Creek meltwater system containing more Cascade-provenance clast types. Recessional sands contain mostly northerly derived polycrystalline quartz and chert (8–24%), plagioclase (6–26%), metamorphic lithic clasts (14–15%), granitic lithic clasts (5–13%), volcanic lithic clasts (12–20%), and sedimentary lithic clasts (5–14%). Some volcanic and sedimentary lithic clasts are locally derived from sources such as the Puget Group. As compared to Snoqualmie River–provenance geologic units (units Qc_o and Qa; $Qm_{54\text{-}61}Qp_{28\text{-}38}PF_{8\text{-}12}$), recessional sands ($Qm_{43}Qp_{54}PF_4$) contain little potassium feldspar due to the scarcity of this mineral in metamorphic and plutonic rocks north of the map area (Dragovich, 2007). Deglaciation commenced about 14,000 yr B.P. along the Cascade foothills directly to the east, and the map area was probably fully deglaciated by about 13,700 yr B.P. (Porter and Swanson, 1998).

Qgos **Outwash sand (Pleistocene)**—Sand and pebbly sand, with some interbeds of silty sand, silt, or gravel; loose or soft; varies from nonbedded to weakly stratified to plane bedded, laminated, or rarely crossbedded. Facies relations, including vertical and horizontal fining trends, suggest deposition mostly as shallow-water glaciolacustrine deposits. Recessional sand, gravel, and lake deposits commonly interfinger. Some sand bodies are overlain by gravel and underlain by finer-grained lake deposits, such as unit Qgl_r, due to local deltaic progradation. (this study; Booth, 1990; Dragovich, 2007)

Qgl_r **Recessional glaciolacustrine (lake) deposits (Pleistocene)**—Silt, clayey or sandy silt, and silty sand, typically with scattered dropstones; may contain layers and lenses of sand or gravel; loose or soft; massive, laminated, or thinly bedded, with some varve-like rhythmites; locally contains soft sediment deformational features, including flames and sand dikes. Deposited in glacial lakes, such as glacial Lake Snoqualmie, or small lakes formed in kettles. Locally forms distinct upward-coarsening sequences from glacial lake (units Qgl_r and Qgos) to terrestrial environments (units Qgog and Qgof) due to progradation of fluvial-deltaic complexes. Otherwise upward-fining sequences record waning lake sedimentation during ice recession. (this study; Anderson, 1965; Booth, 1990)

Qgic **Stratified ice-contact deposits, undivided (Pleistocene)**—Bouldery cobbly gravel, diamicton, (silty) pebbly gravel, pebbly sand, and lesser sand and silt; loose; sorting highly variable, locally displays abrupt grain-size changes; mostly moderately stratified and medium to very thickly bedded. Ice-contact primary structures include collapse features (syndepositional slumps, oversteepened and contorted bedding). Interstratified soft diamictons are interpreted as melt-out till and flow till deposited on granular supraglacial, englacial, and subglacial meltwater deposits. Surface is hummocky or irregular as a result of sedimentation in, around, and on stagnant ice in controlled moraine(?) and pitted outwash-plain settings. Kettles and semi-open depressions are common. Some short NE–SW-trending ridges may be moraines. Large stratified ice contact deposits are commonly bounded on the southeast by relatively thick kame (for example, Griffin Creek kame delta) or ice-dammed lake deposits reflecting vigorous sedimentation adjacent to stationary ice. (this study; Anderson, 1965; Booth, 1990)

Locally divided into:

Qgi **Ice-contact deposits, melt-out, ablation, or flow tills (Pleistocene)**—Poorly exposed sandy silty pebble gravel to bouldery gravelly sandy silt; loose; massive or moderately interstratified with sand or gravel layers. Represents recessional silty diamicton deposited near melting ice. These deposits are spatially associated with other moderate to low-density near-ice deposits and occur above Vashon till. (this study, GeoEngineers, 1995; Associated Earth Sciences, 1987, 2003, 2005)

Qgie **Ice-contact deposits, eskers (Pleistocene)**—Sand and gravel, locally with boulders; loose; moderately to well sorted and stratified. Deposited as fluvial outwash, probably in ice tunnels. Forms two elongate sinuous hills surrounded by undivided ice-contact stratified drift east of Beaver Lake. The southernmost deposit may be an esker or alternatively may be an elongate ice-contact debris fan or till-cored ridge. (this study, Anderson, 1965)

Qgik **Ice-contact deposits, kames (Pleistocene)**—Sandy gravel, pebbly sand, sand, and cobble gravel, with scattered lenses of diamict (mostly melt-out till from buried ice blocks) in some areas; loose; medium to very thickly bedded, moderately to well stratified. Contains till or silt rip-up clasts, crossbedding, cut-and-fill structures, and oversteepened and slumped bedding. Lateral ice buttressing produced these elevated fluvial or deltaic deposits. We locally mapped fluvial outwash topset beds (unit Qgof) atop kame delta deposits where the topset–foreset contact was readily mapped and deltaic foreset bedding is conspicuous. For example, a kame delta perched against Snoqualmie ridge (site 2, Plate) contains high-amplitude foreset-bedded (boulder) gravels with silty diamicton lenses and is overlain by horizontally stratified meltwater deposits of fluvial origin (unit Qgof). Some kame deposits grade laterally into glaciolacustrine deposits (units Qgos and Qgl_r). For example, at site 3 (Plate) oversteepened deltaic foreset beds of sandy pebble gravel grade laterally into glaciolacustrine deposits. Includes the pitted outwash plain of the Griffin Creek kame delta complex. (this study; Anderson, 1965; Booth, 1990)

Qgof **Fluvial outwash deposits (Pleistocene)**—Boulder cobble gravel, pebbly sand, sand, and rare silt; loose; moderately to well stratified; mostly medium to very thickly bedded with local bar crossbedding. These deposits lack ice-contact features and occur mostly as topset beds above kame deltas. Also includes fluvial valley-train or nonpitted outwash plain deposits above glaciolacustrine or ice-contact sediments. The outwash plain in the northeastern corner of the map area contains braided channels that fed the later stages of the Griffin Creek delta (see lidar at http://pugetsoundlidar.ess.washington.edu/). Elsewhere, occurs as west to southwest-trending, 300 to 1000 ft wide recessional channels incised into older recessional ice-contact deposits.

Qgod **Deltaic outwash and kame deltas (Pleistocene)**—Sandy cobble gravel, gravel, and pebbly sand; loose; moderately to well sorted; thin to very thickly bedded and well stratified; contains high-amplitude planar foreset beds graded to temporary ice-dammed lake levels. Griffin Creek delta gravels contain volcanic clasts (~78%), metamorphic and granitic clasts (~17%), and sedimentary clasts (~5%) that indicate a Cascade provenance. Deltaic deposits commonly grade laterally to bottomset beds of glaciolacustrine sand (unit Qgos) and silt or clay (unit Qgl_r). Includes either deltaic front portions of large kames or smaller deltas graded to varying glacial Lake Snoqualmie levels. The small deltas are younger and lack evidence for near-ice deposition. They were fed by local upland streams that vigorously incised the newly exposed and unstable uplands surfaces. Includes part of the Griffin Creek kame delta (this study; Anderson, 1965; Booth, 1990)

Qgog **Outwash gravel deposits, undivided (Pleistocene)**—Poorly exposed bouldery pebble cobble gravel to pebbly cobbly sand; loose; massive to crudely bedded. Probably kame outwash deposits but may include any of the gravelly Vashon recessional facies described above. Gravels mapped around late-glacial strandlines are glacial Lake Snoqualmie beach deposits. The lower terraces mapped as unit Qgog in the Raging River valley may be perched Holocene bouldery old alluvium stranded during valley incision. (this study; Booth, 1990)

Vashon Stade Proglacial and Subglacial Deposits

Glacial flutes and drumlins show that the Puget lobe ice advanced over the map area from northwest to southeast (azimuth ~140°). Ice advance occurred about 14,500 yr B.P. (Porter and Swanson, 1998; Associated Earth Sciences, 2005) and blocked ancient rivers, creating an extensive temporary ice-dammed lake across much of the map area (Mackin, 1941; Booth, 1990; Associated Earth Sciences, 2005). The resultant glacial lake deposits (unit Qgl_v) are widespread and complexly interlayered with proglacial river and delta sediments (unit Qga_v)(Cross Sections A–C). Sands are a mixture of northern and local Cascade detritus. Advance outwash and lake deposits contain volcanic lithic clasts (15–21%), granitic lithic clasts (14–18%), chert–polycrystalline quartz (11–21%), plagioclase (10–15%), metamorphic lithic clasts (6–15%), and sedimentary lithic clasts (7–11%)(Dragovich, 2007). Sands contain more volcanic and sedimentary lithic clasts where deposited near bedrock. Vashon advance outwash (average $Qm_{39}Qp_{55}PF_6$) is similar to other outwash deposits. Advance outwash contains lower amounts of monocrystalline quartz (10–13%) and potassium feldspar (1–3%) than Cascade provenance deposits such as the Olympia beds ($Qm_{61}Qp_{28}PF_{12}$). (See units Qc_o, Qgo_p, and Vashon recessional deposits.)

Qgt_v **Vashon lodgment till (Pleistocene)**—Nonstratified, unsorted mixture of clay, silt, sand, and gravel (diamicton), commonly with disseminated cobbles and boulders in a silt-sand matrix; may contain lenses of sand and gravel; grayish blue to very dark gray, weathered to a mottled yellowish brown; dense; massive, matrix-supported, locally has a friable shear fabric. Clast types include both northern and local rounded to subangular clasts. May contain angular clasts where directly overlying bedrock. Till is generally 10 to 20 ft thick, but ranges from a thin veneer to a 100-ft-thick layer. Till was accreted at the base of Vashon ice and mantles topography. Geotechnical borings indicate that till locally occurs at a shallow depth in Snoqualmie valley (Cross Sections B, C). Till unconformably overlies mostly bedrock and advance deposits, but locally overlies older Quaternary deposits, particularly in areas of suspected active faulting and (or) growth folding (Cross Sections A–C). (this study; Anderson, 1965; Booth, 1990)

Qga_v **Advance outwash deposits (Pleistocene)**—Sand, sandy (pebble) gravel, and cobble gravel with local silt interbeds; typically dense; moderately to well sorted and stratified and thinly to very thickly bedded; deltaic foreset beds common; contains cut-and-fill structures, rip-up clasts, sand dikes, flames, and laminated silts observed in some outcrops. Composite sections of fluvial-deltaic advance outwash and glacial lake deposits (unit Qgl_v) are up to 220 ft thick and coarsen upwards locally. Advance outwash was deposited by streams issuing from the front

Table 1. Radiocarbon (^{14}C) ages from Olympia beds (unit Qc_o) and advance outwash (unit Qga_v) in the study area obtained by Associated Earth Sciences (AESI). Ages corrected for $^{13}C/^{12}C$ ratio; dates are years before present (yr B.P.), where present is 1950. Radiocarbon analyses by Beta Analytic, Inc. Includes subsurface AESI age samples located on Cross Sections A and B (see boring numbers) or AESI surface age samples located on the Plate (sites AES1 and AES2); includes a few AESI samples directly east of the study area (see notes). NA, not applicable.

Boring or site no.	Surface (sample) elevation (ft)	Unit Qc_o thickness (ft)	Unit Qc_o top elevation (ft)	Analyzed material	Radio-carbon age (yr B.P.)	Notes and references
EB-12 (AESI boring)	878 (799)	NA	756	organic sediment in unit Qga_v	14,500 ±130	Associated Earth Sciences (2005); sampled from N1 pond area; see Cross Section B near Lake Alice
MW-3 (AESI boring)	881 (702)	134	795	organic sediment in unit Qc_o	23,450 ±130	Associated Earth Sciences (2003); see Cross Section A directly south of Lake Alice
TW-1 (AESI boring)	~670 (~270)	429	559	organic sediment in unit Qc_o	24,750 ±980	Associated Earth Sciences (1987); located 1.3 mi directly east of MW-3 and 0.8 mi east of the Fall City 7.5-minute quadrangle in the Snoqualmie 7.5-minute quadrangle
TW-1 (AESI boring)	~670 (~500)	429	559	wood in unit Qc_o	25,280 ±330	Associated Earth Sciences (1987); located 1.3 mi directly east of MW-3 and 0.8 mi east of the Fall City 7.5-minute quadrangle in the Snoqualmie 7.5-minute quadrangle
TW-2 (AESI boring)	~830 (~530)	405	570	wood in unit Qc_o	29,460 ±1,380	Associated Earth Sciences (1987); surface site located 8.4 mi directly east of MW-2 and 0.14 mi east of the map area in the Snoqualmie 7.5-minute quadrangle
MW-4 (AESI boring)	811 (748.3)	134	795	organic sediment in unit Qc_o	29,650 ±230	Associated Earth Sciences (2005); see Cross Section B
AES1	~835 (~800?)	100?	~835	organic sediment in unit Qc_o	24,300 ±130	Associated Earth Sciences unpublished radiocarbon age (C. Koger, AESI, written commun., 2007); surface site AES1 on Plate directly west of Snoqualmie Parkway; sample from organic sediments and peat below Vashon till and gravelly recessional outwash
MW-2 (AESI boring)	812 (582)	57	631	organic sediment in unit Qc_o	31,700 ±330	Associated Earth Sciences (2005); N1/N2 study in cluster by old pit; see Cross Section B
MW-4 (AESI boring)	811 (746.5)	134	795	organic sediment in unit Qc_o	32,310 ±320	Associated Earth Sciences (2005); see Cross Section B
AES2	~970 (~955)	15+	~955	organic sediment in unit Qc_o	41,270 ±1,610	Associated Earth Sciences unpublished radiocarbon age (J. Saltonstall, AESI, written commun., 2007); located 0.15 mi directly east of radiocarbon site AES2 in the Snoqualmie 7.5-minute quadrangle; surface sample from organic sediments and peat below Vashon till and recessional gravel outwash; age may be slightly contaminated and thus infinite (note proximity of age to 40–44 ka limit of the radiocarbon age dating method)

of the advancing ice. This outwash fed many deltas that graded to proglacial lake elevations as high as 870 ft. Unit Qga_v conformably overlies, is complexly interlayered with, or may locally underlie unit Qgl_v, mostly as a result of deltaic migration. Unit Qga_v is overlain by Vashon lodgment till along a sharp contact (Cross Sections A–C). Associated Earth Sciences (2005) reports a ^{14}C age of 14,500 ±130 yr B.P. (Table 1; Cross Section B) similar to ^{14}C ages of 14,450 to 14,560 yr B.P. reported by Porter and Swanson (1998) from directly west of the study area. (Anderson, 1965; Booth, 1990; Associated Earth Sciences, 1987, 2003, 2005; Dragovich, 2007)

Qgl_v **Advance glaciolacustrine deposits (Pleistocene)**—Silt and clayey silt, locally with scattered dropstones and beds or lenses of massive diamicton that may be iceberg melt-out till or flow-till diamicton; commonly contains beds of laminated to thinly bedded silt ± sand with beds of gravel; stiff or dense; varies from massive to thinly bedded, laminated, or varved; contorted or folded bedding and sand dikes locally observed. This unit is typically overlain by and (or) interbedded with unit Qga_v (Cross Sections A–C). Site 15 (Plate) is a well-exposed example of thinly to thickly bedded silt, sand, and diamicton. Sands at this site are typical of the unit and contain mostly polycrystalline and monocrystalline quartz, plagioclase, hornblende, and metamorphic, volcanic, and granitic lithic clasts. Most outcrops contain dropstones, are interlayered or spatially associated with probable advance outwash, and thus likely to be Vashon lake deposits. However, some silt-clay exposures lacking these features but included in unit Qgl_v may be older glacial or nonglacial units. Unit includes some of the advance outwash or transitional beds of Booth (1990). (this study; Associated Earth Sciences, 1987, 2003, 2004; 2005; Dragovich, 2007)

Deposits of the Olympia Nonglacial Interval

Qc_o **Olympia beds (Pleistocene)**—Sand, silt, cobbly gravel, clay with some organic silt-clay, and peat; dense; laminated to very thickly bedded and mostly well stratified; may contain charcoal, disseminated organic matter, trough and ripple crossbedding, and flutes; very thick, massive to crudely graded beds of sand likely represent fluvial overbank levee deposits; may include lake deposits. Subsurface exploration by Associated Earth Sciences (1987, 2003, 2005) indicates that the Olympia beds on Snoqualmie ridge (Cross Sections A, B) form upward-fining gravel-sand-silt sequences typical of meandering river systems. Saltonstall and others (2003) indicate that the Vashon glacial deposits are geochemically distinguishable from Olympia beds. Mounted sand point-count and sand geochemical data (Dragovich, 2007) show that the Olympia beds in the eastern half of the map area are mostly ancient Snoqualmie River alluvium that varies from volcanic sand and tuffaceous silt to monocrystalline quartz-rich sand and polymictic silt. Volcanic sands and silts of Snoqualmie provenance (sites 14 and 18, Plate) contain abundant volcanic lithic clasts (22–87%) with monocrystalline quartz (3–21%), plagioclase (2–16%), granitic lithic clasts (1–11%), potassium feldspar (1–4%), sedimentary and metamorphic lithic clasts (1–11%), and hornblende-pyroxene (0–3%). Typical Olympia monocrystalline quartz-rich sands are similar to Holocene Snoqualmie River alluvium and contain monocrystalline quartz (20–24%), plagioclase (12–26%) with granitic lithic clasts (4–15%), sedimentary and metamorphic lithic clasts (1–10%), potassium feldspar (3–7%), and mica (~1%). The similarity between ancient and modern Snoqualmie River alluvium is best demonstrated by a comparison of December 2006 flood sands collected near Fall City (site 1, Plate) and elevated Olympia sands collected along Snoqualmie ridge (site 4, Plate). Both have very similar geochemical and sand point-count compositions (Dragovich, 2007). The geochemical similarity coefficient for these two samples is 0.94. These medium sands are modally similar with no category differing by more than 1.4% (greatest difference is monocrystalline quartz, 22.9% and 21.5%, ancient and modern respectively). Compared to glacial deposits, Olympia beds and modern alluvium contain more potassium feldspar and limited amounts of chert-polycrystalline quartz (2–9%). Unit Qc_o in the western half of the map area was deposited in alluvial, alluvial fan, and swamp settings. One Olympia alluvial-fan sand deposit (site 5, Plate) has a strong local Puget Group provenance with abundant sedimentary and volcanic lithic clasts, including scattered coal fragments (66%), monocrystalline quartz (12%), plagioclase (9%), and granitic-metamorphic lithic clasts (9%). The Olympia beds are likely faulted, folded, and uplifted within the Rattlesnake Mountain and Seattle fault zones (Cross Sections A–C)(see 'Quaternary Faulting in the Study Area'). A thick tan tuffaceous siltstone marker bed may be folded around the Tolt Hill growth fold. The Olympia nonglacial interval occurred from ~15,000 to 60,000 yr B.P. Associated Earth Sciences obtained nine surface and subsurface ^{14}C ages from Olympia beds around Snoqualmie ridge that range from 23,450 ±130 yr B.P. to 41,270 ±1,610 yr B.P. (sites AES1 and AES2, Table 1 and Plate; Cross Sections A, B). Olympia beds as shown here include some of the advance outwash or transitional beds of Booth (1990). (this study; Associated Earth Sciences, 1987, 2003, 2005; GeoEngineers, 1995; Booth and others, USGS, written commun.[2], 2007)

Deposits of the Possession Glaciation

Qgt_p **Till (Pleistocene)**—Nonstratified, unsorted mixture of clay, silt, sand, and gravel (diamicton), commonly with disseminated cobbles and boulders in a silt-sand matrix; weathered light tannish brown; very dense; massive and matrix-supported. Clast types include northern-provenance and locally derived, rounded to subangular clasts. Relative stratigraphic position is best constrained on the northern slopes of Snoqualmie ridge where an older till occurs under Olympia beds (Cross Sections A, B). Mafic volcanic clasts in this till have 0.8 to 1.0 mm weathering rinds, and there are some deeply weathered granite clasts. Tentatively correlated with the Possession Glaciation on the basis of stratigraphic position and weathering characteristics. The Possession Glaciation occurred from ~60,000 to 80,000 yr B.P. Includes part of the pre-Olympia deposits of Associated Earth Sciences (2003, 2005) and part of the pre-Fraser deposits of Booth (1990).

Qgo_p **Outwash (Pleistocene)**—Fluvial (cobble) gravel and (pebbly) sand and minor silt and rare glaciolacustrine gravelly silt; gray to weathered and iron-stained; very thick crudely defined beds typical; locally laminated or medium bedded with crossbeds and scours; very dense. Contains northern-provenance and locally derived, rounded to subangular clasts. Sands contain volcanic lithic clasts (10–16%), granitic lithic clasts (9–11%), chert-polycrystalline quartz (14–20%), plagioclase (9–11%), metamorphic lithic clasts (8–10%), and sedimentary lithic clasts (6–15%)(sites 6–7, Plate; see Dragovich [2007] for other sites). Sands contain low amounts of monocrystalline quartz and potassium feldspar relative to nonglacial units ($Qm_{54-61}Qp_{28-38}PF_{8-12}$) and have, on average, $Qm_{37}Qp_{59}PF_4$ composition similar to other glacial outwash ($Qm_{37-43}Qp_{54-59}PF_{4-6}$). Relative stratigraphic position is best constrained on the northern slopes of Snoqualmie ridge where very compact older outwash and till with a northern provenance occur beneath dated Olympia beds (site 6, Plate; Cross Sections A, B). Similar compact, northern provenance outwash also occurs at site 7 (Plate) near the Seattle fault zone. We emphasize the tentative nature of this correlation with Possession Glaciation.

Pre-Fraser Glacial and Nonglacial Deposits

Qgn_{pf} **Glacial and nonglacial deposits, pre-Fraser (Pleistocene to Pliocene?)**—Sand, silt, clay, (boulder) gravel, peat, and diamicton; dense to very dense; mostly below older till (unit ot) in the subsurface, locally includes thick nonglacial stratigraphic sections containing conspicuous organic-rich layers (Cross Sections A–C). Booth (1990)

[2] Map by D. B. Booth, T. J. Walsh, K. G. Troost, and S. A. Shimel, currently in review, projected to be released as "Geologic map of the Issaquah 7.5-minute quadrangle, King County, Washington: U.S. Geological Survey Scientific Investigations Map XX, 1 sheet, scale 1:24,000. [http://geomapnw.ess.washington.edu/services/publications/map/data/Issaquah_6-29-06.pdf]

reports strong oxidation, grusification, rind development, and clay mineral development for some pre-Fraser exposures. Includes some areas mapped as pre-Fraser sediments by Anderson (1965), Walsh (1984), and Booth (1990) and unit 0 (ancient colluvium) by Johnson and O'Connor (1994) that were not examined during this study. Locally divided into:

Qc_w **Whidbey Formation (Pleistocene)**—Silt, clay, peat, sand, and pebbly sand and some gravel; some fine-grained strata contain disseminated organic material, logs, or sticks; mostly well stratified and thinly laminated to thickly bedded; mapped mostly in the subsurface (Cross Sections A–C). However, an exposure of dense laminated silt with ashy layers and probable thin organic-rich laminae northwest of MW-4 (Cross Section B) is tentatively correlated with the Whidbey Formation. The depositional environment for the nonglacial Whidbey Formation (~80,000–125,000 yr B.P.) may include ancient Snoqualmie River alluvium and lacustrine deposits.

oo **Older outwash (Pleistocene)(cross sections only)**—Dense sand and gravel. Occurrences of unit oo are spatially associated with unit ot and may be advance outwash of the Double Bluff glaciation (~125,000–185,000 yr B.P.). We assign an informal geologic unit symbol to emphasize the tentative nature of the correlation with older glaciations.

ot, oot **Older tills (Pleistocene)(cross sections only)**—Dense diamicton; may be till of the Double Bluff glaciation (Cross Sections A–C). A lower diamicton designated as older older till (unit oot on Cross Sections B, C) is likely pre-Double Bluff(?) in age. We assign an informal geologic unit symbol to emphasize the tentative nature of the correlation with older glaciations.

Tertiary Volcanic, Sedimentary, and Intrusive Rocks

Mvc **Volcanic and Sedimentary rocks (Miocene)(cross sections only)**—Nonmarine tuffaceous and volcanic sandstone, volcanic to polymictic conglomerate, hornblende tuff, claystone, siltstone, and lignite exposed west of the map area; locally contains logs; sandstone is tuffaceous, mostly friable, well sorted, massive to crossbedded, and commonly muscovitic. Porphyritic andesite or basalt is the most common rock type in the conglomerate. Our petrography on samples collected west of the map area indicates that some of the volcanic sandstones and conglomerates are hyperconcentrated flood deposits composed of moderately to well sorted andesitic clasts (~85%), plagioclase ± quartz, and minor exotic clasts. Unit Mvc overlies the Blakeley Formation. We infer thrusting of the Puget Group over unit Mvc in the map area. (See Seattle fault no. 3 on Cross Section C and 'Quaternary Faulting in the Study Area'.) Ages west 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). Lignites and siltstones have a middle Miocene flora pollen (Sherrod and others, 2002). Includes the informally named Vasa Park tuff and is chronostratigraphically equivalent to the marine Blakeley Harbor Formation near Seattle. (Yount and Gower, 1991; Booth and others, USGS, written commun.[2], 2007)

Φvc **Ohanapecosh Formation (Oligocene)(cross sections only)**—Two-pyroxene andesite flows and tuffs with rare tuff breccia and volcanic siltstone. We infer that unit Φvc occurs in transpressional basins below the Snoqualmie River valley (Cross Sections A, B). The formation has produced plant fossils assigned to the Kummerian Stage (Wolfe, 1968; Vine, 1969) and K-Ar and zircon fission-track ages of ~25 to 36 Ma. Includes volcanic rocks of Rattlesnake Mountain southeast of the map area (Fig. 1 on Plate) where the unit is locally heavily altered and deformed within the Rattlesnake Mountain fault zone. See Tabor and others (1982) and Dragovich and others (2002) for tentative correlation of the Rattlesnake Mountain volcanics with the Ohanapecosh Formation. (Walsh, 1984; Tabor and others, 1993)

ΦEn **Blakeley Formation (Oligocene to Eocene)(cross sections only)**—Nearshore feldspathic to lithic (tuffaceous) sandstone, conglomerate, tuff, and minor siltstone and shale; massive to well bedded; quartz, feldspar, and lithic volcanic grains present in varying amounts; deposited in a shallow marine to coastal environment and distinguished from older Renton Formation by presence of marine fossils and by the absence of micaceous sandstone. We infer thrusting of the Puget Group over mostly Blakeley Formation in the map area. (See Seattle fault no. 3 on Cross Section C and 'Quaternary Faulting in the Study Area'.) Sherrod and others (2002) report a fission track age of 31.6 ±2.1 Ma. Middle to late Oligocene foraminifera (Zemorrian) are typical (Fulmer, 1975; Walsh, 1984), but there are late Eocene foraminifera (Refugian Stage) in the lower part of the unit. (Walsh, 1984; Yount and Gower, 1991; Booth and others, USGS, written commun.[2], 2007)

Ev? **Volcanic rocks of Mount Persis (Eocene)(cross sections only)**—Porphyritic two-pyroxene andesitic flows, breccia, and tuff, with some basalt and dacitic breccia and rare interbedded volcanic sandstone, siltstone, and conglomerate. Unit Ev occurs directly east of the map area as a small knob in the Snoqualmie valley (Fig. 1) and is inferred to be faulted against younger Tertiary rocks across Rattlesnake Mountain fault no. 1 (Cross Section C). This late(?) Eocene unit was intruded and metamorphosed by the 34 Ma Index batholith and has produced a poor hornblende K-Ar age (38.1 Ma) and an apatite fission-track age (47.4 Ma). Includes the Snoqualmie Falls volcanics. (Tabor and others, 1993, 2000)

Ei **Andesite porphyry dikes and sills (Eocene?)**—Sills and dikes of andesite porphyry that are mostly too small to show at map scale. They invade many Raging River (unit Em_r) Formation and Tiger Mountain (unit Ec_t) outcrops and are exposed in the core of the Raging River anticline, particularly around the fold axis (Cross Sections A, B). These sills may have been fed by a laccolith(?) or stock(?) at depth that produced a prominent magnetic high over the Raging River Formation in the southern part of the map area (Fig. 2 on Plate). This body may be another subvolcanic intrusive center to the extrusive Tukwila Formation. However, we cannot exclude the possibility that this magnetic high is partially or wholly reflective of shallow intrusion of the mafic Snoqualmie batholith rocks observed at the surface south of the study area.

PUGET GROUP

The Puget Group 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 volcanism of the Tukwila Formation erupted onto this coastal plain and interrupted the fluvial deposition. The Tukwila Formation occurs between the Renton and Tiger Mountain Formations in the local area. The intrusive equivalent to the mostly extrusive Tukwila Formation occurs directly west of the southwest corner of the map (Vine, 1962)—a premise consistent with overall fining trends away from the intrusive. However, other volcanic centers are possible (see unit Ei). Away from this volcanic center, the volcanic rocks of the Tukwila Formation are absent and only Puget Group fluvial-deltaic rocks occur. The top of the Tukwila Formation forms a relatively sharp contact with the overlying Renton Formation, indicating a rapid extinction of volcanism or perhaps a period of erosion prior to deposition of the Renton Formation. Conversely, the top of the Tiger Mountain Formation interfingers with the Tukwila Formation indicating volcanic sedimentation onto the adjacent fluvial plains early in the volcanic episode. The Puget Group overlies the marine Raging River Formation.

Ec_r **Renton Formation (middle? to late Eocene)**—Continental (nonmarine) feldspathic to lithofeldspathic subquartzose sandstone, with interbedded carbonaceous claystone, siltstone, and subbituminous coal beds; sandstone is characteristically micaceous and light gray to white, fine to medium grained, and crossbedded to massive. Sandstones contain quartz (30–45%), plagioclase and potassium feldspar (40–50%), and lithic grains (10–20%). The Renton Formation may be as much as 4900 ft thick regionally, but is ~4100 ft thick in the map area (Cross Section C). Near the Reynolds mine (site 8, Plate) and farther south along Grand Ridge, we have expanded the geographic extent of unit Ec_r by not showing overlying Quaternary deposits. The Renton Formation was deposited as a meandering river channel and overbank sediments but may locally include nearshore marine deposits. Contains plant fossils of the Ravenian and Kummerian stages of Wolfe (1968) and conformably overlies the Tukwila Formation dated by Turner and others (1983) to ~42.0 ±2.4 Ma. (Vine, 1969; Walsh, 1983, 1984; Yount and Gower, 1991; Tabor and others, 2000)

Evt_t **Tukwila Formation, tuff (middle Eocene)**—Nonmarine andesitic tuff breccia, lapilli tuff, and tuff, and minor basaltic dikes (unit MEib), volcanic sandstone, tuffaceous siltstone, and mudflow breccia and conglomerate of mostly laharic origin; mostly poorly to nonstratified; includes massive porphyritic andesite dikes, sills, or possibly flows (columns and flow breccia rare or absent); mostly massive, but sedimentary interbeds or aligned welded clasts in pyroclastic beds indicate bedding structure. Tuff breccia typically contains a lithic crystal vitric or crystal vitric tuff matrix with abundant plagioclase ± pyroxene and (or) hornblende crystals. The matrix surrounds scattered breccia clasts of similar intermediate composition. Clasts are porphyritic andesite, locally with some dacite. Chemical analyses of a lapilli tuff (site 9, Plate), crystal vitric tuff (site 10, Plate), and a lahar clast (site 11, Plate) indicate andesitic to almost dacitic chemical composition (58.98–60.85% SiO_2). Aphanitic dikes (unit MEib) are basaltic (site 12, Plate; 46.7% SiO_2; Dragovich, 2007) and may be younger than the formation. The Tukwila Formation is regionally as thick as 6800 ft and was deposited as an andesitic stratovolcano complex with one or possibly more volcanic centers. Block and ash flows deposits are common. The lower part of the formation is interstratified with unit Ec_t fluvial deposits (Cross Sections A, B). The top of the formation is overlain by unit Ec_r fluvial deposits (Cross Section C). Contains fossil leaves referable to the Ravenian floral stage (Wolfe, 1968). Turner and others (1983) reported middle Eocene fission-track and K-Ar ages of 39.4 ±2.4 to 45.7 ±2.7 Ma (avg. 42.0 ±2.7 Ma) near the top of the formation west of the map area. (Vine, 1962, 1969; Walsh, 1984; Yount and Gower, 1991; Tabor and others, 1993, 2000; Booth and others, USGS, written commun.[2], 2007)

Locally divided into:

Evs_t **Tukwila Formation, volcanic and sedimentary rocks (middle Eocene)**—Nonmarine volcanic sandstone, tuff, lapilli tuff, and tuffaceous siltstone with some intercalated volcanic conglomerate, feldspathic sandstone, carbonaceous shale, siltstone, and impure coal beds; typically thinly to very thickly bedded; moderately to well stratified and sorted; coalified organic debris, such as sticks, are common. At site 13 (Plate), an andesitic to dacitic (62.5% SiO_2) crystal vitric lapilli tuff is interbedded with volcaniclastic rock containing coalified logs. Includes andesitic hyperconcentrated flood, lahar, alluvial fan, and alluvial deposits with pyroclastic beds. Unit occurs as broad lenticular bodies that are typically hundreds of feet thick (Cross Sections A–C) and represent either proximal drainages emanating from the Tukwila volcanic center(s) or more distal aprons of volcaniclastic rocks that grade laterally to the more mature Tiger Mountain Formation plain deposits that are rich in coal (swamp) deposits. (Vine, 1962, 1969; Walsh, 1984; Yount and Gower, 1991; Tabor and others, 1993, 2000; Booth and others, USGS, written commun.[2], 2007)

Ec_t **Tiger Mountain Formation (middle Eocene)**—Micaceous feldspathic to feldspatholithic subquartzose to rarely quartzose sandstone interbedded with carbonaceous siltstone, siltstone, minor pebble conglomerate, and coal beds; light colored; typically well stratified, laminated to thickly bedded; moderately to well sorted; mostly plane laminated to crossbedded. Sandstones contain monocrystalline quartz (~28%), plagioclase feldspar (~29%), volcanic lithic clasts (~21%), sedimentary lithic clasts (~8%), polycrystalline quartz (~3%), chert (~3%), biotite (~3%), and a trace of metamorphic lithic clasts and potassium feldspar. Unit is ~2000 ft thick. The fluvial upper part of the formation is interstratified with the Tukwila Formation and has a magmatic arc or arc orogen provenance. A prodelta shelf setting is suggested for the lower part of the formation because of the interfingering between the marine Raging River and Tiger Mountain Formations on Tiger Mountain (Cross Sections A, B). These shelf deposits occur between the fluvial deposits of unit Ec_t and bathyal (deep water) marine sediments of unit Em_r. Contains fossil leaves referable to the Fultonian floral stage (Wolfe, 1968). (See units Evt_t and Em_r for age constraints.) (Vine, 1962, 1969; Walsh, 1984; Yount and Gower, 1991; Tabor and others, 1993, 2000; Johnson and O'Connor, 1994)

RAGING RIVER FORMATION

Em_r **Raging River Formation (early? to middle Eocene)**—Subquartzose lithic to feldspatholithic volcanic sandstone, siltstone, and shale, locally containing pebble conglomerate; conglomerate clasts mostly volcanic lithic sandstone and (or) chert pebbles; typically medium to very thickly bedded; shallow marine to fluvial lower part of formation contains plane laminated to hummocky beds, locally with fining-upward sequences, scours, and bioturbation; fluvial middle part of formation contains imbricated deposits, paleosols, low-angle (braided river) stratification and scours; bathyal to outer-shelf marine uppermost part of formation contains hummocky bedded to ripple laminated or massive bioturbated beds. Sandstone contains volcanic lithic clasts (28–40%), plagioclase (12–33%), monocrystalline quartz (13–33%), polycrystalline quartz (3–8%), sedimentary lithic clasts (3–10%), and chert (0–4%), with some metamorphic lithic clasts and mica. Sandstone composition varies strongly with shifting provenance but generally has a pre-Tertiary mélange belt and (or) Tertiary volcanic provenance.

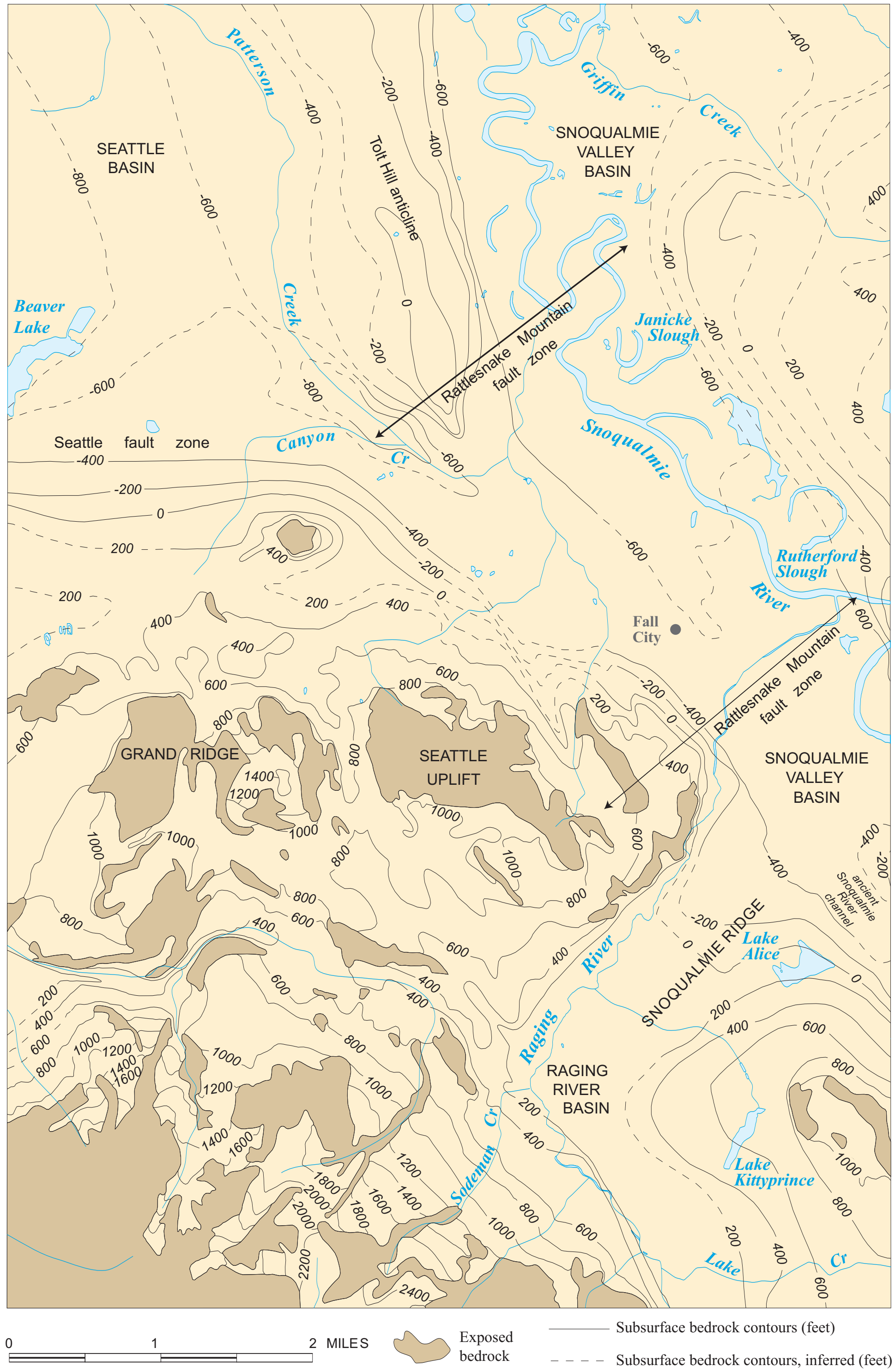

Figure 3. Top-of-bedrock contour map of the Fall City 7.5-minute quadrangle (contour interval 200 ft above and below sea-level). Approximate Quaternary–Pliocene(?) deposit thickness can be obtained by comparing top-of-bedrock elevations (this map) with the Fall City topographic base map (Plate). This map was compiled using surface mapping, water well and boring logs, and existing published and unpublished depth to bedrock information (Jones, 1996; Turney and others, 1995; M. Jones, USGS, written commun., 2007). Geophysical data (Fig. 2 on Plate) was consulted in areas of sparse data (see approximate contacts). Dark polygons are bedrock outcrops or shallow bedrock overlain by a thin mantle of till and (or) landslide deposits. The main data source was 852 water wells and ~550 geotechnical borings, as well as some test pits; 281 wells or borings penetrated the top of bedrock. Includes areas of intensive geotechnical investigation, such as along major highways and on Snoqualmie ridge, western Grand Ridge, and southeastern Tolt Hill where multiple shallow geotechnical borings firmly established minimum bedrock depth and (or) provided clear top-of-bedrock topographic information. (For example, GeoEngineers [1995], Dept. of Transportation borings, and all referenced Associated Earth Sciences reports.) See text for a discussion of the basins, growth folds, and faults zones inferred from this map.

Thickness is at least 3300 ft (base is not exposed). The lower part of the formation is shallow marine to terrestrial fluvial, the middle part is fluvial, and the upper part is marine shelf to bathyal slope deposits and contains some turbidites. This sequence suggests that the lowermost part of the Tiger Mountain Formation (unit Ec_t) is shallow marine. Unit Em_r is exposed in the core of the Raging River anticline, where sills and dikes of andesite porphyry (unit Ei), mostly too small to show at map scale, invade many Raging River Formation outcrops, particularly around the Raging River fold axis (Cross Sections A, B). Unit Em_r locally contains abundant marine mollusks, plant fossils, radiolarians, pelecypods, and gastropods. Foraminifera in the upper part of the formation are of the *Bulimina* cf. *B. jacksonensis* zone, which correlates with the lower part of the Narizian benthic foraminiferal stage (W. Rau, DGER, written commun. to Johnson and O'Connor, 1994). (Vine, 1962, 1969; Walsh, 1984; Johnson and O'Connor, 1994; Yount and Gower, 1991; Tabor and others, 1993, 2000)

Tertiary to Recent Tectonic Zones

tz **Tectonic zones (Tertiary to Recent)**—Protomylonite, mylonite, cataclasite, fault breccia, and strongly slickensided and fractured rocks in fault zones. Most kinematic indicators, such as shallow slickenlines on steep shear planes and (or) en echelon vein arrays, suggest strike-slip or oblique-slip faulting. Some of these zones align with mild to intense siliceous, argillic, and ferric hydrothermal alteration zones and (or) fault zones mapped by Vine (1969) directly south of the map area. Tectonic zones are argillically altered on Mitchell Hill (this study). (See 'Quaternary Faulting in the Study Area' for deformation of Quaternary sediments, particularly along Rattlesnake Mountain fault nos. 4 and 5 [Cross Section C]).

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

KJm **Western mélange belt (Cretaceous to Jurassic)(cross sections only)**—Dominantly metamorphosed argillite, sandstone, greenstone, and diabase with some metachert, metatonalite, metagabbro, slate, phyllite, marble, and ultramafite (Fig. 1; Tabor and others, 1993). The mélange is inferred to underlie the easternmost portion of map area east of Rattlesnake Mountain fault no. 1 (Cross Section C). Walsh (1984) reports Cretaceous or Jurassic radiolarians from the mélange south of the map area (site 3, Fig. 1). (See 'Quaternary Faulting in the Study Area'.)

QUATERNARY FAULTING IN THE STUDY AREA

The Seattle and Rattlesnake Mountain fault zones (Fig. 1)—both with numerous strands, some possibly active—interact in the map area. The fault strands that make up these fault zones are mapped on the basis of the interpretation of geographic, geophysical, geomorphic, and stratigraphic lineaments and (or) anomalies as well as the interpretation of deformational features observed both locally and more regionally. Most of the faults are shown as inferred and should be considered interpretive extensions of previously mapped faults. We have queried faults where (1) the evidence of faulting is only indirect (for example, geophysical lineaments), and (or) (2) the evidence for faulting is made on the basis of poorly exposed outcrop information. In the following, we provide some of the data, observations, and interpretations related to fault and fold mapping in the map area. Available information indicates that these structures have been active in the Pleistocene and locally in the Holocene.

Rattlesnake Mountain Fault Zone

We have divided the Rattlesnake Mountain fault zone (RMFZ) into five strands in the map area. The RMFZ was originally mapped on Rattlesnake Mountain southeast of the map area by Walsh (1984). We project the RMFZ north of the map area and correlate this structural zone with the Southern Whidbey Island fault zone, consistent with Rogers and others (1996) and Sherrod (USGS, written commun., 2007)(Figs. 1 and 2 on Plate). We suggest that much of the Snoqualmie valley is structurally controlled (Fig. 1). Strike-slip offset is suggested for the RMFZ by (1) the northerly vergence on the Seattle fault zone, (2) the outcrop structures (this study; Walsh, 1984; Walsh and Logan, 1985), and (3) the fault strand linearity. Several small strike-slip basins and en-echelon fold axes may occur within the fault zone (Fig. 1), including the informally named Snoqualmie valley basin (Fig. 3).

Thinning of the strata across the fold axes (Cross Sections A–C), most bedding attitudes in Olympia and older beds, and the geometry of the bedrock in the subsurface (Fig. 3) are evidence for growth folds on Snoqualmie ridge and Tolt Hill. The evidence is most compelling on Tolt Hill, where bedrock approaches the surface along the mapped anticlinal axis and subsurface data suggests that older Quaternary strata, including nonglacial strata, approach the surface (Cross Section C; Associated Earth Sciences, 2000a,b). Tolt Hill is also associated with a mild magnetic high (Fig. 2, anomaly TH), which corresponds well with shallow, moderately magnetically susceptible nonglacial Olympia beds and Miocene rocks as determined by field susceptibility measurements (average 3.43×10^{-3} SIU, 95% confidence 0.35×10^{-3}; other glacial ~2×10^{-3} SIU). Moderately dipping beds on the flank of Tolt Hill are also consistent with an anticline, particularly at site 14 (Plate) where well-exposed Olympia tuffaceous siltstones dip 34 degrees to the southwest away from the anticlinal axis. These tannish tuffaceous siltstones are observed at three locations on Tolt Hill (sites 14, 18 [Plate], and along northwest Tolt Hill) and may form a marker bed that rises and thins as the fold axis is approached.

Growth folding may also extend north of the map area (sites 1–2, Fig. 1). For example, a growth fold northeast of Tolt Hill (site 1, Fig. 1) contains elevated nonglacial volcanic sands along its inferred axis. We speculate that fold growth here is interrupted by extensional basin development in this part of the Snoqualmie River valley. An alternative to the Tolt Hill growth fold hypothesis involves glacial shear to explain the tilt of the Olympia beds and the apparent thinning of the strata across the crest of the hill. In this scenario, the normal draping of strata over a nontectonic paleogeographic high may explain our observations.

Rattlesnake Mountain fault no. 1 (RMF-1) is the main strand of the RMFZ (Fig. 1). Available information indicates that this fault regionally juxtaposes pre-Tertiary mélange belt basement rocks east of the main strand against thick Tertiary rocks that lack a pre-Tertiary basement west of the fault. This is similar to the basement geometry across the Southern Whidbey Island fault zone, where Tertiary Olympic peripheral rocks are faulted against pre-Tertiary basement and overlying Tertiary rocks (Johnson and others, 1996; Brown and Dragovich, 2003). This is best demonstrated at the base of Rattlesnake Mountain (site 3, Fig. 1) where rocks of the

Cretaceous–Jurassic Western mélange belt containing Mesozoic radiolarian-bearing metasedimentary rocks, greenstones, and serpentinites are in fault contact with Tertiary volcanic rocks (Fuller, 1925; Walsh, 1984; Walsh and Logan, 1985). We infer that RMF-1 juxtaposes Tertiary and pre-Tertiary rocks in the map area (Cross Section C).

In the map area, RMF-1 bounds a gravity low just east of Fall City, as well as buried bedrock escarpments evident in the top-of-bedrock topography, and bounds part of the Snoqualmie valley basin—a structural feature we suggest is related to transpressional or transtensional faulting along strands of the Rattlesnake Mountain fault zone (Figs. 1–3 and Cross Section C). We tentatively project RMF-1 across the Snoqualmie valley basin (SB on Fig. 2) in the northern part of the Fall City quadrangle and toward a strong lineament and other anomalies in the Carnation quadrangle. In the Carnation quadrangle, the trace of RMF-1 aligns with a northwest-trending lineament near Ames Lake and is inferred to follow the linear break in slope formed between Snoqualmie valley and glacial uplands north of Ames Lake (site 4, Fig. 1). This portion of the projected fault follows a long linear magnetic low that separates moderate magnetic highs evident on upward continued magnetic maps of the area (Blakely and others, 1999; R. Blakely, USGS, written commun., 2007). Directly to the northwest of the linear magnetic low, the RMF-1 aligns with the Cottage Lake lineament of Blakely and others (2004). The lineament is an active Southern Whidbey Island fault zone strand in the Woodinville area, west of the Carnation 7.5-minute quadrangle (R. Blakely, USGS, written commun., 2007). Holocene displacement on the main strand may occur at two locations: (1) along the eastern base of Rattlesnake Mountain where a small exposure reveals possible faulted Holocene colluvium (Josh Logan, DGER, oral commun., 2007); and (2) north of Ames Lake (Fig. 1), where deformed recessional outwash (identified by J. Dragovich, 2006) is likely tectonically offset (Fig. 4 on Plate). Further work is required to discount landslides or glacial deformation as possible causes of structural features for both these sites. Growth folding and (or) uplift across RMF-1 north of Ames Lake is consistent with the occurrence of paleogeographic highs beneath Bear Creek Plateau (site 4, Fig. 1). There, westerly tilted(?) pre-Possession-age deposits can be found at elevations up to 560 ft and Olympia beds at elevations up to 650 ft (Saltonstall and others, 2003; Associated Earth Sciences, 2004; Dragovich, 2007).

Quaternary faulting along the Southern Whidbey Island fault zone near Woodinville (Blakely and others, 2004; Brocher and others, 2005; Sherrod and others, 2005) occurs along our projection of the RMFZ (site 5, Fig. 1). The alignment, width, pre-Tertiary basement geometry, and apparent activity of both the RMFZ and the Southern Whidbey Island fault zones provide a compelling case for the correlation of these fault zones as first elucidated by Rogers and others (1996), Brown and Dragovich (2003), and Sherrod (USGS, written commun., 2007).

The 5.3-magnitude Duvall earthquake occurred northeast of the main strand (site 6, Fig. 1). One main-shock focal mechanism solution suggests a north-northwest-striking, moderately east-northeast-dipping fault (Pacific Northwest Seismic Network, http://www.ess.washington.edu/SEIS/PNSN/). This solution, combined with the depth of the earthquakes, implies that the fault may be on the down-dip extension of one of the faults west of the epicenter (Fig. 1). We speculate that the dip of the fault zone here may be due to a restraining bend where the RMFZ bends slightly to the northwest to meet the Southern Whidbey Island fault zone. This bend may also be coincident with a transition from mostly strike-slip faulting evident along the RMFZ (Walsh and Logan, 1985; this study) to reverse faulting proposed by Brocher and others (2005) along the Southern Whidbey Island fault zone. A change from strike-slip to reverse faulting is also consistent with along-strike variation in structural style of the Southern Whidbey Island fault zone (Blakely and others, 2004; Brocher and others, 2005; Sherrod and others, 2005; B. Sherrod, USGS, written commun., 2007).

Rattlesnake Mountain fault no. 2 (RMF-2) is a possible active fault that may offset the Raging River alluvial fan. The fault is suggested by possible southwest-side-up scarps interpreted from aerial photographs, as well as by topographic anomalies noted in the field. Lidar images of the RMF-2 area do not unequivocally support a fault across this urbanized alluvial fan. However, elevation contours of the detailed lidar elevation data suggest an inflection in the slope of the fan approximately along the inferred trend of the fault. Alternatively, the scarps may be fortuitously aligned geomorphic features, such as abandoned channels or fluvial terraces, developed on the Raging River alluvial fan. RMF-2 may also align with topographic lineaments along the northernmost slopes of Snoqualmie ridge.

Rattlesnake Mountain faults nos. 3 and 4 (RMF-3 and -4) are mapped on the basis of several stratigraphic, geomorphic, and geophysical anomalies across these structures (Figs. 1–3). Lineaments on Snoqualmie ridge align with Rattlesnake Mountain faults mapped by Walsh (1984) directly southeast of the map area. These faults merge to form a major fault separating Eocene and Oligocene volcanic rocks on Rattlesnake Mountain (Fig. 1). South of Fall City and in the map area, the faults coincide both with a boundary between a magnetic high associated with Tukwila Formation units on the flanks of the Raging River anticline and a magnetic low under the Snoqualmie valley basin (Fig. 2). Below northeastern Snoqualmie ridge, RMF-4 locally bounds steep bedrock contours and both faults bound an ancient Snoqualmie River channel (Fig. 3) that was first documented by Associated Earth Sciences (1987). These faults are inferred to be strike-slip to oblique-slip faults, bounding the west side of the Snoqualmie valley basin (Fig. 3).

The Snoqualmie valley basin is a magnetic and gravity low (SB in Fig. 2). The gravity low is obscured to the north, where the valley merges with the larger amplitude gravity low associated with the greater Seattle basin. However, the probable fault bounding, a deep basement rock/sediment interface, and both of the anomaly lows suggest a potential pull-apart basin origin for much of the Snoqualmie valley. The thickening of the Olympia beds to at least 430 ft (Cross Section A) on Snoqualmie ridge is attributed to valley fluvial aggradation in the Snoqualmie River structural basin (Table 1; Cross Sections A–C). Variation in Olympia bed thickness suggests that RMF-3 has the most Quaternary vertical displacement. Olympia bed sands, consisting of ancient Snoqualmie River alluvium, at 480 ft on Snoqualmie ridge (site 4, Plate) are very similar both geochemically and modally to modern Snoqualmie River alluvium (Dragovich, 2007). This observation, combined with the overall thickening of the Olympia beds in the basin, argues for Quaternary tectonism along basin margin faults to account for all the stratigraphic, structural, and geophysical anomalies across Snoqualmie ridge. Otherwise, we have difficulty explaining the anomalies by normal valley aggradation in the Quaternary—alluvial river deposits along major rivers in western Washington are typically only tens of feet thick. Furthermore, sea level was about 160 to 260 ft lower during the deposition of the nonglacial Olympia beds (Lambeck and others, 2002) and thus Snoqualmie River entrenchment, not Olympia bed aggradation, should be the norm in the foothills.

RMF-3 and RMF-4 merge along the eastern side of Tolt Hill near a magnetic boundary that is steep enough to be a fault (Fig. 2). This magnetic boundary parallels, but is not completely coincident with, the topographic contact between Tolt Hill and Snoqualmie valley. It appears spatially related to the boundary between the Snoqualmie valley basin and Tolt Hill anticline (Fig. 3), but may not be completely coincident because the boundary of the anticline may be dipping or in some other way complex. We found no evidence for post-Olympia offset on RMF-3 and RMF-4 and currently regard these structures as dormant strands.

Rattlesnake Mountain fault no. 5 (RMF-5) (site 7, Fig. 1) is indicated by deformed Olympia beds, magnetic anomalies (Fig. 2), and top-of-bedrock geometry (Fig. 3). The fault also bounds the inferred Tolt Hill anticline (growth fold?) (Cross Section C). The fault deformation is best exposed along the foot of Tolt Hill (site 5, Plate), where conspicuous fractures and sand dikes pervade tilted Olympia bed strata. The steep, northwest-trending fractures are tightly spaced, and some contain liquefaction features, including thin sand selvages or broader pebbly sand dikes. Similar northwest-trending fractures occur at site 14 (Plate), where compact beds dip 34 degrees to the west-southwest away from the proposed Tolt Hill anticline. Detailed mapping around this site indicates that these beds are likely tectonically tilted and not deformed as a result of landslide slumping or glacial shear. Brecciated Pleistocene nonglacial beds occur in the subsurface (Associated Earth Sciences, 2000a) and also align with this fault (Cross Section C, unit tz). The compact nature of the beds and deformational features at sites 5 and 14 (Plate) suggest that fault offset is pre-Vashon. A 3-ft-thick clastic dike intruding advance outwash is exposed in a gravel mine 1500 ft northwest of site 14 (Plate). The north-trending dike contains friable silty sand with scattered pebbles and is likely a clastic dike (not a fault) formed during a late Pleistocene or Holocene liquefaction event. If this feature is a fault, the alignment of deltaic beds on either side of this structure indicates a pure strike-slip fault.

Seattle Fault Zone

The Seattle fault zone is defined as a series of east–west-striking reverse faults, thrusts and folds in a ~2-mi-wide zone in the west-central part of the map area. The Seattle fault zone terminates at the RMFZ in the center of the map area. Two models have been proposed for the Seattle fault zone: (1) a thrust fault with multiple strands including backthrusts and a major fault bend fold (Pratt and others, 1997; ten Brink and others, 2002) and, (2) a passive duplex (Brocher and others, 2004). Model 1 best explains the structural relations along the easternmost portion of the Seattle fault (Liberty and Pratt, written commun.[3], 2007; this study). A substantial part of the Seattle fault zone ruptured between 900 and 930 A.D. producing a M7 earthquake, uplifted terraces, tsunami deposits, and landslides (Atwater and Moore, 1992; Bucknam and others, 1992; Jacoby and others, 1992). Several studies also map areas of shallow deformation and constrain the locations of Seattle fault zone structures over a broad area to the west (Yount and Gower, 1991; Logan and Walsh, 1995; Johnson and others, 1999; Pratt and others, 1997; Blakely and others, 2002; ten Brink and others, 2002, 2006; Brocher and others, 2004). Studies by Sherrod (2002), Booth and others (USGS, written commun.[2], 2007), and Liberty and Pratt (written commun.[3], 2007) provide constraints on the location, structure, and activity of the Seattle fault zone directly west of the map area. We map three fault strands within the Seattle fault zone in the map area (Seattle faults nos. 1–3 on Plate).

Seattle fault no. 1 is likely active and corresponds to the Vasa Park fault of Liberty and Pratt (written commun.[3], 2007). This fault is suggested by geologic mapping, magnetic anomaly data, and a subtle lineament observed on lidar. It is along the expected extension of the Seattle fault within the quadrangle. Also, the fault appears to coincide with the boundary between the thin and thick Quaternary deposits expressed as a 600 to 800 ft high bedrock escarpment in the subsurface (Fig. 3). This boundary generally separates the easternmost part of the Seattle uplift and the Seattle basin. The location of Seattle fault no. 1 also is consistent with seismic reflection data of Liberty and Pratt (written commun.[3], 2007) directly west of the map area and follows the sole east–west-striking linear magnetic anomaly in the map area (Fig. 2, anomaly SF). This anomaly follows the Seattle fault (with a few breaks) to Bainbridge Island (Blakely and others, 2002) and likely originates in steeply dipping beds in unit Mvc (Cross Section C). Although several interpretations are possible, the steep southern boundary of this magnetic high is consistent with steeply dipping beds above a reverse fault. A slight deviation in the gravity anomaly is associated with the Seattle fault magnetic anomaly, which is also consistent across the entire Seattle basin and suggests a common origin. This anomaly is likely associated with subvertical density boundaries associated with the Seattle monocline shown on the geologic map; both the deviation in the gravity and the east–west-striking magnetic anomaly end in proximity to RMF-5 near Tolt Hill. Although the main strand of the Seattle fault may splay into the RMFZ, we infer right lateral offset of the Seattle fault by RMF-5 on the geologic map.

Trenching of the Vasa Park fault (5.4 mi west of the map area) uncovered Vashon Stade glacial deposits or Miocene bedrock (unit Mvc) thrust over Vashon glacial deposits and forest soil; this thrusting records at least 10 ft of horizontal motion and 6.5 ft of vertical motion during the latest Pleistocene and (or) Holocene (Sherrod, 2002). We similarly infer that Seattle fault no. 1 is active, but with some caveats. Detailed mapping of spotty outcrops where a subtle lidar lineament crosses Canyon Creek implies that the contact between advance outwash and lake deposits is vertically offset perhaps as much as 20 to 40 ft (Plate and Cross Section C). Although the apparent offset contact may be due to interfingering of units Qgl_v and Qga_v, tectonic offset seems likely given other ancillary evidence. For example, a small outcrop of loose advance outwash sand may be tectonically tilted where the fault crosses the western slope of Patterson Creek. Also, north-tilted Vashon strata occur at several locations in Canyon Creek south of Seattle fault no. 1 (Plate). Although landsliding can be mostly discounted as a cause for tilting at these sites, ice shear could be responsible for some of the tilting. For example, overturned, tight folding of well-stratified, advance glaciolacustrine silts and sands at site 15 (Plate) is very likely the product of south-directed ice shear during glacial advance. However, the consistent nature of the tilt at several sites (including possible tilting of ice-shear strata), combined with probable tectonic tilting of Pleistocene strata observed both to the west and east of Canyon Creek (Liberty and Pratt, written commun.[3], 2007), suggests a tectonic mechanism. (Also see possible growth folding and (or) monoclinal bending south of Seattle fault no. 1 on Cross Section C.)

Seattle fault no. 2 is a blind reverse fault or thrust along the northern edge of the Seattle fault zone and is coincident with the northern boundary of a positive magnetic anomaly associ-

[3] Paper by L. M. Liberty and T. L. Pratt, currently in review, projected to be released as “Structure of the eastern Seattle fault zone—New insights from seismic reflection data” in the Bulletin of the Seismological Society of America.

ated with the Seattle fault (Fig. 2). Liberty and Pratt (written commun.[3], 2007) consider this structure the main strand of the Seattle fault zone. (See seismic reflection line SM-1 of Liberty and Pratt [written commun.[3], 2007] located 0.2 to 0.4 mi west of the map area.) The monocline mapped directly north of this inferred fault demarks the northern edge of the Seattle fault zone deformation front of Liberty and Pratt (written commun.[3], 2007) and is inferred to cut older Quaternary sediments (Cross Section C).

Seattle fault no. 3 is the southernmost fault in the Seattle fault zone in the study area and is inferred to thrust the Puget Group over younger bedrock (units Mvc and ΦEn). Shortening across this thrust is best recorded by the asymmetry and tightness of the overlying Raging River anticline. A structural discontinuity at the base of the Puget Group along the western margin of the map area is indicated by the proximity of the Puget Group to the main strand of the fault. The Renton Formation, which is part of the Puget Group, is mapped within 2000 ft of Seattle fault no. 1 (Plate and Cross Section C). This observation, combined with adjacent mapping in the Issaquah quadrangle (Booth and others, USGS, written commun.[2], 2007), requires significant structural telescoping of strata along a shallowly dipping fault to place the Puget Group this close to Seattle fault no. 1.

The proximity of the Puget Group to Seattle fault no. 1 differs from the stratigraphic-structural arrangement south of the Vasa Park fault and north of the Newcastle Hills anticline to the west of the map area (site 8, Fig. 1). Near Issaquah, a thick sequence of ‘younger strata’ (units Mvc and ΦEn) depositionally overlies the Puget Group with minor internal structural disruption (Liberty and Pratt, written commun.[3], 2007). The broad northern limb of this thrust-bend fold dips gently to moderately to the north and records relatively low strain with some superimposed bedding-parallel backthrusting and minor parasitic folding (Liberty and Pratt, written commun.[3], 2007; Booth and others, USGS, written commun.[2], 2007). In the map area, the Raging River anticline above Seattle fault no. 3 appears to be a fault-generated overturned anticline with a gently dipping western limb (western edge of the quadrangle) and a near vertical to overturned northeastern limb. This relation is well exposed in and around the Reynolds mine on the westernmost part of Grand Ridge (Fig. 1; site 8, Plate; Walsh, 1983) where west-dipping Renton Formation is folded abruptly around the west-northwest-plunging Raging River anticline. Well-exposed coal measures in the strip mine directly north of this fold axis dip almost vertically and strike subparallel to the Seattle fault zone (Cross Section C). This structural geometry may also occur in the easternmost part of the Issaquah quadrangle directly to the west of the study area where overturned bedding in unit Mvc directly mimics steeply dipping strata in the Puget Group (Booth and others, USGS, written commun.[2], 2007), suggesting that a steeply dipping ‘younger section’ underlies Seattle fault no. 3.

Raging River Anticline and Seattle Fault/ Rattlesnake Mountain Fault Interactions

The Raging River anticline is a complex doubly plunging fold (Fig. 1) that parallels both the Seattle fault zone and the Rattlesnake Mountain fault zone. This fold may be refolded or oroclinally bent and likely records a complex fault displacement history. The composite Raging River anticline and Seattle fault no. 3 structural arrangement has some aspects similar to sheath folds described in metamorphic rocks, implying significant shortening along the easternmost part of the Seattle fault zone. We suspect these structures are the result of the interaction of the Seattle fault zone with the RMFZ, perhaps as a result of early transpression across the RMFZ and some early folding of the Raging River anticline prior to deposition of younger Oligocene and Miocene rocks. This is somewhat similar to the view of Liberty and Pratt (written commun.[3], 2007), who suggest that a slight angular unconformity exists between the Blakeley Formation and the overlying Miocene rocks to the west, as a result of anticlinal growth folding within the Seattle fault zone south of the Vasa Park fault (which correlates with Seattle fault no. 1).

We show the Seattle fault zone as truncated against the dextral Rattlesnake Mountain fault zone. In this model, the northerly vergence of the Seattle fault is accommodated by right-lateral slip along RMF-3 through -5. (Note the inferred right-lateral offset of the low-angle Seattle faults on either side of RMF-5 on the Plate.) We envision north–south shortening across the Seattle fault zone as being bounded by the RMF system as a whole. A different model would directly connect the main strand of the Rattlesnake Mountain fault zone near North Bend with the Seattle fault zone and not involve a structural correlation of the Rattlesnake Mountain fault zone with the Southern Whidbey Island fault zone (R. Blakely, USGS, written commun., 2007). In this model: (1) the Southern Whidbey Island terminates in a series of fault splays mostly north of the Fall City quadrangle, and (2) our suggested extensions of RMF-1, -3, and -4 north of Fall City proper are the result of a fortuitous alignment of unconnected anomalies, lineaments, and geologic features.

Lake Alice Fault

The Lake Alice fault (our informal name) was initially suggested by Associated Earth Sciences, (1987) on the basis of aerial photo analyses, backhoe trenching, and ground-penetrating radar. They describe this zone as containing highly disturbed till and ice-contact-stratified drift with vertical, N60°W discontinuities in the till–drift contact. After further trenching across this deformation zone, Associated Earth Sciences concluded that the structures were likely related ice-shear processes and not active faulting (J. Saltonstall, AESI, oral commun., 2007). However, we retain this structure as a fault (Cross Sections A, B), because (1) the Lake Alice fault lineaments on Snoqualmie ridge align with strands of the Mitchell Hill fault zone identified during our mapping, and (2) the two largest earthquakes in the map area occur near the Lake Alice fault. The earthquake epicenters are located at site 16 (Plate; M3.1 at 4.1 mi depth) and site 17 (Plate; M3.5 at 4.6 mi depth).

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