WASHINGTON STATE DEPARTMENT OF Natural Resources
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Division of Geology and Earth Resources
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WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
MAP SERIES 2013-01
Sultan 7.5-minute Quadrangle
October 2013
Pamphlet accompanies map

Geologic Map of the Sultan 7.5-minute Quadrangle, Snohomish and King County, Washington

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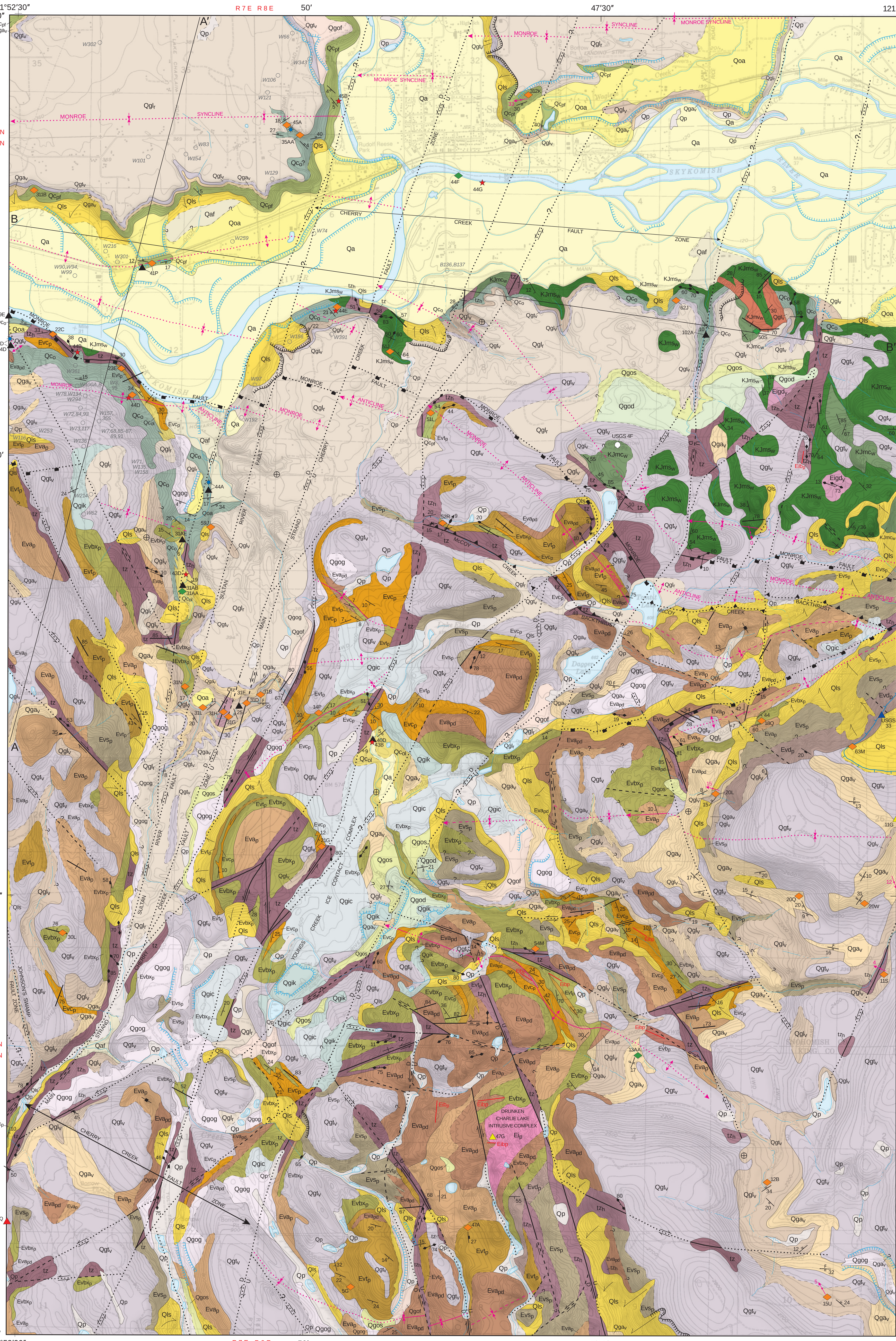


MAJOR FINDINGS

- On the basis of their distribution, composition, and stratigraphic style, Pleistocene Skykomish River or Elwell–Youngs Creek nonglacial alluvium can be correlated with deposits of the Olympia nonglacial interval (hereinafter 'Olympia beds').
- The Olympia beds have been folded across the Monroe anticline and likely uplifted along the Monroe fault, which is potentially active.
- The northeast-trending Cherry Creek fault zone, a left-lateral strike-slip fault system, is conjugate to the northwest-trending southern Whidbey Island fault zone and is seismically active.
- The 1996 Duvall earthquakes (max. magnitude 5.3) likely resulted from shallow displacements along strands of the Cherry Creek fault zone.
- Facies relations and new U-Pb dates indicate that the volcanic rocks of Mount Persis partially emanated from volcanic center(s) in and east of the map area, including the Youngs Creek and Drunken Charlie Lake intrusive complexes (units Eigd$_y$ and Ei$_p$, respectively); mafic flows and interbedded volcanic sediments were deposited more distally.

DESCRIPTION OF MAP UNITS

(See the pamphlet for detailed map unit descriptions)

Quaternary Sedimentary Deposits

HOLOCENE NONGLACIAL DEPOSITS

Qp — **Peat**—Peat, muck, and organic silt and clay with local thin beds of tephra, including the Mazama ash; loose or soft.

Qa — **Alluvium**—Generally silt, sand, sandy pebble gravel, (cobble) gravel, and gravelly sand; organic sediments, peat, wood debris, and detrital wood are common; loose; clasts subrounded to rounded; well sorted; well stratified; plane-bedded sands. See SP and LP sand provenance on Table 1 in pamphlet.

Qoa — **Older alluvium (Holocene to latest Pleistocene)**—Silt, sand, and cobble to pebble gravel; loose; in elevated terraces along the valley margins.

Qls — **Landslide deposits (Holocene to latest Pleistocene)**—Diamicton (unsorted mixture of clay, silt, sand, gravel, and wood debris) or boulder gravel, including talus deposits and local minor sand or gravel; loose.

Qaf — **Alluvial fan deposits (Holocene to latest Pleistocene)**—Debris-flow diamicton, sand, alluvial gravel, and boulder gravel; loose; massive to moderately stratified; poorly to moderately sorted.

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Vashon Stade of the Fraser Glaciation

Vashon recessional deposits

Qgl$_r$ — **Recessional glaciolacustrine (glacial lake) deposits**—Silt and clayey or sandy silt to silty sand, typically with scattered dropstones; soft; light brown-gray to gray; deposited in proglacial lakes.

Qgos — **Outwash sand**—Sand with some interbeds of silt or gravel; dark blue-gray; loose or soft; unstratified to weakly stratified to plane bedded, laminated, and locally crossbedded.

Qgod — **Deltaic outwash and kame deltas**—Sandy cobble gravel, gravel, pebbly sand, and minor sand; loose; moderately sorted to well sorted; thin to very thickly bedded; well stratified with conspicuous high-amplitude foreset beds.

Qgof — **Fluvial outwash deposits**—Boulder and cobble gravel, gravel, and pebbly sand, with interbeds of sand and silt and rip-up clasts; loose; moderately to well stratified; subhorizontal beds and locally crossbedded.

Qgic — **Ice-contact deposits, undivided**—Boulder and cobble gravel, gravel, silty pebbly gravel, sand, and pebbly sand and silt, locally with lesser diamicton; loose; moderately stratified and medium to very thickly bedded; abrupt grain-size changes are common. Locally divided into:

Qgik — **Ice-contact kames**—Boulder and cobble gravel, gravel, sand, and pebbly sand, with rare lenses of diamicton that is mostly flow or melt-out till from buried sediment-laden ice blocks; loose; crossbedded, with localized oversteepened or slumped strata; cut-and-fill structures and till or silt rip-up clasts common.

Qgog — **Outwash gravel deposits, undivided**—Poorly exposed bouldery cobble gravel to pebble gravel and pebbly sand; loose; massive to crudely bedded; largely ice-contact deposits; may include any of the gravelly Vashon recessional facies.

Vashon advance proglacial and subglacial deposits

Qgt$_v$ — **Lodgment till**—Diamicton (unsorted mixture of clay, silt, sand, and gravel); grayish blue to very dark gray; dense; matrix-supported; accreted at the base of the Vashon ice and thus typically displays a friable shear fabric.

Qga$_v$ — **Advance outwash deposits**—Sandy gravel, pebble gravel, cobble gravel, and sand, with local silt interbeds (some laminated); tan to dark green-gray; dense; well sorted and stratified; thinly to thickly bedded; deltaic and bar foreset beds common; silt rip-up clasts and cut-and-fill structures. See GP sand provenance on Table 1 in pamphlet.

Qgl$_v$ — **Advance glaciolacustrine deposits**—Clayey silt, silt, pebbly silt, and diamicton; locally contains very thin to thick beds of sand, scattered dropstones, and iceberg melt-out or flow till; gray to grayish blue; stiff or dense; stratification and sorting vary; massive to thinly bedded, laminated or varved.

Pre-Fraser glacial and nonglacial deposits

Qc$_{ol}$ — **Sediments of the Olympia nonglacial interval, local facies**—Cobble and boulder gravel to pebble gravel, sand, silt, and clayey silt, with minor local peat, organic sediments, and disseminated organic matter; orange-gray; dense; very thickly to thinly bedded, well stratified and well sorted. See LP sand provenance on Table 1 in pamphlet.

Qc$_o$ — **Sediments of the Olympia nonglacial interval, ancient Skykomish River facies**—Silt, sand, sandy silt to silty sand, and organic silt, with some clay, minor peat, charcoal, disseminated detrital organic matter, and few gravel beds; sands typically yellow-brown-gray, weathering to a distinctive orange-gray or light yellowish brown or gray; dense; well stratified; laminated to very thickly bedded; graded beds, trough-and-ripple crossbedding, and liquefaction features common. See SP sand provenance on Table 1 in pamphlet.

Qc$_{pf}$ — **Pre-Fraser continental nonglacial deposits, ancient Skykomish River facies (Pleistocene)**—Sand, silt, clay, some organic silt-clay and peat, minor charcoal, and disseminated organic matter, with lesser pebbly sand and gravel; sands typically yellow-brown-gray, weathering to a distinctive orange-gray or light yellowish brown or gray; dense; mostly well stratified; laminated to very thickly bedded; graded beds, trough-and-ripple crossbedding, and liquefaction features common. See SP sand provenance on Table 1 in pamphlet.

Qgn$_{pf}$ — **Pre-Fraser glacial and nonglacial deposits, undivided (Pleistocene to Pliocene?) (cross sections only)**—Dense to very dense gravel, boulder gravel, sand, silt, clay, and diamicton; may locally contain peat or organic sediments.

Tertiary Volcanic, Sedimentary, and Intrusive Rocks

Ts — **Sedimentary or volcaniclastic rocks, undivided (Miocene to Eocene)(cross sections only)**—Undivided Tertiary sedimentary rocks; may correlate with the distal volcaniclastic rocks of Mount Persis, Blakeley Formation, or Miocene sedimentary rocks. See units Evc$_p$, ΦEc, ΦEn, and Mv$_c$ within the Monroe syncline in the Monroe area (Dragovich and others, 2011a,b).

Eigd$_y$ — **Youngs Creek intrusive complex (Eocene)(cross section B only)**—Massive, medium-grained granodiorite (~66% SiO_2); locally contains tabular mafic enclave bodies (2–12 cm wide) of fine-grained gabbro. We obtained a U-Pb age range of 39.35–42.99 Ma from the granodiorite stock directly east of the Sultan quadrangle that was likely a subvolcanic intrusive source for the volcanic rocks of Mount Persis.

Evs$_p$ — **Volcanic rocks of Mount Persis of Tabor and others (1993), undivided (Eocene)**—Interbedded andesite to basaltic andesite flows, locally with dacite and basalt flows, lesser andesitic to rhyolitic tuff, tuff breccia, breccia, volcanic to tuffaceous sandstone and siltstone, lahar deposits, volcanic conglomerate, shale, organic siltstone, and coal. Locally divided into:

Eva$_p$, Evd$_p$ — **Andesite flows**—Andesite; may locally include dacite or basaltic andesite flows; medium bluish gray to dark gray, weathered or altered to dark reddish gray, brown-gray, maroon-gray, or yellow-brown-gray. Unit Evd$_p$ dacite flows are generally similar to unit Eva$_p$, but are lighter gray and contain quartz phenocrysts.

Eva$_{pd}$ — **Dark basaltic andesite flows**—Basaltic andesite to andesite flows; may include basalt flows; typically dark gray to bluish gray to very dark gray, weathered or altered to reddish gray, reddish brown, or brownish yellow.

Evb$_p$ — **Basalt flows and dikes**—Basalt to basaltic andesite; dark gray to reddish or greenish gray, weathered or altered to very dark grayish brown or light olive-brown.

Evt$_p$ — **Tuff**—Variable composition, including crystal vitric, lithic vitric, crystal lithic, lithic, and vitric lithic andesitic to dacitic (59–67% SiO_2) and rhyolitic tuff, with lesser lapilli tuffs and lapillistone; typically light to dark gray to bluish or greenish gray to light yellowish brown; lithic tuff beds typically greenish.

Evbx$_p$ — **Volcanic breccia**—Dacitic to andesitic lithic tuff breccia with lesser (crystal) lithic lapilli tuff and minor agglomerate; typically dark green-gray to light gray, with multicolored red, green, and gray to black volcanic clasts; weathers gray-brown; moderately to poorly sorted; very thick to massive.

Evc$_p$ — **Volcaniclastic rocks**—Lithic and feldspatholithic volcanic to tuffaceous sandstone, silty sandstone, and siltstone containing some interbeds of volcanic (pebble) conglomerate, tuff, lapilli tuff, breccia, shale, organic tuffaceous siltstone, and coal; leaf fossils and petrified wood common; generally light yellowish brown to very pale brown to light bluish gray to greenish gray sandstone, with some dark red to reddish brown to grayish black siltstone.

Ei$_p$ — **Drunken Charlie Lake intrusive complex**—Dacitic porphyry and tuff breccia with basaltic andesite or basalt dikes; dacite is medium bluish gray to dark greenish gray; mostly massive porphyry with fine-grained dacite locally intruding(?) the porphyry. We obtained a U-Pb age of 46.46 ± 0.37 Ma from unit Ei$_p$ at age site 47G near Drunken Charlie Lake in the southeastern part of the map area.

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

KJm$_w$ — **Western mélange belt of Tabor and others (1993), undivided (Cretaceous to Jurassic)**—Dominantly meta-argillite, metasandstone, greenstone, metagabbro, metachert, metadiabase, metatonalite, slate, phyllite, marble with metaquartz diorite, hornblendite, and (banded) amphibolite, with rare ultramafite observed regionally. Locally divided into:

KJmv$_w$ — **Metavolcanic rocks**—Greenstone derived from metamorphosed andesite to basaltic tuff, volcanic flows, and rare volcanic breccia; greenish gray to dark greenish black, altered to dark green-gray.

KJms$_w$ — **Metasedimentary rocks**—Marine lithofeldspathic to feldspatholithic subquartzose metasandstone, silty metasandstone, meta-argillite, and metatuff, with minor marble and (chert pebble) metaconglomerate; typically greenish gray to dark or bluish gray or gray-green, weathers to brown; meta-argillite typically black or greenish or bluish black to dark gray.

KJmc$_w$ — **Metachert**—Metachert, locally with meta-argillite interbeds; mapped separately from the metasedimentary rocks where very thick; maroon to reddish with white veining.

KJigb$_w$ — **Metagabbro (cross sections only)**—Metagabbro; occurs as tectonic lenses in the mélange as modeled in the subsurface.

Holocene to Tertiary Tectonic Zones

tz, tz$_h$, Qtz — **Tectonic zone**—Cataclasite, fault breccia, clay-rich fault gouge, protomylonite, or moderately to strongly slickensided, fractured, and veined rocks in fault zones; yellowish to variously colored, mottled, and commonly altered. Unit tz$_h$ represents mappable zones of hydrothermal alteration; typically along tectonic zones; principally propylitic alteration mineral assemblages, but may locally include higher grades of hydrothermal alteration. Unit Qtz represents zones of Quaternary deformation and (or) liquefaction along the main strand of the Cherry Creek fault zone along Youngs Creek.

GEOLOGIC SYMBOLS

- Contact—Solid where location accurate; dashed where inferred; queried where identity or existence questionable
- Fault, unknown offset—Solid where location accurate; dashed where inferred; dotted where concealed
- Thrust fault—Solid where location accurate; dashed where inferred; dotted where concealed; sawteeth on upper (tectonically higher) block
- Reverse fault—Solid where location accurate; dashed where inferred; dotted where concealed; rectangles on upthrown block
- Right-lateral strike-slip fault—Solid where location accurate; dashed where inferred; dotted where concealed; queried where identity or existence questionable; arrows show relative motion
- Left-lateral strike-slip fault—Solid where location accurate; dashed where inferred; dotted where concealed; queried where identity or existence questionable; arrows show relative motion
- High-angle right-lateral, oblique-slip fault—Solid where location accurate; dashed where inferred; dotted where concealed; arrows show relative horizontal motion; U, upthrown block; D, downthrown block
- High-angle left-lateral, oblique-slip fault—Solid where location accurate; dashed where inferred; dotted where concealed; queried where identity or existence questionable; arrows show relative horizontal motion; U, upthrown block; D, downthrown block
- Anticline—Solid where location accurate; dashed where inferred; dotted where concealed; queried where identity or existence questionable; arrowhead shows direction of plunge
- Syncline—Solid where location accurate; dashed where inferred; dotted where concealed; queried where identity or existence questionable; arrowhead shows direction of plunge
- Eib$_p$ Basalt dike—Identity and existence certain; location accurate
- Continental ice limit, late Wisconsinan—Identity and existence certain; location accurate
- Fluvial terrace scarp—Identity and existence certain; location accurate; hachures point downscarp
- Landslide scarp—Identity and existence certain; location accurate; hachures point down slope
- A — A′ Cross section line
- Direction of downslope movement of landslide
- 25 Bedding, including flow banding in volcanic rocks of Mount Persis—showing strike and dip
- 28 Cleavage—showing strike and dip
- Horizontal bedding
- Vertical bedding—showing strike
- 20 Bedding in unconsolidated sedimentary deposits—showing strike and dip
- 13 Foreset bedding in unconsolidated sedimentary deposits—showing strike and dip
- 43 Joint—showing strike and dip
- Vertical or near-vertical joint—showing strike
- 76 Minor fault—showing strike and dip
- Minor vertical or near-vertical fault—showing strike
- 54 Slickenside—showing strike and dip
- Vertical slickenside—showing strike
- 15 Minor ice-shear folds in units Qc$_{pf}$, Qga$_v$, or Qgl$_v$—showing bearing and plunge
- 10 Inclined slickenline, groove, or striation on fault surface—showing bearing and plunge of offset
- 0 Minor fold in unit KJms$_w$—showing bearing and plunge
- 30 Mylonitic foliation—showing strike and dip
- 9 Inclined aligned stretched-object lineation—showing bearing and plunge
- W62 Water well (*W62*) or geotechnical boring (*B136,137*)
- 44D Significant site
- 44A Age sample, radiocarbon (^{14}C)
- 45A Age sample, optically stimulated luminescence
- 44B Age sample, infrared stimulated luminescence
- 8F Age sample, fossil
- USGS 33 Age sample, zircon fission-track
- 11G Age sample, uranium-lead (U-Pb)
- DQ Earthquake epicenter (see Appendix D)
- 31AA Geochemistry sample

Abbreviations used in unit descriptions	Definition *(See pamphlet for detailed definitions)*
SP	**Snoqualmie and Skykomish River basin or Central Cascade (nonglacial) provenance.** Easterly erosional sources; carried by rivers generally flowing west.
LP	**Local provenance.** Nonglacial small-basin provenance with local sources; carried by low-order rivers flowing generally west, away from the Cascade foothills.
PG	**Puget Group nonglacial provenance.** Local erosional sources to the south and southwest originating from the Seattle uplift; delivered via fluvial mechanisms.
NP	**Northern provenance.** Deposited during continental glaciations.

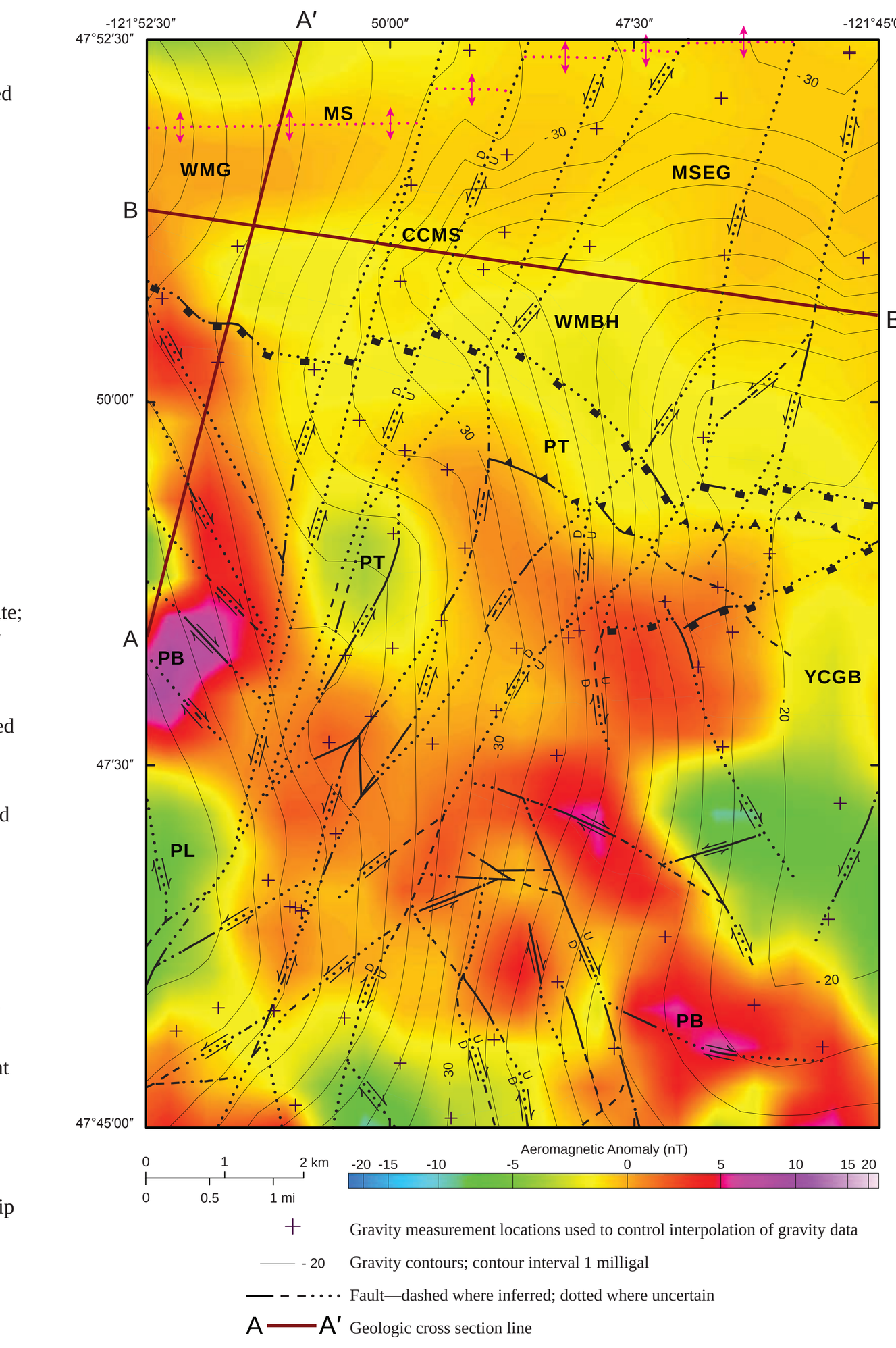


Figure 1. Aeromagnetic and gravity map of the Sultan quadrangle. Base map is reduced-to-pole aeromagnetic anomaly, filtered (upward continued and differenced with original grid) to bring out magnetic anomalies originating from near-surface sources. Isostatic gravity contours (1 mGal interval) are labeled in mGals. Crosses indicate the location of gravity measurements controlling the isostatic gravity grid. Darker lines are faults from the geologic map. CCMS, gradient associated with the main strand of the Cherry Creek fault zone; MS, Monroe syncline; MSEG, gravity gradient along the edge of the Monroe syncline; PB, magnetic highs due to Mount Persis basalt or basaltic andesite; PL, gravity low due to thick volcanic rocks of Mount Persis (volcaniclastic rocks or tuff); PT, magnetic lows due to Mount Persis tuff, volcaniclastic, or tectonized subunits; WMBH, gravity high due to near-surface Western mélange belt; WMG, magnetic highs due to Western mélange belt metagabbro; YCGB, gravity high due to the Young's Creek complex gabbro.

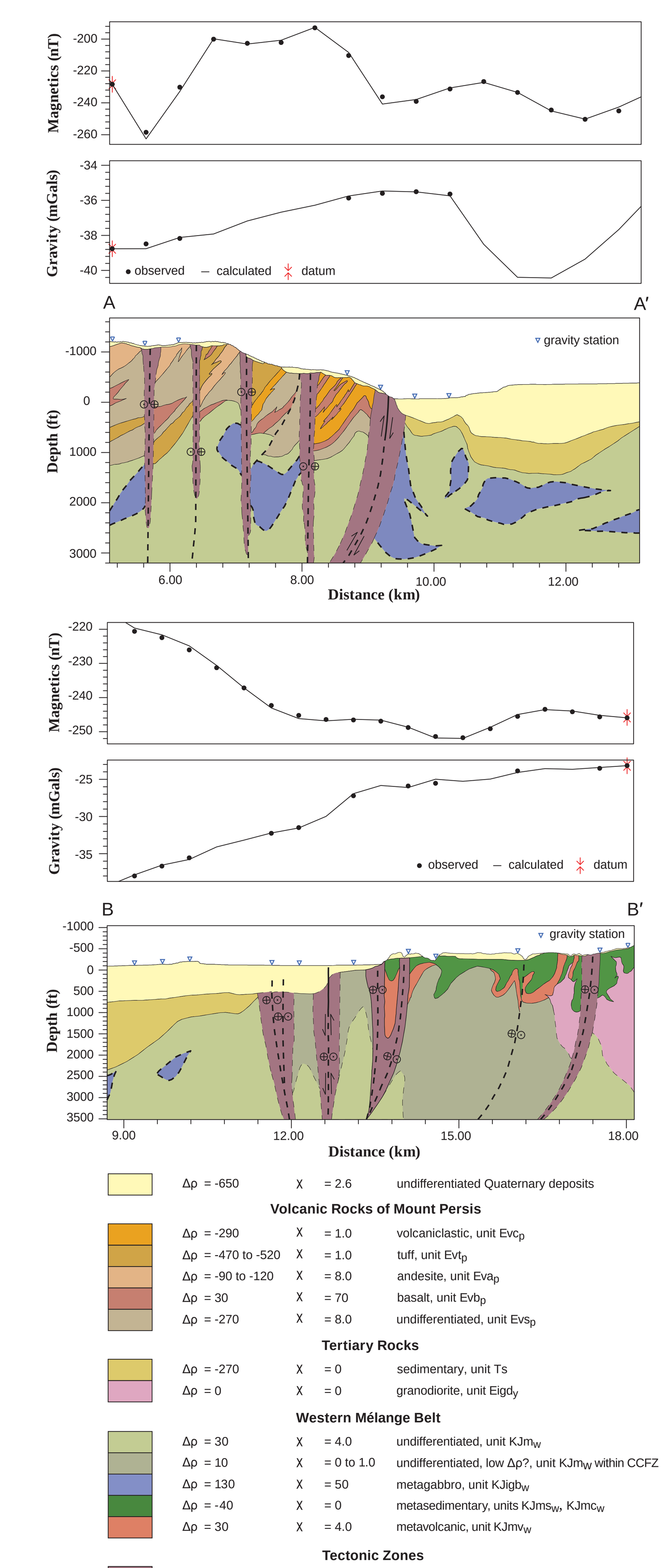
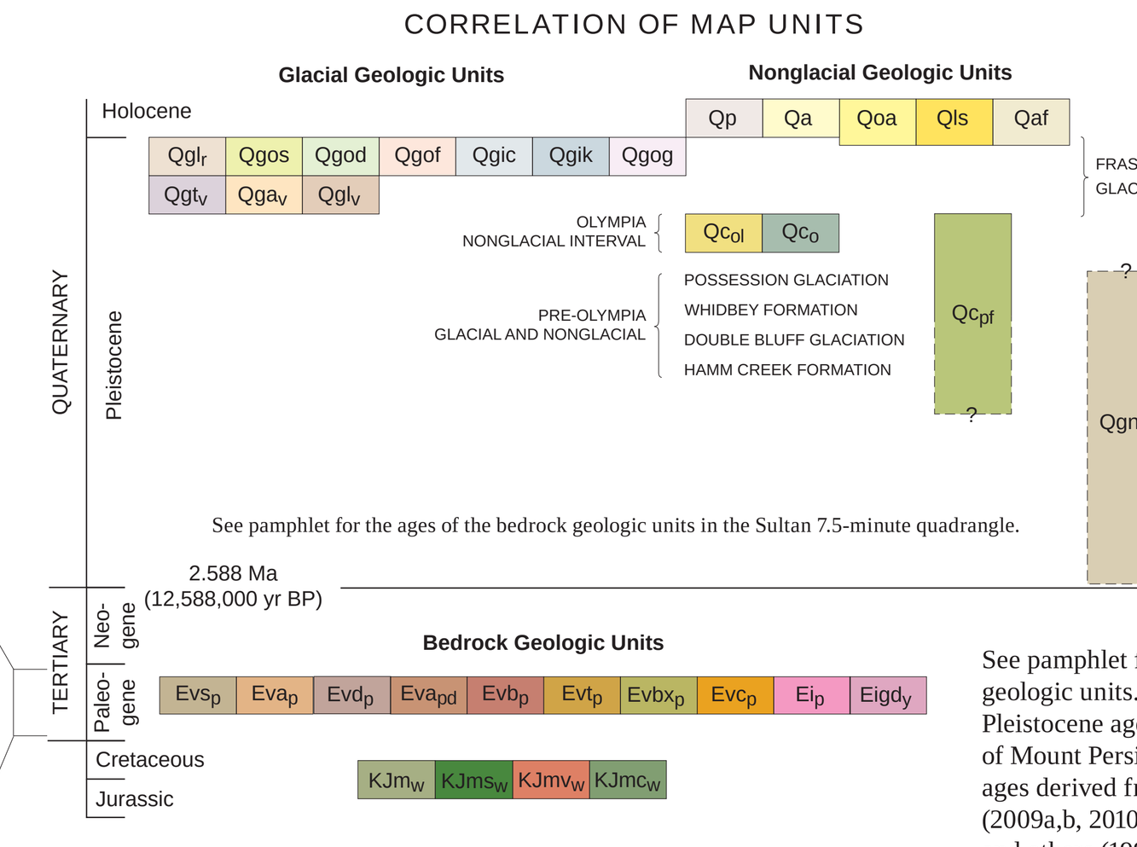


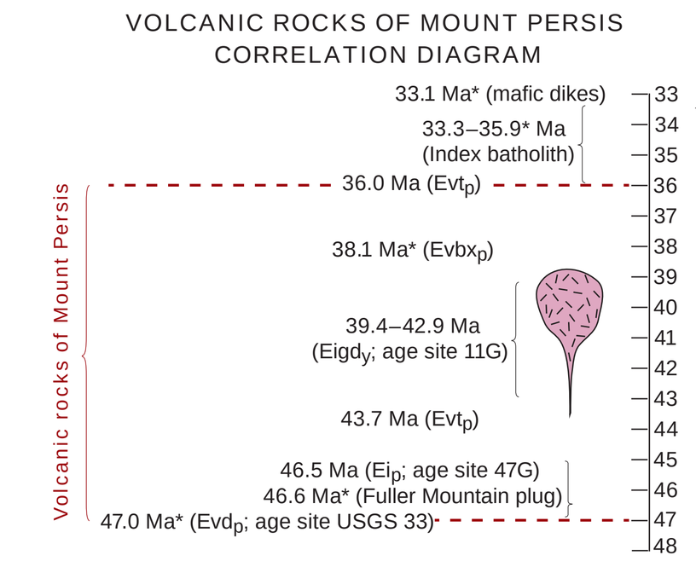
Figure 2. Geophysical models A and B, which coincide with lithologic Cross Sections A and B on the geologic map and match predicted gravity and aeromagnetic anomalies from the cross sections to data from the region (2.5x vertical exaggeration). Aeromagnetic data sampling distance is twice the flightline spacing. Gravity stations shown are within 1.5 km of the line. The model extends to infinity in both directions perpendicular to the profile. Δρ is the density contrast relative to normal crust (2670) in kg/m^3; χ is magnetic susceptibility in SI units multiplied by 1,000. See the geophysical properties tables and discussion in Dragovich and others (2011b) for further geologic unit property information. Solid lines show fault locations that are well constrained by the geophysical data. Dashed lines show fault locations that are controlled by geologic mapping at the surface, but are less certain at depth. Unlike the map, where we focus on high-resolution magnetic anomalies that allow us to easily generate qualitative interpretations of near-surface structures, here we use the total field magnetic anomaly for the geophysical modeling; the total field magnetic anomaly constrains both the shallow and deep-seated structures that contribute to the magnetic anomalies of the region.

CORRELATION OF MAP UNITS



See pamphlet for the direct or indirect age constraints for geologic units. Also see Morrison (1991) for further Pleistocene age constraints. The inset of the volcanic rocks of Mount Persis age diagram is constructed using the U-Pb ages derived from this study and Dragovich and others (2009a,b, 2010a,b). Radiometric ages derived from Tabor and others (1993) are shown with an asterisk (*). The distribution of the U-Pb age peaks determined for sample 11G (Youngs Creek intrusive complex) suggests intrusive activity in pulses over ~6–10 Ma (Appendix F).

VOLCANIC ROCKS OF MOUNT PERSIS CORRELATION DIAGRAM

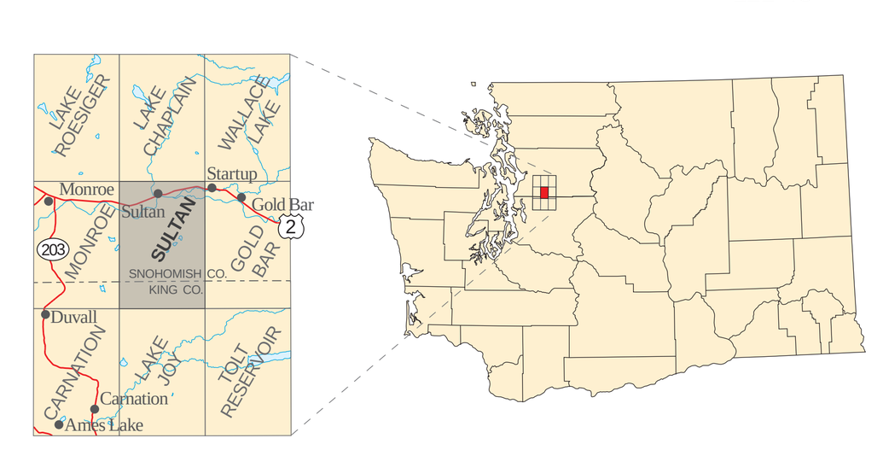


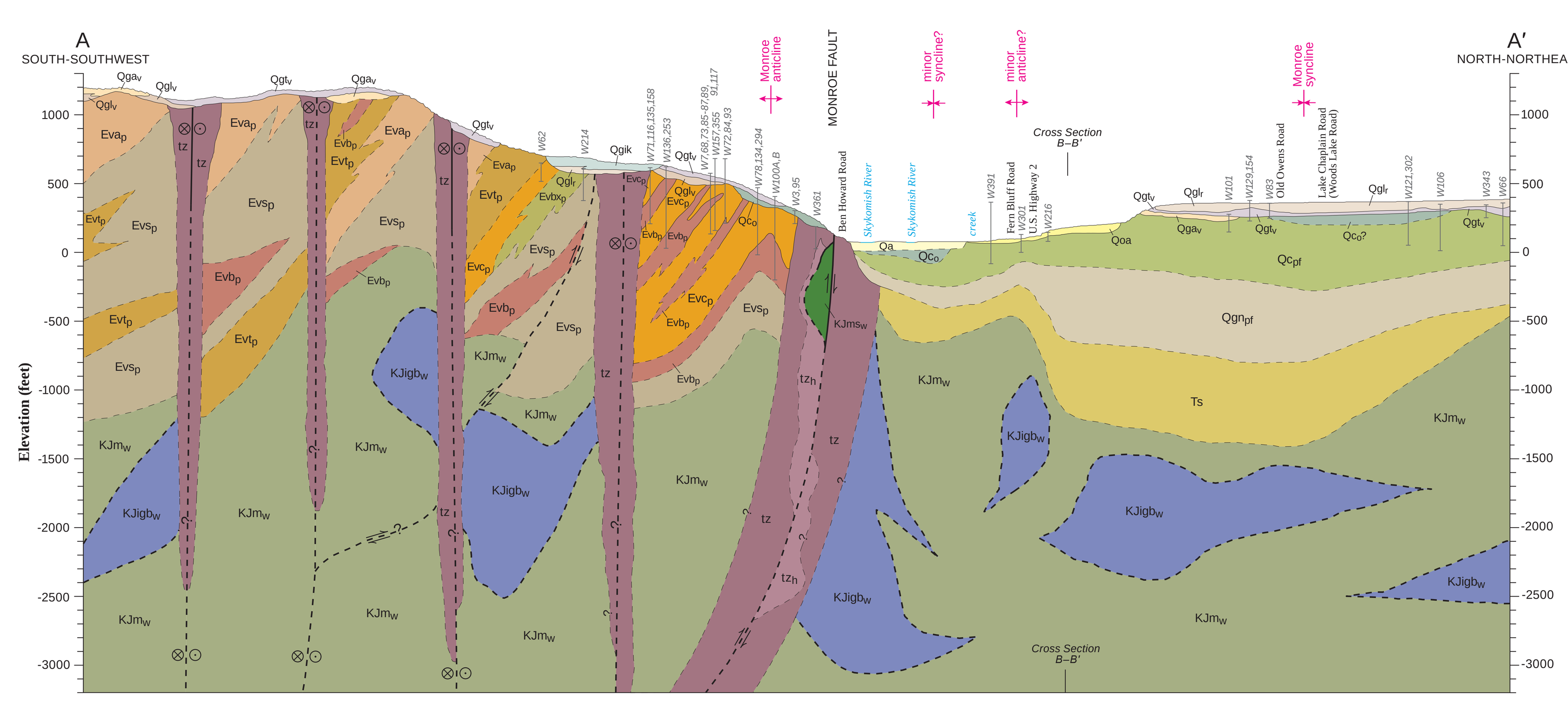
Lambert conformal conic projection
North American Datum of 1927; to place on North American Datum of 1983, move the projection lines approximately 94 meters east and 19 meters north as shown by crosshair corner ticks
Base map from scanned and rectified U.S. Geological Survey Sultan 7.5-minute quadrangle, 1997
Shaded relief generated from U.S. Geological Survey 30-meter digital elevation model; altitude, 70°; azimuth, 340°; vertical exaggeration 1x
GIS by Joe D. Dragovich, Heather A. Littke, and J. Eric Schuster
Digital cartography and GIS by J. Eric Schuster and Anne C. Olson
Editing and production by Meredith C. Payne, Jaretta M. Roloff, and Jessica L. Czajkowski

SCALE 1:24,000
1 0.5 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 0.5 0 1 KILOMETER
contour interval 20 feet

This geologic map was funded in part by the U.S. Geological Survey National Cooperative Geologic Mapping Program.

16.8° TRUE NORTH MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2013





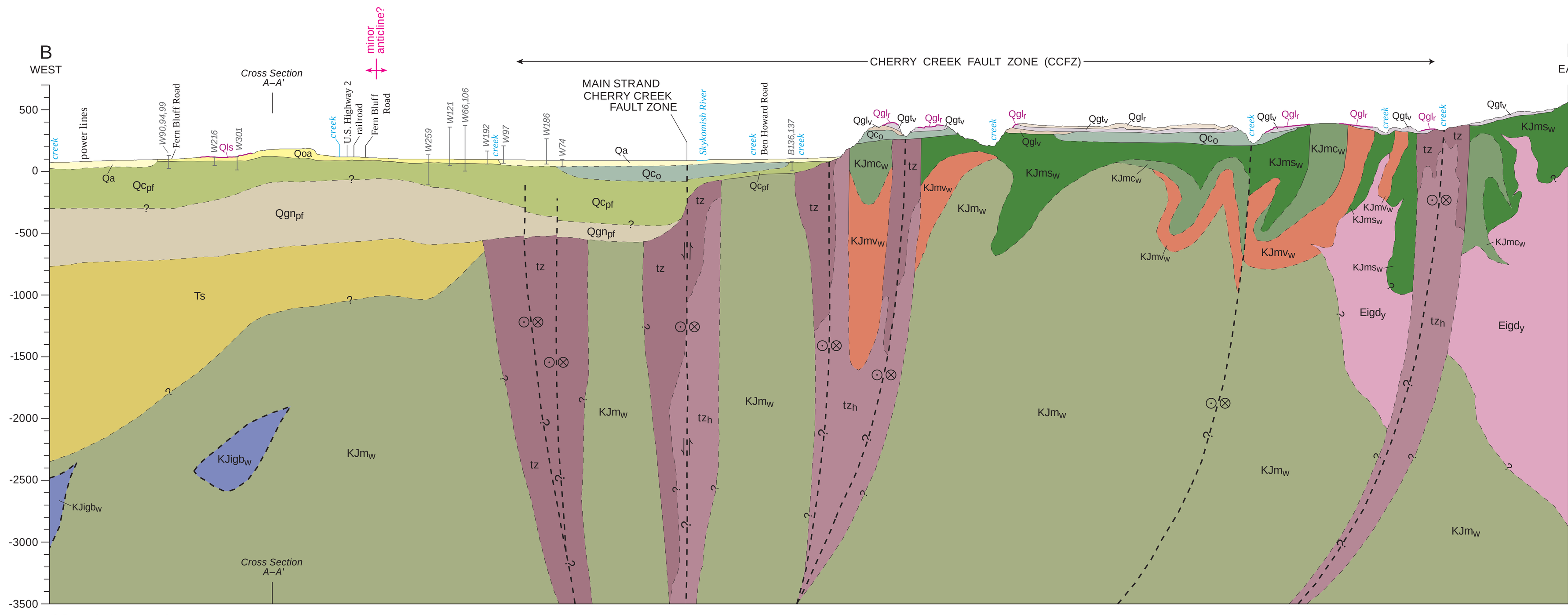
GEOLOGIC SYMBOLS IN CROSS SECTIONS

Fault—Solid where location accurate; dashed where inferred; queried where identity or existence questionable. Arrows indicate relative vertical motion. Arrow point (⊙) indicates motion toward the viewer, and arrow feathers (⊗) indicate motion away from the viewer.

Qls — Surficial geologic units too thin to show as polygons at the scale of the cross sections.

W10 — Water well or boring

Lithologic Cross Sections A and B. For our analyses of subsurface conditions, we obtained 402 stratigraphic logs for wells, geotechnical borings, and test pits. Most high-quality well and boring data near the cross sections are shown directly. We show composited information where wells and borings are closely spaced and (or) where subsurface geologic conditions are stratigraphically consistent over a short distance. Although other solutions are possible, our geophysical model of the map area is consistent with the stratigraphic arrangement we postulate here (see Figs. 1 and 2). Appendix D in the accompanying pamphlet provides information on earthquake hypocenters near the cross sections. (See 'Duvall earthquake' and Cherry Creek fault zone information south of the cross sections.) Pleistocene ancient SP alluvial sediments, such as the Olympia beds (units Qc$_o$ and Qc$_{ol}$) are likely folded in the vicinity of the Monroe anticline and syncline and uplifted by the Monroe fault (Cross Section A and Table 1). Tight to isoclinal folds of Western mélange belt strata shown on Cross Section B are stylized structures resulting from Jurassic–Cretaceous accretionary tectonics. These fold axes are not shown on the map and the structures should be regarded as only generally constrained.



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