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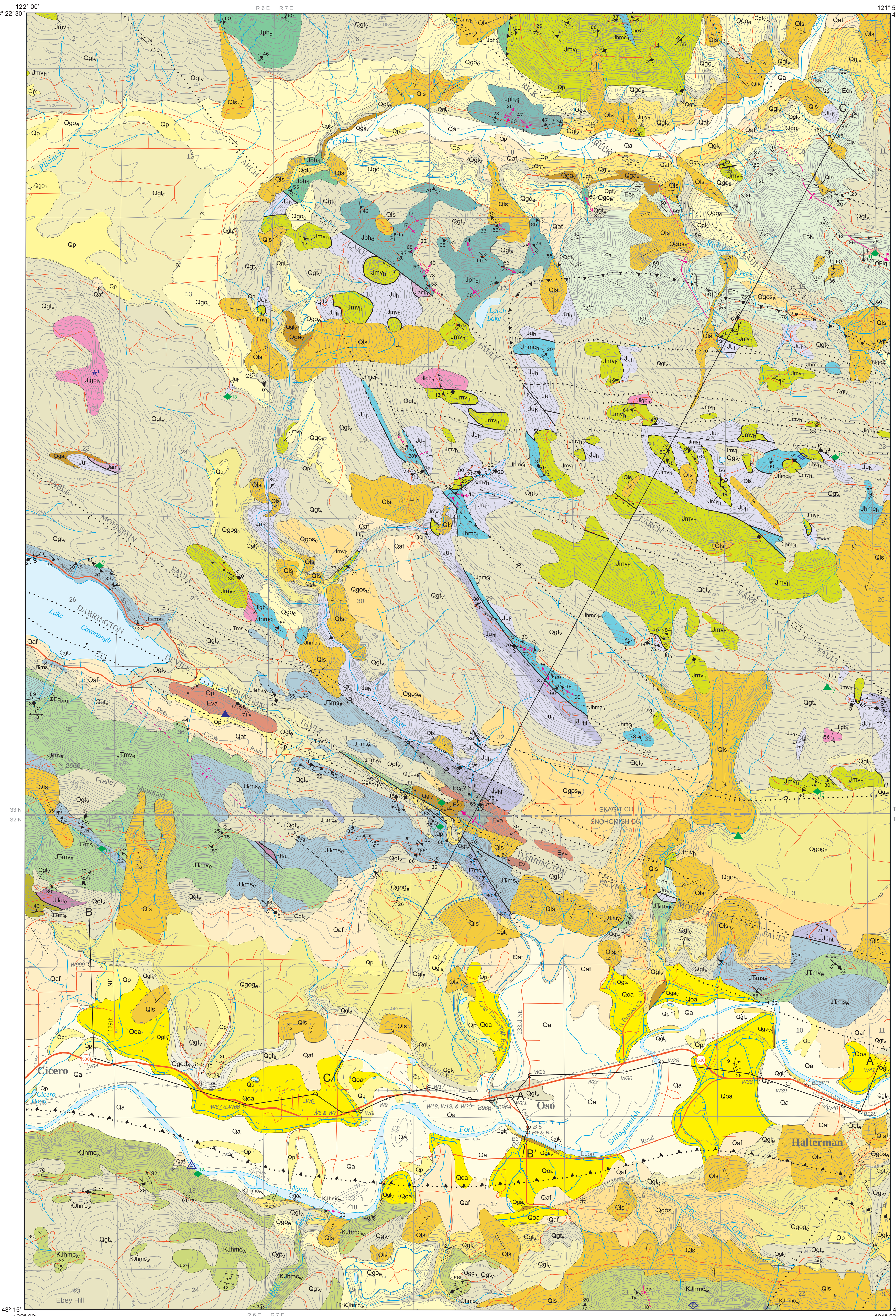

Lambert conformal conic projection
North American Datum of 1927
Base map information from the Washington Department of Natural Resources, Geographic Information System, and from U.S. Geological Survey digital line graphs
Digital cartography by Charles G. Caruthers, Anne C. Heinitz, Donald T. McKay, Jr., and J. Eric Schuster
Edited by Karen D. Meyers and Jaretta M. Roloff

SCALE 1:24 000

contour interval 40 feet
supplementary contour interval 20 feet

Geologic Map of the Oso 7.5-minute Quadrangle, Skagit and Snohomish Counties, Washington

by Joe D. Dragovich, Benjamin W. Stanton, William S. Lingley, Jr., Gerry A. Griesel, and Michael Polenz

2003

DESCRIPTION OF MAP UNITS

Information for the unit descriptions was compiled from the sources listed at the end of each description. The classification schemes we use are described in Dragovich and others (2002d). Contact joe.dragovich@wadnr.gov for more detailed information.

Quaternary Sedimentary and Volcanic Deposits

HOLOCENE NONGLACIAL DEPOSITS

Qa, Qp — **Alluvium (Holocene)**—Channel alluvial deposits include sand, gravel, and cobbly gravel; gray; subrounded to rounded clasts; loose, well stratified, and well sorted; plane-bedded sands common. Fine overbank deposits are mostly loose or soft to stiff, grayish brown to olive-gray stratified sand, silt, clay, and peat and muck deposits (similar to unit Qp). Stillaguamish River gravels and cobbles locally contain gray or reddish gray Glacier Peak dacite clasts (5–20%); other clasts are phyllite, slate, other metasediments, greenstone, granite, pegmatite, gneiss, vein quartz, schist, chert, conglomerate, sandstone, and siltstone. Alluvium is generally thin in the study area (<25 ft thick). Peat (unit Qp) is deposited primarily in alluvial settings and is mapped both in conspicuous abandoned channels within floodplains and in poorly drained upland marsh or pond areas. Several radiocarbon ages from sticks in peat and organic sediments yield ages of less than 600 yr B.P. for Stillaguamish River alluvium east of the study area (Dragovich and others, 2002a,b) and a 2,270 ±60 yr B.P. along the Stillaguamish River (site 4).

Qoa — **Older alluvium (Holocene)**—Cobble gravel, sand, and gravel with minor silt and clay interbeds; gray; subrounded to rounded; loose, well stratified, and well sorted; clasts include greenstone, greenschist, granite, gneiss, schist, dacite, pumice, phyllite, slate, vein quartz, chert, quartzite, sandstone, and siltstone; separated from the modern Stillaguamish valley floodplain by distinct topographic scarps (~5-40 ft high); occurs locally as a thin mantle (1-10 ft thick) on Vashon Stade or Everson Interstade glacial deposits exposed in valley bottoms and is separated from the underlying glacial deposits by a scoured surface. Unit Qoa postdates recessional outwash but age relations are ambiguous in some higher elevation localities. Some unit Qoa deposits have dacite clast content (10-15%) suggestive of reworked Glacier Peak volcanic sediments and thus may represent fluvial deposits stranded during incision following volcanic aggradation (this study, Tabor and others, 2002).

Qaf — **Alluvial fan deposits (Holocene)**—Diamicton; massive to weakly stratified; largely angular to subangular, locally derived clasts; mostly poorly sorted debris-flow deposits, locally modified by fluvial processes. The distinction between units Qaf and Qls is at times difficult and differentiation is reliant on the distinct lobate geomorphology of alluvial fan deposits. Alluvial fans occur where upland streams spill out onto valley floors or flat terraces.

Qls — **Landslide complexes (Holocene)**—Diamicton with soft sand, silt, and (or) clay matrix; contains locally derived, angular to subangular clasts and may contain some rounded clasts from older Quaternary deposits; poorly sorted and unstratified; includes deep-seated (slump-earthflows) and shallow (debris flows and torrents) landslides. Some landslides may have been initiated during removal of ice buttressing during late Pleistocene deglaciation or may be seismically induced (this study; Tabor and others, 2002).

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Deposits of the Fraser Glaciation

EVERSON INTERSTADE

Qgo_e — **Recessional outwash (Pleistocene)**—Sand, gravel, and sandy cobble gravel with rare boulders; loose; clasts are subrounded and commonly polymictic; contains interlayered thin to laminated beds of sandy silt and silt, particularly where grading to unit Qgl_e; non- to well stratified; typically contains meter-thick, subhorizontal beds normally crudely defined by variations in cobble, gravel, and sand content. Pebble imbrication, scour, and local low-amplitude trough and other cross-bedding features indicate deposition in braided river and deltaic environments. Some deposits were isolated ice-contact deposits as indicated by the occurrence of rare flow and (or) ablation till lenses and near-ice sedimentary structures. Clast types are dominantly polymictic gravel with a mixed local (phyllite and greenstone) and Canadian to eastern (granite and high-grade metamorphic clasts) provenance. The unit locally contains rip-up clasts of glacial lake silt deposits. Gravel deposits are typically poor in Glacier Peak dacite and (or) pumice clasts (0–5%) (Dragovich and others, 2002a,b; J. D. Dragovich, Wash. Divn. of Geology and Earth Resources [DGER], unpub. data). Dacite boulders in the French Creek and Boulder River channels to the east are probably eroded from a nearby (but unobserved) lahar deposit overlying or interbedded with recessional deposits (Dragovich and others, 2003). Locally divided into:

$Qgog_e$ — **Gravel**—Sandy gravel and cobble gravel; locally contains beds of fine sand to silty fine sand typically 1 to 5 ft thick; loose; subangular to subrounded clasts with mixed local and Canadian provenance and minor dacite clasts (typically less than 3%); also includes clasts of greenstone, granite, meta-argillite, metasandstone, chert, sandstone, volcanic rocks, gneiss, vein quartz, phyllite, and rip-up clasts of lake deposits (up to 4 ft long); generally crudely subhorizontally stratified and imbricated.

$Qgos_e$ — **Sand**—Sand or pebbly sand; locally contains thin interbeds of silt and silty sand; loose; clasts are subangular to subrounded; generally structureless with some local cross-bedding. Thin-section examination of sand indicates a distinct local clast component (for example, subangular serpentinite, phyllite, and silica-carbonate rock) mixed with far-traveled subrounded detritus (such as granite fragments) probably derived from the North Cascades and (or) the Coast Mountains of British Columbia. Deposits are typically fluvial but may include shallow deltaic deposits transitional to lake deposits.

$Qgod_e$ — **Deltaic outwash**—Sandy cobble gravel, gravelly sand, and sand; loose; moderately to well sorted; well stratified; 5 to 10 ft thick, planar foreset beds occur in sets at least 30 ft high dipping 10 to 31 degrees north to northeast that are overlain by fluvial cobble gravel topset beds (unit Qgo_e) along a scoured contact; contains locally derived clasts such as phyllite, vein quartz, and greenstone mixed with clasts of Canadian provenance and about 1 percent Glacier Peak dacite; locally contains boulder sized rip-up clasts of glaciolacustrine clay. Field relations and subsurface analysis indicate that deltaic outwash interfingers with glaciolacustrine deposits at depth (cross section B). However, facies relations, including fining trends, between deltaic deposits and glaciofluvial valley-train outwash (units $Qgog_e$, $Qgos_e$, and Qgo_e) and glacial lake deposits (unit Qgl_e) suggest more widespread deltaic deposits than mapped herein.

Qgl_e — **Recessional glaciolacustrine deposits (Pleistocene)**—Clay, silt, sandy silt, and sand with local dropstones; gray to light gray to blue-gray; weathered to shades of brown; well sorted; loose, soft, or stiff; nonstratified to laminated; varve-like rhythmite beds about 0.4 in. thick and laminated beds of silt to sand common; locally contains ball-and-pillow structures; rare sand dikes; common dropstone clast types include granite and greenstone; deposited in glacial lakes impounded by receding glacial ice and locally interfingers with recessional outwash. Note that differentiation between advance and recessional glaciolacustrine geologic units (units Qgl_v and Qgl_e) is difficult where stratigraphic position, sediment density, and other criteria are ambiguous.

VASHON STADE

Qgt_v — **Till (Pleistocene)**—Nonstratified, matrix-supported mixture of clay, silt, sand, and gravel in various proportions with disseminated cobbles and boulders; compact or dense; mottled dark yellowish brown to brownish gray, grayish blue, or very dark gray; matrix commonly consists of silty fine to coarse sand with or without clay; includes Canadian-provenance and locally derived clasts; where overlying bedrock, up to 90 percent of basal clasts are excavated from underlying bedrock; a "cemented till pavement" resulting from secondary magnesium carbonate precipitation is common where till overlies ultramafic rocks (unit Ju_h) along Deer Creek; generally a few yards thick, but it ranges from a discontinuous veneer to several tens of yards; forms a patchy cover over much of the study area; overlies bedrock in elevated alpine settings but forms a conformable layer in glacial-terrace and low valley-bottom settings and thus mantles topography (cross sections A, B, and C); consists largely of lodgment till but may locally include flow till.

Qga_v — **Advance outwash (Pleistocene)**—Medium to coarse sand, pebbly sand, and sandy gravel with scattered lenses and layers of pebble-cobble gravel; locally contains sand, silt, and clay interbeds; well sorted; compact or dense; clasts consist mostly of Canadian-provenance rock types, some locally derived rock types, and little or no Glacier Peak dacite; subhorizontal bedding or cross-stratification prominent; contains localized cut-and-fill structures and trough and ripple cross-beds; commonly overlain by unit Qgt_v along a sharp contact; interfingers with, conformably overlies, or is complexly interlayered with unit Qgl_v; composite sections of units Qga_v and Qgl_v are up to 130 ft thick. Deposits are primarily fluvial, but based on stratigraphic relations, some are inferred to be deltaic (cross sections A and B). The sedimentary structures and facies arrangement indicate ice-impounded glaciolacustrine conditions during southeasterly ice advance in the Deer Creek valley directly to the east (Dragovich and others, 2003).

Qgl_v — **Advance glaciolacustrine deposits (Pleistocene)**—Clay, silt, silty clay, and silty fine sand with local dropstones; blue gray or gray, weathered to pale yellowish brown; locally contains thick beds of structureless, clast-rich diamicton that may be flow till or iceberg melt-out contact zones; also locally contains lenses and beds of fine- to medium-grained sand; stiff or dense; well sorted. Bedding varies widely from structureless to thinly bedded to laminated and most commonly consists of 0.4 to 1.6 in. thick rhythmite beds (probable varves) that are normally graded from silty clay to fine sand. Rhythmite bedding is locally interrupted by thin to thick beds of sand or silty fine sand. Soft-sediment and (or) ice-shear deformational features include contorted bedding, overturned folds, and flame structures. Overturned fold geometries are consistent with east-southeast-directed ice shear during ice advance up the major river valleys. This unit is typically underlain by unit Qc_o and locally overlain by and (or) interbedded with unit Qga_v (cross sections A and B). Note that differentiation between advance and recessional glaciolacustrine geologic units (units Qgl_v and Qgl_e) is locally difficult where stratigraphic position, sediment density, and other criteria are ambiguous.

Deposits of the Olympia Nonglacial Interval

Qc_o — **Deposits of the Olympia nonglacial interval (Pleistocene) (cross sections only)**—Gravel, sand, silt, clay, peat, and rare diamicton; compact to very compact, well-sorted, and very thinly to thickly bedded; disseminated organic material, logs or wood fragments are common (cross section A and B). Dragovich and others (2003) obtained ages of 35,040 ±450 yr B.P. and 38,560 ±640 yrs B.P.

Deposits of the Possession Glaciation

ot — **Older till (Pleistocene) (cross sections only)**—Clay, silt, sand, and gravel in various proportions, with scattered cobbles and boulders; may locally include Vashon advance glaciolacustrine deposits; correlation with the Possession Glaciation based on stratigraphic thickness is tentative.

oo — **Older outwash (Pleistocene) (cross sections only)**—Sand and (or) gravel; occurs directly below unit ot and may correspond to the Possession outwash or older pre-Possession glacial or nonglacial sediments.

Tertiary Intrusive, Volcanic, and Sedimentary Rocks

INTRUSIVE ROCKS

ΦEiq — **Stock at Granite Lakes of Tabor and others (2002) (Oligocene–Eocene)**—Porphyritic hornblende-clinopyroxene quartz diorite; light greenish gray and weathered to light olive brown; contains subhedral to euhedral blocky plagioclase (20-70%, 0.04 to 0.2 in.), subhedral to euhedral lath-shaped brown hornblende (10-15%, 0.08 to 0.3 in.), subhedral to anhedral biotite (0-10%, 0.04 to 0.11 in.), and anhedral and commonly poikilitic interstitial quartz (1-10%, 0.04 to 0.11 in.); hornblende is frequently corroded and partially replaced by chlorite or stilpnomelane, quartz, and magnetite; plagioclase exhibits both normal zoning (generally with labradorite cores and andesine rims) and oscillatory zoning; biotite occurs as an interstitial phase with quartz and opaque minerals and is locally altered to chlorite; other alteration minerals include quartz, carbonate, pumpellyite, actinolite, sericite, and epidote; potassium feldspar, apatite, and zircon are accessory minerals. The only occurrence is a dike (site 11) in the northeastern part of the study area. East of the study area, the unit has yielded K-Ar hornblende ages of 53.0 ±8 Ma, 38.5 ±7.0 Ma, and 36.7 ±4.0 Ma and a zircon fission-track age of 30.2 ±3.5 Ma (Bechtel, 1979; Tabor and others, 2002). The pluton may be an intrusive source for late Eocene volcanic rocks and hypabyssal intrusive bodies (this study; Cruver, 1981; Jones, 1959; Reller, 1986; Dragovich and others, 2003).

VOLCANIC ROCKS

Ev — **Oso volcanics of Vance (1957) (Eocene)**—Nonmarine rhyolite, andesite, basaltic andesite, dacite, and rare basalt; mostly flows with interbedded pyroclastic deposits and scattered dikes; pyroclastic rocks include vitric crystal tuff, crystal lithic tuff, and tuff breccia; mostly brownish red, green, or bluish gray and weathered to olive brown; felsic tuffs are white, weathered to tan; plagioclase phyric locally with augite and (or) pigeonite phenocrysts; minor thin to thick beds of volcanic lithic sandstone and siltstone (including reworked tuff deposits); generally compositionally bimodal consisting of rhyolite and basaltic andesite; igneous textures vary from aphyric to locally porphyritic and trachyitic; flows commonly amygdaloidal; alteration minerals include disseminated chlorite, calcite, limonite, quartz, prehnite, sulfides, and epidote. Unit ΦEiq may be a source for at least part of this unit. Sandstone is composed of angular to subrounded clasts of zoned plagioclase, clinopyroxene, quartz, and volcanic fragments in a fine-grained matrix containing ash shards (this study; Jones, 1959; Reller, 1986; Tabor and others, 2002). Rhyolite to andesite dikes that intrude the Chuckanut along Deer Creek (site 8) and elsewhere suggest that the volcanics are mostly younger than the Chuckanut. Also, the open folding of unit Ev compared with the tight folding of the Chuckanut suggests an unconformity between these units. Locally divided into:

Eva — **Andesite**—Andesite with some basaltic andesite, minor interbedded basalt, rhyolite, and tuff, and rare volcanic lithic sandstone and argillite; typically occurs as dikes or thick flows with interbedded vitric or crystal vitric tuff; bedding generally obscure; andesite and basaltic andesite contain abundant microlites or slender grains of plagioclase (up to 40%); some rocks also contain blocky subhedral to euhedral plagioclase (up to 0.08 in.); locally contains chloritized hornblende and minor subhedral to euhedral interstitial to microphenocrystic quartz; rarely contains potassium feldspar and altered, fine-grained augite(?); phenocrysts and glass matrix commonly altered to chlorite, actinolite, epidote, carbonate, sphene, or sericite. Porphyritic and trachytoid (flow) textures are common, and the rocks locally contain carbonate or chlorite-carbonate-quartz-filled vesicles. Tabor and others (2002) obtained a zircon fission-track age for the unit of 45.7 ±4.6 Ma (site 2).

SEDIMENTARY ROCKS

$ΦEc_{bcg}$ — **Sedimentary rocks of Bulson Creek of Lovseth (1975) (Oligocene to Eocene)**—Chert and polycrystalline quartz conglomerate with interbeds of pebbly sandstone and sandstone; greenish gray to yellowish brown and weathered to a reddish or yellowish brown; clasts are subangular to subrounded, moderately spherical to elongate; locally displays crude imbrication and subtle to distinct normal grading; sandstone interbeds contain angular to subrounded clasts and vary from structureless to thickly bedded with rare graded bedding, channeling, and festoon cross bedding. The unit overlies and is partially derived from the Eastern mélange belt (unit $JTms_e$). The unit was deposited in tectonically controlled fluvial and alluvial-fan settings south of the main strand of the Darrington–Devils Mountain fault zone (DDMFZ). Lovseth (1975) and Marcus (1981) report late Eocene to early Oligocene shallow-water marine fossils in the unit west of the map area.

Ec_h — **Mount Higgins unit of the Chuckanut Formation (Eocene)**—Fluvial feldspathic to lithofeldspathic sandstone, siltstone, and mudstone with minor conglomerate, coal (anthracite), and altered tuff (bentonite); sandstone is various shades of bluish gray to greenish gray and weathered to dark gray to brown; minor minerals reported by Cruver (1981) include K-rectorite, illite, siderite, anatase, zircon, and ankerite; some black shale horizons contain siderite concretions; clasts are subangular to subrounded and are moderately sorted in sandstone and pebble conglomerate; sandstone–shale ratio is about 2:1; structures include cross-bedding, laminated mudstone, symmetrical ripple marks, mudcracks, leaf litter layers, sole marks, and paleosols (Dragovich and others, 2003; Evans and Ristow, 1994).

Ec_c — **Coal Mountain unit of the Chuckanut Formation (Eocene)**—Fluvial feldspathic sandstone with conglomerate, mudstone, siltstone, and coal; sandstone is light gray and weathered to yellow or yellowish brown, is micaceous, medium to coarse grained, and plagioclase rich, and contains about 10 percent metamorphic lithic clasts (mostly phyllite); sandstone–shale ratio is about 3:1; thick to very thin bedded; well-sorted, rounded to subrounded clasts; trough cross-bedding, ripple lamination, or plane lamination common in the coarse-grained beds; fine-grained beds contain laminated mudstone, ripples, flute and load casts, and plant fossils (this study; Evans and Ristow, 1994; Tabor and others, 2002).

Mesozoic Low-Grade Metamorphic Rocks (Prehnite-Pumpellyite to Blueschist Facies)

EASTON METAMORPHIC SUITE

Jph_d, Jph_{dj} — **Darrington Phyllite and (or) semischist of Mount Josephine (Jurassic)**—Divided into two map units on the basis of the percentage of interbedded phyllite and semischist: unit Jph_d (90–100 percent Darrington Phyllite, 0–10% semischist of Mount Josephine) and unit Jph_{dj} (50–90 percent Darrington Phyllite, 10–50% semischist of Mount Josephine).

Darrington Phyllite—Sericite-graphite-albite-quartz phyllite to graphitic quartz phyllite (metashale) with rare interbeds of micaceous quartzite (metachert), metatuff, and albite schist; phyllite is bluish black to black due to disseminated graphite (relict organic matter); silver-colored phyllites are muscovite rich; metamorphic minerals include albite, chlorite, epidote, clinozoisite, muscovite, lawsonite, and rare garnet and stilpnomelane. We locally observed large albite porphyroblasts and strongly foliated (S1, in places S2), conspicuously F2-folded and L2-crenulated structures with F2–L2 fold axes typically oriented subhorizontally northwest or southeast.

Semischist of Mount Josephine—Semischistose feldspathic to lithofeldspathic metasandstone or metawacke; rare metaconglomerate; greenish to light bluish gray and weathered to a light yellowish brown to dark gray; contains relict sand grains of polycrystalline and monocrystalline quartz, albitized plagioclase, and sparse lithic fragments. Metamorphic minerals are similar to those of the Darrington Phyllite (this study; Brown and others, 1987; Dragovich and others, 1998, 1999, 2000; Jones, 1959).

HELENA–HAYSTACK MÉLANGE

The Helena–Haystack mélange of Tabor (1994) or the Haystack terrane of Whetten and others (1980, 1988) is a serpentinite-matrix mélange. Blocks of greenstone erode out of mélange matrix as steep resistant hillocks. Regional greenstone geochemistry suggests a mid-oceanic-ridge to oceanic-island-arc origin (Dragovich and others, 1998, 1999, 2000; Tabor, 1994). U-Pb zircon ages obtained from meta-igneous rocks indicate a Jurassic age of about 160 to 170 Ma (Dragovich and others, 1998, 1999, 2000; Whetten and others, 1980, 1988). Also, partially recrystallized radiolarians in metacherts (unit $Jhmc_h$) are Mesozoic, possibly Triassic (site 3; Tabor and others, 2002). Mélange formation is probably mid-Cretaceous or younger and may be partially Tertiary (Tabor, 1994). Cretaceous to Tertiary faulting within the broad DDMFZ locally imbricates the ultramafic rocks of the Helena–Haystack mélange with Tertiary and other pre-Tertiary rocks (site 8, cross section C).

Jmv_h — **Greenstone (Jurassic)**—Metamorphosed basalt, andesite, dacite, and rare rhyolite occurring as mafic to intermediate flows and intermediate to felsic tuff and lapilli tuff; bluish gray to grayish green and weathered to dark greenish gray to light yellowish brown; flows locally contain amygdules, pillow breccia, and pillows; commonly nonfoliated but locally contains strong spaced cleavage; relict minerals include augite, saussuritized plagioclase, and rare hornblende; metamorphic minerals include albite, chlorite, acicular actinolite, Fe- and Mg-pumpellyite, prehnite, stilpnomelane, aragonite, and calcite. Pumiceous lapilli metatuff at site 16 contains intermediate (70%), felsic (20%), and mafic (10%) lapilli-sized volcanic clasts and an island-arc geochemical signature (this study; Dragovich and others, 2002a,b; Reller, 1986; Tabor and others, 2002).

$Jigb_h$ — **Metagabbro (Jurassic)**—Medium-grained to rarely coarse-grained and uralitic greenstone; light to dark greenish gray weathered to yellowish or grayish brown; nonfoliated to locally protomylonitic; also includes coarse-grained gneissic quartz diorite and metamorphosed diorite, pegmatitic gabbro, and diabase; relict minerals include saussuritized and albitized plagioclase, augite or pigeonite, brown actinolized hornblende, and minor interstitial quartz; ophitic or subophitic relict igneous textures common; metamorphic minerals include acicular actinolite, tremolite, epidote, chlorite, pumpellyite, white mica, stilpnomelane, calcite, and (or) aragonite; recrystallization partial and typically static. K-Ar ages of 133 ±10 Ma and 164 ±24 Ma (Bechtel, 1979; site 1) are consistent with Jurassic intrusive U-Pb intrusive ages reported elsewhere (this study; Reller, 1986; Tabor and others, 2002).

Ju_h — **Ultramafite (Jurassic)**—Mostly serpentinite with minor nonserpentinized or partially serpentinized dunite, peridotite, and pyroxenite (site 10) and minor metasomatic silica-carbonate rock (unit Ju_{hl}), rodingite, or talc-tremolite rock; serpentinite is greenish gray to greenish black and weathered to a dark yellowish orange and reddish brown; serpentinite composed of serpentine minerals locally with relict pyroxene and (or) olivine and accessory picotite, magnesite, and opaque minerals. A partially serpentinized dunite (site 13) is composed of olivine (70%), serpentinite (25%) and opaque minerals (5%) (this study; Jones, 1959; Tabor and others, 2002).

Ju_{hl} — **Silica-carbonate rocks (Jurassic)**—Silica-carbonate mineralization products (listwaenites) resulting from metasomatism of ultramafites; pods of incompletely altered serpentinite and brecciated silica-carbonate rock locally common; brown to orange-brown weathered to a reddish or brownish yellow; hydrothermal minerals include microcrystalline quartz and magnesite in roughly equal amounts, with magnesite forming granular aggregates and vein swarms; magnetite, pyrite, and marcasite occur as accessory minerals; associated replacement rocks contain talc, tremolite, sphene, and chlorite; vugs contain colorless, euhedral quartz with overgrowths of dolomite; commonly displays compositionally banded veins or replacement bands of microcrystalline or macrocrystalline quartz, microcrystalline magnesite, fibrous chalcedony, and (or) macrocrystalline dolomite. Where silica-carbonate rocks and serpentinites are tectonically juxtaposed against the Chuckanut Formation within the DDMFZ (cross section C), silica-carbonate minerals locally replace the Chuckanut sandstone matrix. Structural relations in these areas suggest that the circulation of hydrothermal fluids accompanied deformation across the DDMFZ and may have been driven partly by hydrothermal circulation cells around Eocene volcanic intrusions. Dragovich and others (2002c) suggested that much of the silica-carbonate mineralization was synchronous with major Tertiary transpression and thrusting in the DDMFZ but locally continued after major fault displacement (this study; Graham, 1988; Lovseth, 1975).

$Jhmc_h$ — **Heterogeneous metamorphic rocks, chert bearing (Jurassic)**—Graphite-bearing, medium gray meta-argillite, bluish gray metasandstone to metawacke, and minor metachert; meta-argillite characterized by a strong phyllitic to slaty cleavage; metasandstone and meta-argillite weathered bluish gray and dark greenish gray. Unlike in the Easton suite, cleavage and bedding are locally nonparallel, quartzose metamorphic segregations are generally lacking, and the rocks are less recrystallized.

Jam_h — **Amphibolite (Jurassic)**—Fine-grained amphibolite with well-crystallized green hornblende and plagioclase; other metamorphic minerals include chlorite, epidote, and pumpellyite. Amphibolite-facies metamorphism of this mafic metavolcanic rock occurred before mélange formation (Bechtel, 1979; Tabor, 1994; Tabor and others, 2002).

ROCKS OF THE EASTERN MÉLANGE BELT OF TABOR (1994)

$JTmt_e$ — **Mixed metavolcanic and metasedimentary rocks (Jurassic–Triassic)**—Greenstone with volcanic subquartzose metasandstone, metawacke, meta-argillite, phyllitic argillite, metachert, and minor marble or marl pods; rocks structureless to locally moderately foliated; greenstone contains relict clinopyroxene (some titaniferous) and plagioclase in an altered matrix of chlorite, carbonate, and pumpellyite; prehnite common in veins; deformed pillows are rare. Up to 50 percent of the unit is highly sheared and disrupted greenstone (this study; Tabor and others, 2002).

$JTmv_e$ — **Greenstone (Jurassic–Triassic)**—Metamorphosed plagioclase- and augite-phyric basaltic andesite, basalt, andesite, and dacite with minor diabase and gabbro; dark to greenish gray or dusky green weathered dark greenish or bluish gray or brown; thin metasandstone, meta-argillite and metachert interbeds occur locally; mostly thick flows with subordinate thinner beds of breccia or crystal-rich pyroxene-bearing tuff; metamorphic minerals include epidote, pumpellyite, prehnite, and chlorite; local amygdaloidal flow tops; massive to incipiently foliate. The greenstone on Frailey Mountain is strongly fractured and locally protomylonitic as a result of low-temperature brittle to semiductile DDMFZ shear (this study; Dethier and others, 1980; Tabor and others, 2002).

$JTms_e$ — **Metasedimentary rocks (Jurassic–Triassic)**—Metamorphosed argillite, sandstone, wacke, siltstone with subordinate chert pebble conglomerate (site 9), chert, marl (site 15), and rare marble; locally contains tuff or greenstone layers and lenses; argillite commonly contains radiolaria and (or) silt-sized grains including angular quartz and plagioclase; sandstone commonly contains large rip-up clasts of argillite; other sandstone clasts include monocrystalline and polycrystalline quartz, chert, plagioclase, sedimentary lithic fragments, quartz mica tectonite, mica, and rare coral fragments; some metasandstones are volcanic lithic to feldspatholithic with a chert-rich provenance; metamorphic minerals include epidote, chlorite, pumpellyite, carbonate, and white mica; prehnite occurs typically in veins; rocks vary from massive to incipiently foliated to rarely strongly cleaved; overturned F1 folds and cleavage geometry in the chert on Frailey Mountain suggest north-northeast vergence; an argillaceous protomylonite-cataclasite from near the main strand of the DDMFZ (site 14) contains a vertical foliation and subhorizontally stretched clasts and provides strike-slip movement indicators (this study; Dethier and others, 1980; Tabor, 1994; Tabor and others, 2002).

$JTmc_e$ — **Metachert (Jurassic–Triassic)**—Metachert locally with greenstone, metawacke, and meta-argillite; chert is red or black and weathered to a white or yellow; chert is ribboned or banded, less commonly occurring as thin laminae in meta-argillite; locally complexly disrupted, boudinaged, and folded, with veins of quartz, prehnite, and white mica; disseminated chlorite in mylonite zones. Deformed and (or) recrystallized radiolarians from chert directly east of the study area provide Triassic and Jurassic ages (this study; Tabor and others, 2002).

JTu_e — **Ultramafite (Jurassic–Triassic)**—Serpentinite, talc-tremolite rock, metaperidotite, and metaclinopyroxenite; serpentinite is light greenish gray to greenish black and weathers to pale green or yellowish orange. The serpentinite on Frailey Mountain is several tens of meters thick, strongly foliated, and lineated, and probably corresponds to a major zone of dislocation within the Eastern mélange belt (this study; Tabor and others, 2002).

ROCKS OF THE WESTERN MÉLANGE BELT OF TABOR (1994)

$KJhmc_w$ — **Heterogeneous metamorphic rocks, chert-bearing (Cretaceous–Jurassic)**—Semischistose metasandstone, slate, and phyllite; also contains greenstone derived from mafic volcanic breccia, tuff, and flows locally with well-developed pillows (site 12); locally abundant metachert and rare limestone; commonly contains pervasively foliated, gray to black, metamorphosed lithofeldspathic to volcanic lithic sandstone and semischist commonly with rip-up clasts of argillite; clasts include angular to subrounded plagioclase, monocrystalline and polycrystalline quartz, chert, volcanic lithic fragments, and scattered detrital mica; an aphyric basaltic greenstone with well-developed pillows contains microphenocrystic augite and plagioclase in a dark green recrystallized glass matrix (site 12); locally, abundant cobble conglomerates are interbedded with argillite or phyllite; rhythmite and laminate bedding, graded bedding, and load casts locally well preserved; metamorphic minerals are carbonate, prehnite (typically in veins), pumpellyite, chlorite, epidote, and sericite; minor metagabbro and diabase and rare marble and ultramafic rocks found in the belt regionally are probably absent in the study area. Sparse fossils, including radiolarians in chert and megafossils in argillite, indicate that the belt (excluding limestone) is Late Jurassic to earliest Cretaceous; radiolarians in metachert at site 5 are Late Jurassic. Limestone blocks (olistostromes?) south of the study area are Permian, and a few chert blocks are Early Jurassic (Tabor and others, 2002).

DARRINGTON–DEVILS MOUNTAIN FAULT ZONE

The Darrington–Devils Mountain fault zone (DDMFZ) divides the Northwest Cascades system on the north from the Eastern and Western mélange belts on the south (Dragovich and others, 2002d; Tabor, 1994). This broad fault zone is composed of numerous en-echelon segments and subsidiary faults with a complex displacement history beginning at latest in the Eocene (and perhaps the mid-Cretaceous) and continuing to recent times (Johnson and others, 2001). Dragovich and others (2002c) modeled the fault zone as a flower structure within an overall left-lateral transpressional fault regime, and we envision a similar deformational style for the current study area. However, the displacement history of the DDMFZ is complex. For example, the DDMFZ switched from transtensional to transpressional in the Eocene (Evans and Ristow, 1994) and is currently under almost pure north–south compression (Ma and others, 1996; Zollweg and Johnson, 1989).

Zollweg and Johnson (1989) defined the active Darrington seismic zone (DSZ) using a local portable seismometer array. Their hypocentral geometry implies that the activity occurs on a fault zone striking N80ºW ±20º, dipping south at 40º ±15º, with a length along strike of at least 6 to 12 miles. Using best-quality hypocentral and focal mechanism DSZ data, as well as seismic data obtained from the Pacific Northwest Seismic Network, we correlate recent seismicity with faults within the DDMFZ, including the steeply dipping main trace of the fault and a proposed shallowly dipping regional décollement (cross section C). (For locations of zones of DSZ high seismicity see sites 6 and 7 on the geologic map.)

Other evidence for recent seismicity and deformation along the DDMFZ includes: (1) probable displacement of Quaternary strata in the Oso quadrangle along a subsidiary fault near Deer Creek (site 8); (2) liquefaction features in recessional lake and outwash deposits; and (3) increased landslide density near the DDMFZ, suggesting landslides may be seismically induced. Additionally, anomalous exposures of deposits of the Olympia nonglacial interval near the main trace of the fault suggest uplift and erosion of Quaternary strata near the main trace of the DDMFZ (Dragovich and others, 2003). Holocene uplift and erosion are also implied by the absence of thick laharic valley fills where the DDMFZ crosses the Stillaguamish River despite occurrences of lahar deposits on both sides of the fault zone (this study; Dragovich and others, 2002a,b, 2003; J. D. Dragovich, DGER, unpub. data).

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REFERENCES CITED

Bechtel, Inc., 1979, Report of geologic investigations in 1978-1979; Skagit Nuclear Power Project: Puget Sound Power and Light Company, 3 v., 3 plates.

Brown, E. H.; Blackwell, D. L.; Christenson, B. W.; Frasse, F. I.; Haugerud, R. A.; Jones, J. T.; Leiggi, P. A.; Morrison, M. L.; Rady, P. M.; and others, 1987, Geologic map of the northwest Cascades, Washington: Geological Society of America Map and Chart Series MC-61, 1 sheet, scale 1:100,000, with 10 p. text.

Cruver, S. K., 1981, The geology and mineralogy of bentonites and associated rocks of the Chuckanut Formation, Mt. Higgins area, North Cascades Washington: Western Washington University Master of Science thesis, 105 p., 3 plates.

Dethier, D. P.; Whetten, J. T.; Carroll, P. R., 1980, Preliminary geologic map of the Clear Lake SE quadrangle, Skagit County, Washington: U.S. Geological Survey Open-File Report 80-303, 11 p., 2 plates.

Dragovich, J. D.; Gilbertson, L. A., Lingley, W. S., Jr.; Polenz, Michael; Glenn, Jennifer, 2002a, Geologic map of the Darrington 7.5-minute quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2002-7, 1 sheet, scale 1:24,000.

Dragovich, J. D.; Gilbertson, L. A., Lingley, W. S., Jr.; Polenz, Michael; Glenn, Jennifer, 2002b, Geologic map of the Fortson 7.5-minute quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2002-6, 1 sheet, scale 1:24,000.

Dragovich, J. D.; Gilbertson, L. A.; Norman, D. K.; Anderson, Garth; Petro, G. T., 2002c, Geologic map of the Utsalady and Conway 7.5-minute quadrangles, Skagit, Snohomish, and Island Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2002-5, 1 sheet, scale 1:24,000.

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

Dragovich, J. D.; Norman, D. K.; Anderson, Garth, 2000, Interpreted geologic history of the Sedro-Woolley North and Lyman 7.5-minute quadrangles, western Skagit County, Washington: Washington Division of Geology and Earth Resources Open File Report 2000-1, 71 p., 1 plate.

Dragovich, J. D.; Norman, D. K.; Grisamer, C. L.; Logan, R. L.; Anderson, Garth, 1998, Geologic map and interpreted geologic history of the Bow and Alger 7.5-minute quadrangles, western Skagit County, Washington: Washington Division of Geology and Earth Resources Open File Report 98-5, 80 p., 3 plates.

Dragovich, J. D.; Norman, D. K.; Lapen, T. J.; Anderson, Garth, 1999, Geologic map of the Sedro-Woolley North and Lyman 7.5-minute quadrangles, western Skagit County, Washington: Washington Division of Geology and Earth Resources Open File Report 99-3, 37 p., 4 plates.

Dragovich, J. D.; Stanton, B. W.; Lingley, W. S., Jr.; Griesel, G. A.; Polenz, Michael, 2003, Geologic map of the Mount Higgins 7.5-minute quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-12, 1 sheet, scale 1:24,000.

Evans, J. E.; Ristow, R. J., Jr., 1994, Depositional history of the southeastern outcrop belt of the Chuckanut Formation—Implications for the Darrington–Devil's Mountain and Straight Creek fault zones, Washington (U.S.A.): Canadian Journal of Earth Sciences, v. 31, no. 12, p. 1727-1743.

Graham, D. C., 1988, Hydrothermal alteration of serpentinite associated with the Devils Mountain fault zone, Skagit County, Washington: Western Washington University Master of Science thesis, 125 p.

Johnson, S. Y.; Dadisman, S. V.; Mosher, D. C.; Blakely, R. J.; Childs, J. R., 2001, Active tectonics of the Devils Mountain fault and related structures, northern Puget Lowland and eastern Strait of Juan de Fuca region, Pacific Northwest: U.S. Geological Survey Professional Paper 1643, 45 p., 2 plates.

Jones, R. W., 1959, Geology of the Finney Peak area, northern Cascades of Washington: University of Washington Doctor of Philosophy thesis, 186 p., 2 plates.

Lovseth, T. P., 1975, The Devils Mountain fault zone, northwestern Washington: University of Washington Master of Science thesis, 29 p.

Ma, Li; Crosson, R. S.; Ludwin, R. S., 1996, Western Washington earthquake focal mechanisms and their relationship to regional tectonic stress. *In* Rogers, A. M.; Walsh, T. J.; Kockelman, W. J.; Priest, G. R., editors, Assessing earthquake hazards and reducing risk in the Pacific Northwest: U.S. Geological Survey Professional Paper 1560, v. 1, p. 257-283.

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

Reller, G. J., 1986, Structure and petrology of the Deer Peaks area, western North Cascades, Washington: Western Washington University Master of Science thesis, 106 p., 2 plates.

Tabor, R. W., 1994, Late Mesozoic and possible early Tertiary accretion in western Washington State—The Helena–Haystack mélange and the Darrington–Devils Mountain fault zone: Geological Society of America Bulletin, v. 106, no. 2, p. 217-232, 1 plate.

Tabor, R. W.; Booth, D. B.; Vance, J. A.; Ford, A. B., 2002, Geologic map of the Sauk River 30- by 60-minute quadrangle, Washington: U.S. Geological Survey Geologic Investigations Series Map I-2592, 2 sheets, scale 1:100,000, with 67 p. text.

Vance, J. A., 1957, The geology of the Sauk River area in the northern Cascades of Washington: University of Washington Doctor of Philosophy thesis, 312 p., 1 plate.

Whetten, J. T.; Carroll, P. I.; Gower, H. D.; Brown, E. H.; Pessl, Fred, Jr., 1988, Bedrock geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-G, 1 sheet, scale 1:100,000.

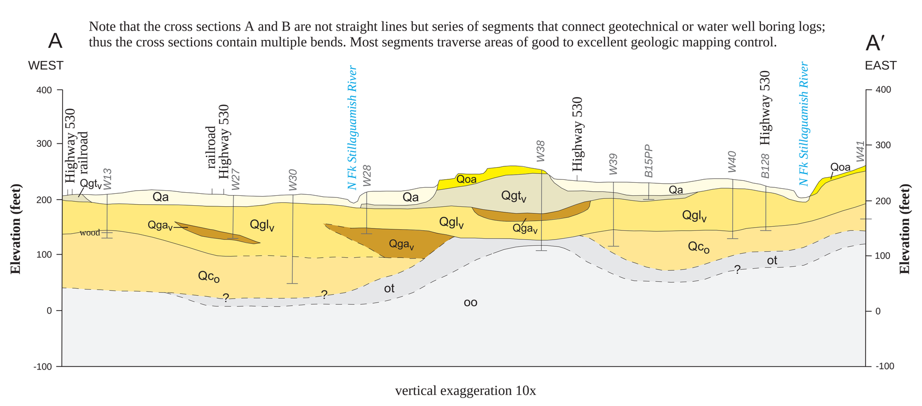
Whetten, J. T.; Zartman, R. E.; Blakely, R. J.; Jones, D. L., 1980, Allochthonous Jurassic ophiolite in northwest Washington: Geological Society of America Bulletin, v. 91, no. 6, p. I 359-I 368.

Zollweg, J. E.; Johnson, P. A., 1989, The Darrington seismic zone of northwestern Washington: Seismological Society of America Bulletin, v. 79, no. 6, p. 1833-1845.

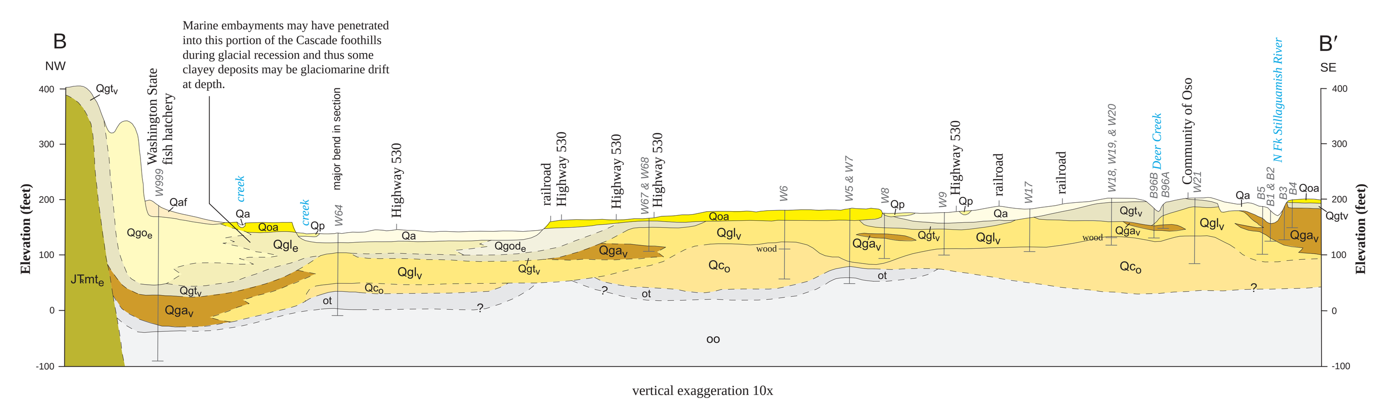
GEOLOGIC SYMBOLS

- Contact—Dashed where inferred
- Fault, unknown offset—Dashed where inferred; dotted where concealed; queried where uncertain
- Normal fault—Bar and ball on downthrown side; dotted where concealed; queried where uncertain
- Strike-slip fault—Half arrows show apparent relative motion; dotted where concealed
- Oblique-slip fault—Bar and ball on downthrown side; half arrows show apparent relative lateral motion; dotted where concealed
- Thrust fault—Sawteeth on upper plate; dotted where concealed
- Overturned anticline—Inferred
- Syncline—Large arrowhead shows direction of plunge; dotted where concealed
- Late Pleistocene to Holocene terrace—hachures point downslope
- Direction of landslide movement
- Horizontal bedding
- Inclined bedding (or flow banding in volcanic rocks)—Showing strike and dip
- Inclined bedding—Showing strike and dip; top direction of beds known from local features
- Inclined bedding in unconsolidated sedimentary deposits—Showing strike and dip; F near symbol indicates foreset bedding; T indicates topset bedding; B indicates bottomset bedding
- Inclined foliation in metamorphic rock—Showing strike and dip
- Inclined foliation parallel to original bedding in metamorphic rock—Showing strike and dip
- Inclined first-generation (S1) foliation in metamorphic rock—Showing strike and dip
- Inclined third-generation (S3) foliation in metamorphic rock—Showing strike and dip
- Vertical or near-vertical foliation in metamorphic rock—Showing strike
- Vertical or near-vertical first-generation (S1) foliation in metamorphic rock—Showing strike
- Minor inclined fault—Showing strike and dip
- Inclined joint—Showing strike and dip
- Vertical or near-vertical joint—Showing strike
- Extensional vein—Showing strike and dip
- Inclined slickensided surface—Showing strike and dip
- Vertical slickensided surface—Showing strike
- Minor first-generation (F1) fold axis—Showing bearing and plunge
- Minor second-generation (F2) fold axis or crenulation lineation—Showing bearing and plunge
- Minor third-generation (F3) fold axis or kink or crenulation lineation—Showing bearing and plunge
- Inclined second-generation (S2) fold axial surface—Showing strike and dip
- Mineral lineation—Showing bearing and plunge
- Slip lineation or slickenside on a fault or shear surface—Showing bearing and plunge of offset
- Stretching lineation—Showing bearing and plunge
- Current flow direction indicator (pebble imbrication, ripples, etc.)—Showing bearing and plunge
- K-Ar radiometric age
- Zircon fission-track age
- Radiocarbon age
- Fossil age (Tabor and others, 2002)
- Approximate center of area of high seismicity within the Darrington seismic zone of Zollweg and Johnson (1989). See Zollweg and Johnson (1989) for full extent of the zone
- Other locations referred to in text
- W27 Water well or geotechnical borehole—*W* indicates water well; *B* indicates geotechnical borehole; number is assigned by authors

Note that the cross sections A and B are not straight lines but series of segments that connect geotechnical or water well boring logs; thus the cross sections contain multiple bends. Most segments traverse areas of good to excellent geologic mapping control.



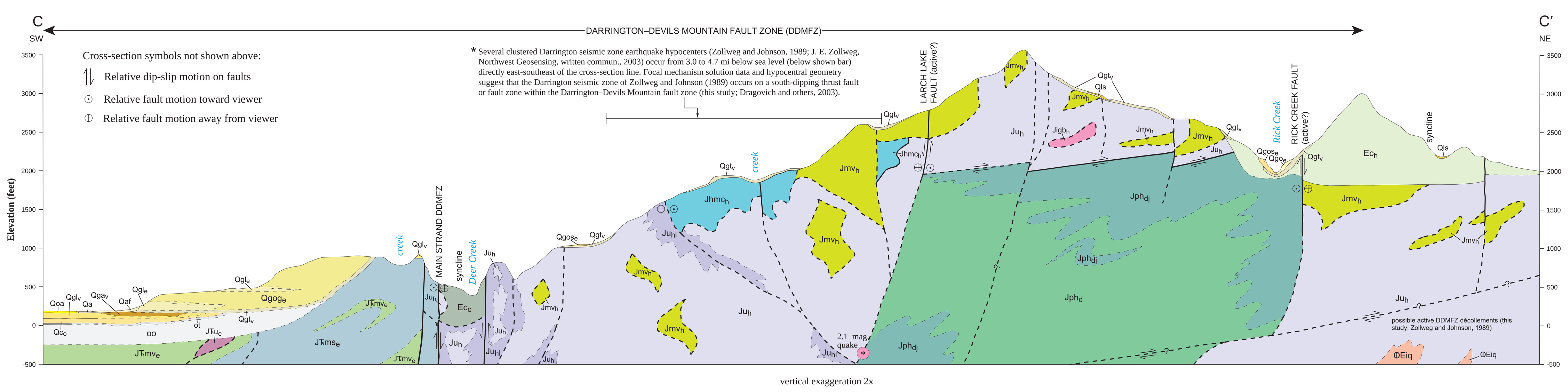
vertical exaggeration 10x



vertical exaggeration 10x

Cross-section symbols not shown above:
- Relative dip-slip motion on faults
- Relative fault motion toward viewer
- Relative fault motion away from viewer

* Several clustered Darrington seismic zone earthquake hypocenters (Zollweg and Johnson, 1989; J. E. Zollweg, Northwest Geosensing, written commun., 2003) occur from 3.0 to 4.7 mi below sea level (below shown bar) directly east-southeast of the cross-section line. Focal mechanism solution data and hypocentral geometry suggest that the Darrington seismic zone of Zollweg and Johnson (1989) occurs on a south-dipping thrust fault



DARRINGTON–DEVILS MOUNTAIN FAULT ZONE (DDMFZ)

vertical exaggeration 2x