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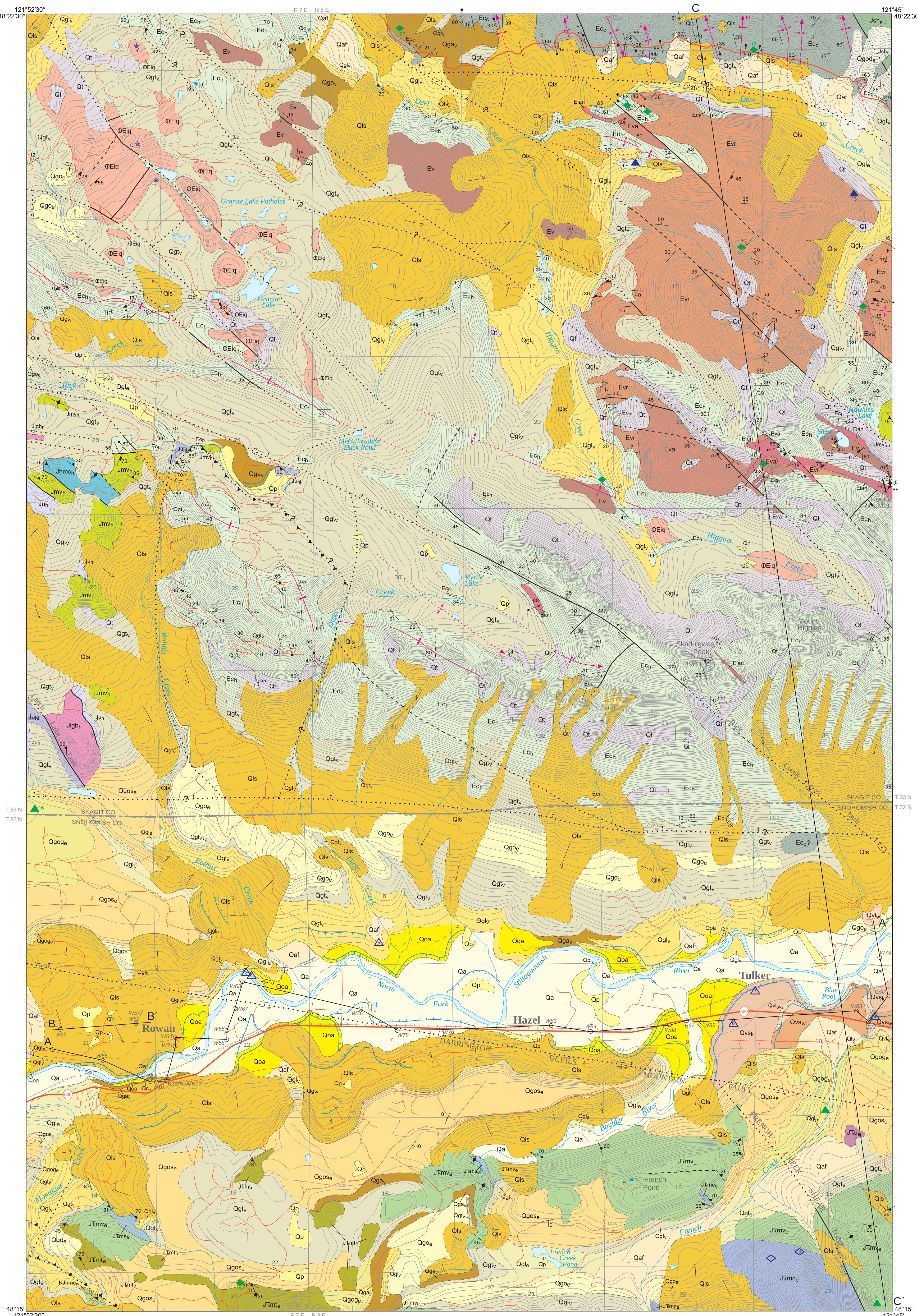
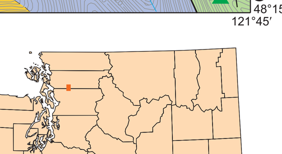
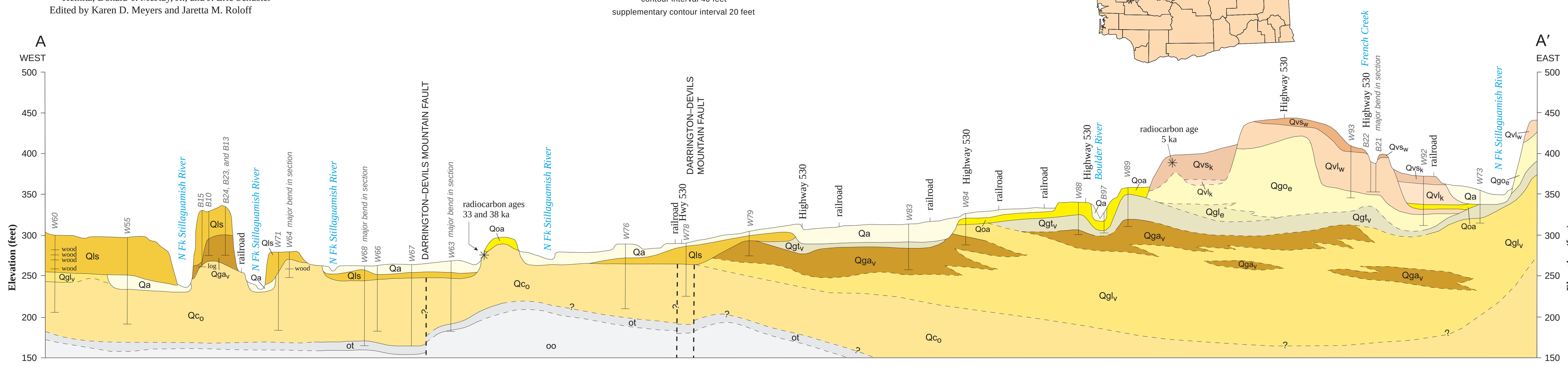
WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
OPEN FILE REPORT 2003-12



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

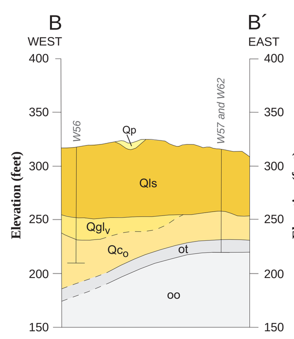
SCALE 1:24 000
contour interval 40 feet
supplementary contour interval 20 feet





Note that the cross section A is not a straight line but a series of segments that connect geotechnical or water well logs; thus the cross section contains multiple bends. Most segments traverse areas of good to excellent geologic mapping control.

vertical exaggeration 20x



vertical exaggeration 20x

Geologic Map of the Mount Higgins 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

Qs — **Surficial deposits, undivided (Quaternary) (cross sections only)**—Surficial units that are too thin to delineate separately in cross section.

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. Radiocarbon ages from sticks in peat and organic sediments yield ages of less than 600 yr B.P. and of 2,270 ±60 yr B.P. near the study area (Dragovich and others, 2002a,b, 2003).

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, siltstone, dacite, pumice, phyllite, slate, vein quartz, chert, quartzite, conglomerate, 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 buffer. Unit Qoa postdates recessional outwash but also includes deposits that are analogous 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 standing 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. We obtained a radiocarbon age of 8,040 ±40 yr B.P. from charcoal in flood silt (site 5).

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-earthflow) 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).

Qt — **Talus deposits (Holocene)**—Nonsorted angular gravel and boulder gravel to diamicton; includes rock-avalanche, rock-fall and rockslide deposits; locally gradational with unit Qaf or Qls and may include Holocene moraine, rock glacier, and protalus rampart deposits. Talus surfaces are generally unvegetated; however, older rock avalanche run-out areas are sparsely to completely revegetated mostly by slide alder and similar pioneer plant species. Near Mount Higgins, talus deposits typically merge downslope with rock avalanche chutes and (or) depositional aprons containing debris flow deposits. Some avalanche deposits may have resulted from seismic activity associated with the Darrington–Devils Mountain fault zone (DDMFZ).

HOLOCENE AND LATE PLEISTOCENE GLACIER PEAK DEPOSITS

Kennedy Creek Assemblage of Beget (1981)

Kennedy Creek assemblage deposits originated from Glacier Peak, flowed down the Sauk River valley to the North Fork Stillaguamish River valley 5,100 to 5,400 yr B.P., and cover much of the Stillaguamish valley directly east of the study area (Beget, 1981; Dragovich and others, 2002a,b; J. D. Dragovich, DGER, unpublished data). Charcoal found in a lahar (unit Qvl$_k$) exposed in a road cut near Hazel (site 7) yielded a radiocarbon age of 5,020 ±100 yr B.P. (Beget, 1981). We obtained a corroborating age of 5,190 ±70 yr B.P. from charcoal in pumiceous flood deposits (site 6). The Kennedy Creek assemblage contains one or more lahars that transformed into hyperconcentrated flood deposits downstream as a result of interaction with surface water. Thick hyperconcentrated flood deposits and only thin lahar deposits are preserved in the study area due to this transformation (cross section A). (See Pierson and Scott, 1985, for similar Mount St. Helens lahar run-out deposits.)

Qvu$_k$ — **Volcanic sediments, undivided (Holocene)**—Dacite-rich hyperconcentrated flood deposits and volcanic alluvium including pumiceous silt flood deposits; consists of medium- to coarse-grained sand and thick beds of gravelly sand and cobbly sandy gravel; loose and moderately sorted; locally contains lahar beds (similar to unit Qvl$_k$) that are too thin to separate at map scale; reworked tephra-capping ash with scattered pumice lapilli probably represents one or more waning flood deposits. Clasts include 70 to 90 percent light to medium gray dacite locally with scattered pale red to dark reddish gray dacite. Stratigraphy and clast compositions indicate both fluvial and hyperconcentrated flood depositional mechanisms for the nonlaharic sediments. Locally divided into:

Qvl$_k$ — **Non-cohesive lahar (cross sections only)**—Silty sandy gravel to gravelly sand locally with cobbles and rare boulders; very pale brown matrix consists mostly of reworked pyroclasts of fine to coarse ash with crystals of hornblende, hypersthene, plagioclase, quartz, and rare augite, as well as vitric and dacite fragments; compact; dacite clasts are angular to subangular, abundant (over 80% of clast component), and locally nonvesicular to vesicular; commonly contains dewatering and (or) gas-escape pipes. Poorly exposed in the present study area, but well exposed directly east of the study area and inferred to occur in the subsurface locally (cross section A) (this study, Dragovich and others, 2002a,b).

White Chuck Assemblage of Beget (1981)

The White Chuck assemblage (~11,200–12,700 yr B.P.) resulted from Glacier Peak eruptions during Everson Interstade deglaciation (Beget, 1981; Foit and others, 1993). Beget (1981) obtained an age of 11,670 ±160 yr B.P. from charcoal in forest duff directly under unit Qvl$_w$ deposits near French Creek (site 8; cross section A); for occupation in the study area appears likely during deposition of at least part of the White Chuck assemblage. From the crest of the grade, area, elevated recessional meltwater channels are partially filled with lahar and indicate volcanic deluge during ice occupation (Dragovich and others, 2002a; J. D. Dragovich, DGER, unpublished data). Elsewhere, deposits of the White Chuck assemblage directly overlie dacite-poor recessional outwash of unit Qgo$_e$ (cross section A). The abundance of gravel- to boulder-sized rip-up clasts of glaciolacustrine or glaciofluvial sediments suggests excavation of lake deposits by either glacial-ice or volcanic-dam breakout mechanisms during the eruptive episode.

Qvu$_w$ — **Volcanic sediments, undivided (late Pleistocene)**—Dacite-rich hyperconcentrated flood deposits and volcanic alluvium; loose; consists of medium- to coarse-grained sand, sandy gravel, and sandy cobble gravel; locally contains lahar beds (similar to unit Qvl$_w$) that are too thin to separate at map scale; volcanic alluvium and hyperconcentrated flood deposits contain 50 to 95 percent dark gray or reddish dacite, commonly with white, yellow, and pale brown pumice that locally constitutes up to 50 percent of the clasts. Locally divided into:

Qvl$_w$ — **Non-cohesive lahar**—Cobbly to locally bouldery gravelly sand commonly with a trace of ash; light reddish brown; compact; contains dacite clasts up to 22 in.; pumice clasts are up to 2 in. and commonly flow-banded; matrix is composed of crystal-vitric fine to coarse sand with hornblende, quartz, plagioclase, pumiceous ash, and pumice; dacite composes 60 to 95 percent of the gravel and cobble component and is white and light to dark gray or weak red; dacite clasts are mostly angular and vesicular with flow banding in some clasts; also contains pumice lenses, cobble to boulder rip-up clasts of lacustrine or glaciofluvial sediment.

clay, and clasts of White Chuck vitric welded tuff; varies from massive to weakly normally graded near the top to symmetrically coarse-tail graded; contains thin reworked (?) ash beds at the base (this study; Beget, 1981; J. D. Dragovich, DGER, unpublished data). Field and subsurface information indicates lahar thickness is laterally variable, ranging from about 5 ft to 50 ft (cross section A).

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 of sandy cobble 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%); however, some of the outwash sands and gravels south of the Stillaguamish River and east-southeast of the study area may have been deposited along with the White Chuck assemblage along the southern margin of the Stillaguamish Valley (Dragovich and others, 2002a,b; J. D. Dragovich, DGER, unpublished data). Locally abundant dacite boulders in the French Creek and Boulder River channels are probably eroded from a nearby (but unexposed) lahar deposit overlying or interbedded with recessional deposits. Locally divided into:

Qgo$_{eg}$ — **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.

Qgo$_{es}$ — **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. Unit Qgo$_{es}$ deposits are typically fluvial but may include shallow deltaic deposits transitional to lake deposits.

Qgo$_{ed}$ — **Deltaic outwash**—Sandy gravel and cobbly sandy gravel; loose; moderately to well sorted; contains mostly locally derived, angular to subangular clasts of phyllite, vein quartz, and greenschist. High-amplitude deltaic foreset beds are generally thick, tens of meters high, dip about 30 degrees toward the Deer Creek valley, and are indicative of deltaic deposition into a recessional ice-dammed glacial lake. Facies relations, including fining trends, between deltaic deposits and glacio-fluvial valley-train outwash (units Qgo$_{eg}$, Qgo$_{es}$, 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 rhythmic bedding consisting of thin 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 glacio-lacustrine 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 quarried from underlying bedrock; generally a few yards thick, but can range 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 and B); 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 sandy silt, 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 Qgl$_v$ 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 position, some are inferred to be deltaic (cross sections A and B). For example, unit Qga$_v$ in the Deer Creek valley (site 23) contains high-amplitude and planar foreset beds that dip 21 to 29 degrees upvalley. These beds are traceable into mud-sand laminated bottomset beds with common gravelly sands. The sedimentary structures and facies arrangement indicate ice-impounded glaciolacustrine conditions in the Deer Creek valley during up-valley ice advance.

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 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 beds of sand or silty fine sand. Soft-sediment and (or) ice-drag 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 Qo$_g$ 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

Qo$_g$ — **Deposits of the Olympia nonglacial interval (Pleistocene)**—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). The Olympia nonglacial interval occurred from about 20,000 to 60,000 yr B.P. (Mullineaux and others, 1965; Pessl and others, 1989). We obtained ages of 35,040 ±450 yr B.P. and 38,560 ±640 yrs B.P. (sites 3 and 4) from deltaic sand in foreset-bedded fluvial sand exposed near the river level (cross section A). Glacier Peak volcanic fragments in the radiocarbon-dated nonglacial sands indicate that Glacier Peak detritus contributed to the Stillaguamish basin during part of the Olympia nonglacial interval. Unit Qo$_g$ consists mostly of fluvial deposits, forms a dissected pre-Vashon stratum in the subsurface, and may be gently warped and uplifted near the main strand of the DDMFZ (cross section A).

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. Several lenticular satellite dikes and sills occur north of Mount Higgins. Bechtel (1979) reports a K-Ar hornblende age of 53.0 ±8 Ma (site 9). Other age determinations vary from late Eocene to early Oligocene and include 38.5 ±7.0 Ma (K-Ar hornblende, site 10), 36.7 ±4.0 Ma (K-Ar hornblende, site 11), 30.2 ±3.5 Ma (zircon fission-track, site 11) (Tabor and others, 2002). The pluton may be an intrusive source for late Eocene volcanic rocks and hypabyssal intrusive bodies. The stock intrudes the Chuckanut Formation, causing contact metamorphism and hydrothermal alteration of the nearby country rock (site 19) (this study; Cruver, 1981; Jones, 1959; Reller, 1986).

Eian — **Intrusive andesite (Eocene)**—Porphyritic andesite dikes and sills; locally chemically dacitic to rarely rhyolitic; structureless with rare intrusive breccia and trachytic flow textures; dark green to greenish gray or bluish gray and weathered to shades of grayish to reddish brown; phenocrysts include euhedral to subhedral plagioclase (albite to andesine) (30-60%, 0.04 to 0.2 in.), usually with normal or oscillatory zoning, and euhedral to subhedral hornblende (20-30%; 0.08 to 0.24 in.) (regularly altered to chlorite); quartz (up to 3%) occurs as microphenocrysts; interstitial biotite occurs locally; other matrix constituents include plagioclase microlites, chlorite, and opaque minerals; common alteration minerals include disseminated chlorite, quartz, zeolites, sulfides, calcite, and stilpnomelane and sericite (after plagioclase); augite occurs to the east of the study area (Dragovich and others, 2002b). Cordierite in sericitized andesitic tuffs (unit Eva) near unit Eian dikes (site 20) suggests contact metamorphism and hydrothermal alteration. This unit is not directly dated but is probably late Eocene and may represent feeder bodies for unit Ev (this study; Jones, 1959). Geochemically and petrologically this hypabyssal unit is similar to unit ΦEiq.

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 trachytic; flows commonly amygdaloidal; alteration minerals include disseminated chlorite, calcite, limonite, quartz, prehnite, sulfides, and epidote. The units Eian and ΦEiq may be feeders 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). Locally divided into:

Evr — **Rhyolite**—High-silica rhyolite (site 22; up to 85% SiO_2) occurring as thick flows with interbedded vitric tuff, lapilli ash-flow(?) vitric tuff, and minor pumiceous sandstone; rhyolite is bluish to greenish gray and weathered to shades of yellow, brown, red, or white; porphyritic rhyolite contains scattered quartz ±plagioclase phenocrysts with local sanidine phenocrysts in a glassy or cryptocrystalline matrix; quartz (microlitic to 0.12 in.) is smokey and varies from euhedral to anhedral with some resorption features; plagioclase is euhedral to subhedral; glass is regularly spherulitic and varies from clear to highly altered; lapilli tuff clasts consist mostly of pumice; secondary minerals include chlorite, epidote, calcite, sericite, and vesicle-filling quartz; trachytoid textures are common; bedding is obscure except where stretched vesicles, flow banding, or flattened pumice fiamme in welded lapilli tuff define a primary foliation (this study; Jones, 1959; Reller, 1986; Tabor and others, 2002). Tabor and others (2002) obtained a zircon fission-track age of 35.2 ±3.5 Ma (site 13). Lovseth (1975) obtained a zircon fission-track age of 41.5 ±3.4 Ma (late Eocene) west of the study area.

Eva — **Andesite**—Andesite with some basaltic andesite, minor interbedded basalt (50.6% SiO_2; site 24) 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. Contact metamorphic cordierite is observed in tuff (site 20) near units Eian and ΦEiq (this study; Jones, 1959; Reller, 1986; Tabor and others, 2002). Tabor and others (2002) obtained a zircon fission-track age for the unit of 45.7 ±4.6 Ma west of the study area.

SEDIMENTARY ROCKS OF THE CHUCKANUT FORMATION

Ec$_h$ — **Mount Higgins unit (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; bentonite beds (primary or reworked volcanic airfall deposits) (sites 18 and 21) are bluish to light gray to white and weathered reddish yellow. Bentonite is rhyolitic (75% SiO_2; site 21) and contains scattered ash-sized fragments of pumice, irregular-shaped (angular and thin) glass shards, a few angular clear fragments of euhedral, broken and embayed volcanic quartz, and minor rounded fragments of very fine-grained sandstone, all in a glass matrix containing secondary sericite or montmorillonite. Cruver (1981) reports some feldspar in bentonites with crystal fragments concentrated in the lower portion of graded beds (this study; Cruver, 1981; Evans and Ristow, 1994).

Ec$_c$ — **Coal Mountain unit (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

Jsh$_s$ — **Shuksan Greenschist (Jurassic)**—Mostly well-recrystallized and strongly S1-foliated metabasaltic greenschist or blueschist; greenschist is shades of greenish gray and weathered to light olive gray; blueschist is bluish gray to bluish green; locally includes quartzite (metachert) and graphitic phyllite interlayers; commonly layered on a centimeter scale and contains conspicuous epidote and (or) quartz segregations; S1 foliation and layering are commonly folded on an outcrop scale. Relict igneous minerals locally include saussuritized and albitized plagioclase laths, actinolized hornblende, and rare clinopyroxene; metamorphic minerals include albite, actinolite, epidote, and chlorite with minor lawsonite, Mg-pumpellyite, muscovite, spessartine, and calcite. This unit consists mostly of mid-oceanic-ridge metabasalt. In rocks of the appropriate iron composition and oxidation state, Na-amphibole (for example, crossite) replaces actinolite as the primary metamorphic amphibole to form blueschist instead of greenschist. The protolith age of the suite is most likely Jurassic. K-Ar and Rb-Sr mineral and rock ages, representing the age of metamorphism, are dominantly in the range of 120 to 130 Ma (Armstrong and Misch, 1987; Bechtel, 1979; Brown and others, 1987; Tabor and others, 2002).

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 often 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). Mélange formation is probably mid-Cretaceous or younger and may be partially Tertiary (Tabor, 1994; Tabor and others, 2002). 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.

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 common augite and saussuritized plagioclase and rare hornblende; metamorphic minerals include albite, chlorite, acicular actinolite, Fe- and Mg-pumpellyite, prehnite, stilpnomelane, aragonite, and calcite (this study; Dragovich and others, 2002a,b, 2003; 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 west of the study area (Bechtel, 1979) 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 rare nonserpentinized or partially serpentinized dunite, peridotite, and pyroxenite and minor metasomatic silica-carbonate rock (unit Ju$_{hl}$), rodingite, or talc-tremolite rock; rare amphibolite; 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 (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 (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.

ROCKS OF THE EASTERN MÉLANGE BELT OF TABOR (1994)

JŦmt$_e$ — **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).

JŦmv$_e$ — **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. At site 25, structureless basaltic greenstone (49.5% SiO_2) contains interlocking plagioclase and augite phenocrysts with disseminated chlorite (this study; Dethier and others, 1980; Tabor and others, 2002).

JŦms$_e$ — **Metasedimentary rocks (Jurassic–Triassic)**—Metamorphosed argillite, sandstone, wacke, siltstone with subordinate chert pebble conglomerate, chert, marl, 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 (this study; Dethier and others, 1980; Dragovich and others, 2003; Tabor, 1994; Tabor and others, 2002).

JŦmc$_e$ — **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 provide Triassic and Jurassic ages (sites 1 and 2) (this study; Tabor and others, 2002).

JŦu$_e$ — **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 (this study; Tabor and others, 2002).

ROCKS OF THE WESTERN MÉLANGE BELT OF TABOR (1994)

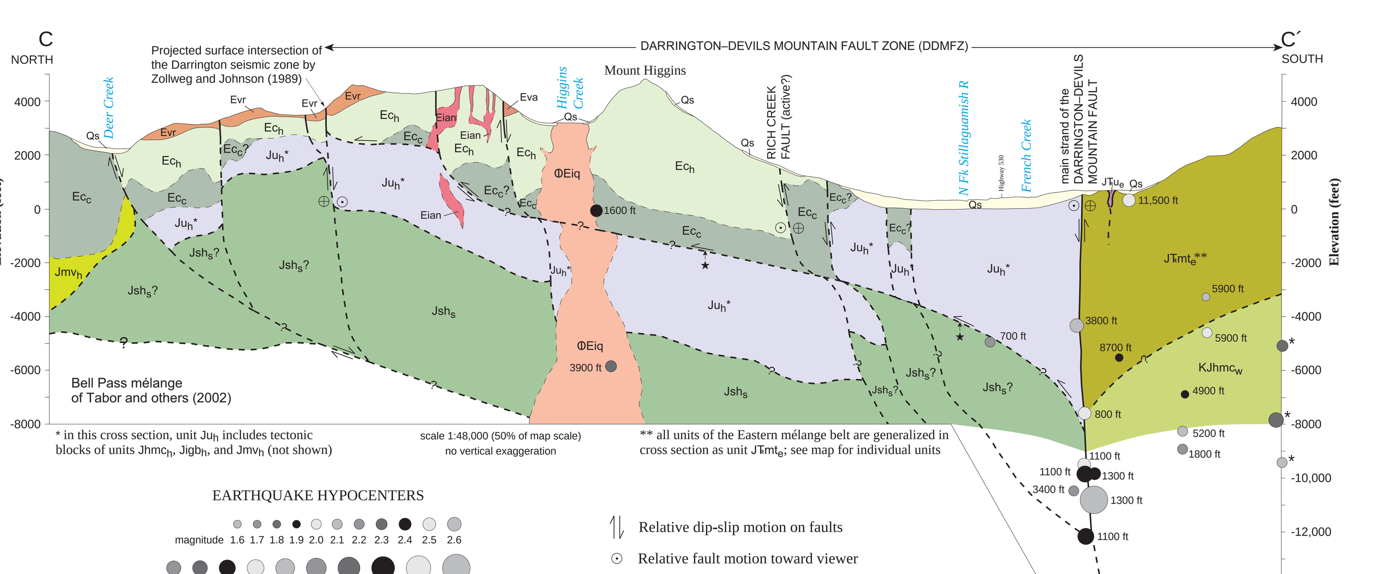
KJhmc$_w$ — **Heterogeneous metamorphic rocks, chert-bearing (Cretaceous–Jurassic)**—Semischistose metasandstone, slate, and phyllite; also contains greenstone derived from mafic volcanic breccia, tuff, and flows locally with well-developed pillows; locally abundant metachert and rare limestone; commonly 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; 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. Limestone blocks (olistostromes?) south of the study area are Permian, and a few chert blocks are Early Jurassic (Tabor and others, 2002).

ACKNOWLEDGMENTS

This report was produced in cooperation with the U.S. Geological Survey National Cooperative Geologic Mapping Program Agreement Number 02HQAG0047. We thank Franklin "Nick" Foit (Wash. State Univ.) for pumice and dacite microprobe analyses; Diane Johnson and Charles Knaack (Wash. State Univ.) for geochemical sample analysis; Jeff Jones (Snohomish County) for providing geotechnical boring logs; Jim Zollweg (Northwest Geosensing) for providing unpublished earthquake hypocenter data and geologic insight; Rowland Tabor (U.S. Geological Survey emeritus) for enlightening discussions; and Green Crow, Inc. for access to their timberlands and test pit logs. Thanks also to Divn.of Geology and Earth Resources staff members Josh Logan and Tim Walsh for map reviews, Connie Manson and Lee Walkling for assistance with references, and Diane Frederickson, Tara Salzer, and Jan Allen for clerical support.

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; dashed where inferred; dotted where concealed; queried where uncertain
- Oblique-slip fault—Bar and ball on downthrown side; half arrows show apparent relative lateral motion; dashed where inferred; dotted where concealed
- Thrust fault—Sawteeth on upper plate; dotted where concealed
- Anticline—Large arrowhead shows direction of plunge; dashed where inferred; dotted where concealed
- 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
- Overturned bedding—Showing strike and dip
- Inclined bedding—Showing strike and dip; top direction of beds known from local features
- Inclined bedding in unconsolidated sedimentary deposits or unconsolidated fragmental deposits of volcanic origin— Showing strike and dip; F near symbol indicates foreset bedding
- Inclined foliation in metamorphic rock—Showing strike and dip
- Inclined foliation parallel to bedding in metamorphic rock—Showing strike and dip
- 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
- Inclined slickensided surface—Showing strike and dip
- Vertical slickensided surface—Showing strike
- 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
- Glacial stria—Showing bearing
- 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) and this study. See Zollweg and Johnson (1989) for full extent of the Darrington seismic zone
- Other locations referred to in text
- W55 — Water well or geotechnical borehole—W indicates water well; B indicates geotechnical borehole; number is assigned by authors



* in this cross section, unit Ju$_h$ includes tectonic blocks of units Jhmc$_h$, Jigb$_h$, and Jmv$_h$ (not shown)

scale 1:48,000 (50% of map scale)
no vertical exaggeration

** all units of the Eastern mélange belt are generalized in cross section as unit JŦmt$_e$; see map for individual units

EARTHQUAKE HYPOCENTERS

magnitude 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0 3.1 3.2 3.3 3.4 3.5 3.6

- Relative dip-slip motion on faults
- Relative fault motion toward viewer
- Relative fault motion away from viewer

Earthquakes occurring between 1971 and 1988 are evidence for a zone of crustal seismicity associated with the Darrington-Devils Mountain fault zone (DDMFZ). Zollweg and Johnson (1989) termed this feature the Darrington seismic zone (DSZ) and characterized it using a portable seismometer array. Focal depths in the DSZ range between 3 and 15 km and decrease to the north. (Only those hypocenters near the plane of the cross section are shown, labeled with distance from the cross section; unlabeled hypocenters are within about 1000 ft of the cross section.) Zollweg and Johnson show that the DSZ focal mechanism solutions and the overall hypocentral geometry show nearly pure roughly north-south thrust faulting. *P* (compression) axes trend N20–25°W (approximately the azimuth of this cross-section), in accord with a regional stress direction due to the relative motion of the Pacific and North American plates. We correlate much of the hypocentral data with the main strand of the DDMFZ and infer that some of the shallow seismicity is associated with a décollement (★) between Tertiary sedimentary and volcanic rocks and pre-Tertiary metamorphic rocks. The cross-section also shows some Pacific Northwest Seismic Network (PNSN) hypocentral data. Comparison of locally imaged earthquake data with the PNSN data indicates that the broader PNSN locates earthquakes much too shallow. For example, hypocenters marked with asterisks are PNSN hypocentral data shown to be much deeper by Zollweg and Johnson (1989). The cross-section also shows unpublished hypocentral data (J. E. Zollweg, Northwest Geosensing, written commun., 2002). For more information on the DDMFZ in this area and nearby, see Dragovich and others (2003).

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