Geologic Map of the McMurray 7.5-minute Quadrangle, Skagit and Snohomish Counties, Washington, with a Discussion of the Evidence for Holocene Activity on the Darrington–Devils Mountain Fault Zone

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DESCRIPTION OF MAP UNITS

Information for the unit descriptions was compiled from the sources listed at the end of each description. The classification schemes we use are described in Dragovich and others (2002d). DDMFZ, Darrington–Devils Mountain fault zone. See plate for age and other site locations.

Quaternary Sedimentary Deposits

HOLOCENE NONGLACIAL DEPOSITS

Qa **Alluvium of Pilchuck Creek (Holocene)**—(Boulder) gravel and sand; gray; subrounded to rounded clasts; loose, well stratified, and well sorted; plane-bedded sands common. Gravels are distinctly greenstone rich. Sands contain abundant serpentinite (15–20%), greenstone (~10%), metamorphic and sedimentary lithic clasts, chert, and polycrystalline quartz, with some monocrystalline quartz, pyroxene, and plagioclase. The high serpentinite content of the alluvium is the result of erosion and fluvial reworking of the Helena–Haystack mélange serpentinite. Soft serpentinite (unit Ju_h) is easily mobilized by mass-wastage and deep glacial scour.

Qp **Peat (Holocene)**—Peat, muck, and organic silt and clay, locally with thin beds of Mount Mazama tephra (~6,900 yr B.P.). Peat occurs in Pilchuck Creek flood plains and (or) in marshy upland depressions. Many of these depressions delineate faults, including the DDMFZ. Dendrochronology of the many snags (dead trees) found in the marshes may reveal systematic death ages related to active faulting in the area. (this study; Dethier and Whetten, 1980)

Qoa **Older alluvium of Pilchuck Creek (Holocene to latest Pleistocene)**—Cobble gravel, gravel, and sand and minor silt; gray; loose; subangular to rounded; well stratified and well sorted. Gravel contains significant greenstone, serpentinite, and chert clasts. Sands contain abundant serpentinite (5–20%) and greenstone (~10%), as well as chert and polycrystalline quartz, and have an overall lithic-rich composition similar to unit Qa. Unit Qoa is separated from the Pilchuck Creek modern channel by up to four inset terraces (~5–120 ft high). We obtained a ^{14}C age of 1,440 ±50 yr B.P. on sticks from near the top of a 4- to 6-ft-high scarp adjacent to Pilchuck Creek (age site 1 on plate). This is the lowest of three older alluvial terraces and may date meter-scale uplift of the creek in the late Holocene as a result of active DDMFZ faulting. Dragovich and others (2004) also obtained ^{14}C ages of 5,890 ±60 and 5,600 ±120 yr B.P. from twigs in the peat near the top of a 20-ft-high river terrace along Pilchuck Creek directly east of the study area. This older alluvium may have been stranded during Holocene tectonic uplift within the DDMFZ (Table 1). Dethier and Whetten (1980) map most of our unit Qoa as recessional outwash. Indeed, age relations are ambiguous for some higher-elevation terraces and thus more work remains. However, the uppermost unit Qoa terraces along the mid-reaches of Pilchuck Creek (site 1 on plate) are greenstone rich and thus likely older alluvium.

Qls **Landslide deposits (Holocene to latest Pleistocene)**—Diamicton with lesser (boulder) gravel; contains minor sand or gravel beds where locally modified by stream processes; loose or soft; typically poorly sorted and nonstratified. Clasts are angular to subangular and locally derived, but may contain some rounded clasts where sourced by Quaternary deposits. Landslide types are slump-earthflows, debris slumps or flows, and rock avalanches (talus). Also includes a few alluvial fans and thick colluvial deposits. Some landslides may be seismically induced and (or) initiated during late Pleistocene deglaciation. (this study; Dethier and Whetten, 1980)

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Deposits of the Fraser Glaciation

EVERSON INTERSTADE RECESSIONAL DEPOSITS

Lateral and vertical facies changes between fluvial, deltaic, lacustrine, and marine deposits are regionally common in Everson Interstade sediments. As a result, contacts are commonly gradational and interfingering. Polymictic recessional sands are of mixed local and northern (Canadian) metamorphic-granitic provenance. Recessional sands in the western part of the study area contain more Canadian detritus (for example, hornblende and granite) than recessional sands in the eastern part of the area where locally derived clast types, such as greenstone, greenschist, phyllite, blue amphibole, serpentinite (1–4%), and blueschist, are more abundant. Everson Interstade deglaciation commenced ~13,500 yr B.P., and the map area was probably fully deglaciated by ~11,500 yr B.P. (this study; Dethier and others, 1995; Dragovich and others, 1998, 1999, 2000a,b, 2002a,b,c, 2003a,b; 2004; 2005)

$Qgdm_e$ **Glaciomarine drift (Pleistocene)**—Silt, clay, and dropstone-bearing diamicton, locally with lenses of sand or gravel; soft or loose; typically massive or crudely stratified on a scale of several meters. Dethier and others (1995) reported ^{14}C shell ages of 13,515 ±140 and 13,370 ±370 yr B.P. from fossiliferous sand and gravel along Big Lake north of the study area. The site was probably a glaciomarine beach at about 13,400 yr B.P., prior to being overlain by lake silt containing fresh water gastropods. In the study area, extensive deposits of silt also flank the south and southeast shores of Big Lake. The silt contains marine mollusks and gastropods ^{14}C dated at 13,040 ±65 yrs B.P. (S. Robinson, pers. commun., 1980, to Dethier and Whetten, 1980). (this study; Dragovich and others, 1999, 2002c; Dethier and Whetten, 1980)

$Qgog_e$ **Outwash gravel (Pleistocene)**—Gravelly sand and sandy (cobble) gravel, locally with lenses or beds of sand and silt and rare beds of poorly sorted gravels and diamicton; loose or soft; subangular to subrounded clasts; generally forms subhorizontal beds a few feet thick that are crudely defined by variations in grain size; pebble imbrication, scour features, and cross-bedding are locally common. Sand composition indicates a mixture of eastern and northern sources with locally derived greenstone; greenschist and serpentinite locally significant. Well-sorted sand and gravel beds deposited as fluvial outwash. Some poorly exposed soft diamicton beds (melt-out or flow till; site 2 on plate) in gravels are suggestive of near-ice deposition as moraines, eskers, kames, or debris fans. (See units $Qgod_e$ and $Qgik_e$.) (this study; Dethier and Whetten, 1980; Dragovich and others, 2003a,b, 2004)

$Qgik_e$ **Ice-contact kame deposits (Pleistocene)**—Sandy gravel, sand, and pebbly sand; loose; thinly to thickly bedded; well stratified; cross-bedded with cut-and-fill structures and distinctive ice-contact features such as collapse structures displaying slumped bedding. Lateral ice buttressing is required to produce these elevated fluvial deposits with ice contact structures. A kame deposit is well exposed in a gravel mine southeast of Lake McMurray (site 3 on plate). (this study; Dethier and Whetten, 1980)

$Qgod_e$ **Deltaic outwash (Pleistocene)**—Sandy cobble gravel, gravel, pebbly sand, and sand; loose; moderately to well sorted; thin to very thickly bedded and well stratified; contains high-amplitude planar foreset beds graded to temporary ice-dammed lake levels. Deltaic deposits distinctly fine laterally to bottomset beds of glaciolacustrine sand (unit $Qgos_e$) and silt (unit Qgl_e) in the south-central part of the study area. This deltaic complex was fed by fluvial valley train deposits (unit $Qgog_e$) mapped above Pilchuck Creek northeast of the complex. (this study; Dragovich and others, 2002c, 2004)

$Qgos_e$ **Outwash sand (Pleistocene)**—Sand and pebbly sand, locally with interbeds of silty fine sand or silt; loose or soft; varies from nonbedded to weakly stratified to locally plane bedded, laminated, or rarely cross-bedded. Although some sand bodies are glaciofluvial, facies relations, including fining trends, suggest deposition in shallow-water glaciolacustrine settings. Both surface and subsurface mapping show that recessional sand, gravel, and lake deposits are commonly interfingering. Some sand bodies are overlain by gravel and underlain by finer-grained lake deposits. The unit correlates with the Stillaguamish Sand Member of the Vashon Drift of Minard (1985). (this study; Dragovich and others, 2002a,b, 2003a,b, 2004; Dethier and Whetten, 1980)

Qgl_e **Glaciolacustrine deposits (Pleistocene)**—Clay, silt, sandy silt, silty sand, sand, and diamict with scattered dropstones; light gray to blue-gray, weathered to shades of brown; loose, soft, or stiff; nonbedded, laminated, or very thinly bedded, with some varve-like rhythmites; locally contains flame and ball-and-pillow structures and sand dikes. Dropstone clast types commonly include granite and greenstone. Sediments were deposited in glacial lakes impounded by receding glacial ice, such as glacial Lake Stillaguamish of Minard (1985) and glacial Lake Pilchuck of Dragovich and others (2004). Locally forms distinct upward-coarsening sequences from glacial lake (units Qgl_e and $Qgos_e$) to terrestrial environments (units $Qgod_e$ and $Qgog_e$) due to progradation of fluvial-deltaic complexes into proglacial lakes. (this study; Dragovich and others, 2002a,b, 2003a,b, 2004)

VASHON STADE DEPOSITS

Ice-flow indicators, such as glacial fluting, show that the Puget ice lobe advanced over the map area from west-northwest to east-southeast. Advancing ice blocked ancient rivers, creating extensive temporary ice-dammed lakes (Dragovich and others, 2002a,b, 2003a,b, 2004). Vashon Stade continental ice advanced easterly up the North Fork Stillaguamish valley about 15,000 yr B.P. (Pessl and others, 1989; Porter and Swanson, 1998). The resultant advance glaciolacustrine deposits (unit Qgl_v) are widespread and complexly interlayered with advance fluvial and deltaic deposits (unit Qga_v) (Cross Section A). Sands show a mixture of northerly derived Canadian detritus, such as hornblende and granite, and local detritus, such as minor greenstone and serpentinite. Advance outwash has a more local provenance along the easternmost part of the study area. (See Dragovich and others [2000a,b, 2002c, 2004] for further provenance information.)

Qgt_v **Lodgment till (Pleistocene)**—Nonstratified, unsorted mixture of clay, silt, sand, and gravel (diamicton) with disseminated cobbles and boulders; grayish blue to very dark gray, weathered to a mottled yellowish brown; compact or dense. Clast types include both Canadian-provenance and locally derived clasts. Basal till is serpentinite rich where it overlies the Helena–Haystack mélange. Till is generally 10 to 20 ft thick, but ranges from a discontinuous veneer to a many tens of feet thick layer that mantles topography. Till unconformably overlies mostly bedrock or advance outwash. Subglacial excavation of the valley extending southeast of Lake McMurray is evidenced by the widespread exposure of 'dynamic till' in this valley (for example, site 4 on plate). Dynamic till is lodgment till containing conspicuous layers and lenses of sand and gravel. These sorted layers indicate meltwater flow along subglacial paths, such as tunnels. Subglacial erosion is also evidenced by the stratigraphy of this valley (Cross Section A). Most of the Vashon advance fluvial and lake deposits, which partly filled this valley during Vashon advance, appear to have been subglacially removed and overlain by lodgment till during ice occupation. (See 'Subglacial Erosion' of Booth and Hallet [1993].) Weak rocks associated with the McMurray fault zone may have concentrated subglacial erosion along this valley. (this study; Dragovich and others, 2002a,b,c, 2003a,b, 2004)

Qga_v **Advance outwash deposits (Pleistocene)**—Sand, pebbly sand, and sandy gravel with scattered beds of cobble gravel with local silt and clay interbeds; typically dense or compact; moderately to well sorted; dominantly moderately stratified and thinly to thickly bedded; displays cross-stratification, rip-up clasts, sand dikes, flame structures, and cut-and-fill structures, with deltaic foreset beds locally observed. Composite sections of units Qga_v and Qgl_v are up to 250 ft thick and locally crudely coarsen upwards. Advance outwash is primarily fluvial and is overlain by lodgment till along a sharp contact. Advance outwash conformably overlies or is complexly interlayered with unit Qgl_v (Cross Sections A and B).

Qgl_v **Advance glaciolacustrine deposits (Pleistocene)**—Clay and silt with local scattered dropstones; dropstone diamict commonly contains beds of laminated silt ± sand; commonly contains beds of medium to very thick bedded sandy silt, sand, and gravel; locally contains thick beds of massive, clast-rich diamicton that may be iceberg melt-out till; blue gray or gray, weathered to yellowish brown; stiff or dense; varies from massive to thinly bedded, laminated, or varved; contorted or folded bedding, sand dikes, and flame structures locally observed. This unit is locally underlain by unit Qc_o and is typically overlain by, and (or) interbedded with, unit Qga_v (Cross Sections A and B). Site 5 (on plate) is a well-exposed example of thinly to thickly bedded glaciolacustrine silt, sand, and diamicton. Sands at this site are typical of the unit and contain polycrystalline and monocrystalline quartz, plagioclase, hornblende, and metamorphic, volcanic, and granitic lithic clasts, with lesser potassium feldspar, epidote, serpentinite, and greenstone. Puget Sound Power and Light Company (Puget Power) (1974) obtained a ^{14}C age of 14,725 ±470 yr B.P. from charcoal and wood fragments in glaciolacustrine sand (age 1, Cross Section B). They interpreted the enveloping strata as pre-Vashon, and thus the sample as anomalously young and likely contaminated. However, an advance lake deposit age is strongly implied by the trench-log stratigraphy, our nearby mapping, and the Vashon ice advance chronology forwarded by Porter and Swanson (1998). Unit correlates with the Pilchuck Clay Member of the Vashon Drift of Newcomb (1947). (this study; Dragovich and others, 2002a,b,c, 2003a,b, 2004)

Deposits of the Olympia Nonglacial Interval

Qc_o **Olympia beds (Pleistocene)**—Boulder gravel, cobbly gravel, gravel, sand, and silt, with minor clay, peat, and diamicton; very compact, well sorted, and very thinly to thickly bedded; organic material common regionally (for example, peat, logs, and charcoal). Olympia beds in the study area are divided into (1) ancient Pilchuck Creek alluvium exposed along the modern Pilchuck drainage (for example, site 6 area on plate), or (2) buried remnants of ancient alluvium, swamp deposits, and paleosols mapped only in the subsurface or in trenches in the western part of the study area (Cross Sections A and B). Ancient Pilchuck Creek alluvium is dominantly iron oxide-stained (boulder) gravel containing abundant Helena–Haystack mélange greenstone and serpentinite. Ancient and modern Pilchuck Creek alluvium have similar lithic-rich, locally derived sand compositions. Sands dominantly contain serpentinite (5–20%), greenstone (5–20%), chert, polycrystalline quartz, and foliate metamorphic and sedimentary lithic fragments. The Olympia beds form a dissected pre-Vashon stratum in the subsurface that we infer to be locally gently folded and tectonically uplifted south of the main strand of the DDMFZ (Cross Sections A and B). The Olympia nonglacial interval occurred from ~16,500 to 60,000 yr B.P. Puget Power (1974) obtained Olympia bed ages of 35,030 +3340 –2350 yr B.P. from paleosol and >37,000 yr B.P. from decayed wood in sand and silt alluvium directly south of the main strand of the DDMFZ (age sites 2 and 3 and Cross Section B on plate). (See 'Darrington–Devils Mountain Fault Zone'.) Dragovich and others (2004) correlated ancient Pilchuck alluvium directly east of the study with the Olympia beds. Farther to the east, Dragovich and others (2003a) obtained ^{14}C ages of 38,560 ±640 and 35,040 ±450 yr B.P. from detrital wood in ancient Stillaguamish River alluvium directly north of the DDMFZ main strand. Minard (1985) also reports ^{14}C ages of 23,700 ±210 yr B.P. (peat) and 24,700 ±160 yr B.P. (flattened sticks) from Olympia beds exposed in the lowermost portion of erosional terraces at elevations slightly above modern river levels directly south of the quadrangle. These Olympia sediments represent ancient Pilchuck and Stillaguamish River flood plain sediments laid down in these major river valleys prior the last glaciation. (this study; Puget Power (1974); Dragovich and Grisamer, 1998; Dragovich and others, 2002a,b,c, 2004; 2005)

Deposits of the Possession Glaciation

ot **Older till (Pleistocene)**—Diamicton. A well exposed example of a very compact older till under Vashon advance outwash occurs at site 7 (on plate). We did not assign a formal geologic symbol to this unit in order to emphasize the tentative nature of this correlation with Possession Glaciation.

oo **Older outwash (Pleistocene) (Cross Section B only)**—Silty sand, locally with scattered gravel and occasional gravel interbeds, occurring below Olympia beds and above older till in Cross Section B. We did not assign a formal geologic symbol to this unit in order to emphasize the tentative nature of this correlation with Possession Glaciation.

Tertiary Volcanic, Intrusive, and Sedimentary Rocks

VOLCANIC AND HYPABYSSAL INTRUSIVE ROCKS

We correlate the volcanic rocks in the study area with the Barlow Pass Volcanics of Vance (1957) and Tabor and others (2002). Regionally, Barlow Pass Volcanics consist of rhyolite, andesite, dacite, and basalt with local nonmarine sedimentary interbeds. Volcanic rocks in the map area are a bimodal suite of rhyolite–andesite preserved in fault-bounded blocks of the DDMFZ. Volcanic rocks overlie the early Eocene Coal Mountain unit of the Chuckanut Formation (unit Ec_c). The Coal Mountain unit is volcanic-lithic-poor. This differs from younger Chuckanut units east of the study area that commonly contain significant amounts of volcanic lithic clasts, bentonites, and other indicators of contemporaneous volcanism. Hypabyssal intrusive rocks, including dikes, are intrusive into the Chuckanut. It seems likely that intrusive emplacement of these volcanic rock feeder bodies was strongly controlled by pre-existing strands of the DDMFZ; later continued faulting along the DDMFZ locally imbricated these bodies, leading to intrusive and (or) faulted contacts with the Chuckanut. (Lovseth, 1975; Whetten and others, 1988; Evans and Ristow, 1994; Mustoe and others, 1996; Tabor and others, 2002; Dragovich and others, 2002b,c, 2003a,b, 2004)

Eib **Diabase (Eocene)**—Homogeneous, medium-grained, subophitic basaltic diabase dikes and sills; contains euhedral, randomly oriented blocky plagioclase, subhedral augite, bladed opaque minerals, and interstitial quartz in an altered matrix of brown chlorite and rare carbonate; dark greenish gray. Diabase dikes intrude the Chuckanut Formation. Bechtel, Inc., (1979) obtained whole-rock K-Ar ages of 41.2 ±1.8, 46.4 ±2.2, and 49.9 ±2.2 Ma directly east of the study area. The petrographic similarity of the diabase dikes with basalt flows near Lake Cavanaugh east of the study area suggests that the dikes may have been feeders for the basalt flows. (this study; Dethier and Whetten, 1980; Dethier and others, 1980; Dragovich and others, 2002a, 2004)

Evr **Rhyolite (Eocene)**—Rhyolite, andesite, and minor volcanolithic sandstone, conglomerate, and breccia; rhyolites typically composed of quartz ± plagioclase ± sanidine phenocrysts in a glassy matrix; (smokey) quartz phenocrysts vary from euhedral to anhedral and are locally resorbed; plagioclase phenocrysts are euhedral to subhedral and locally microlitic; glass is spherulitic and highly altered; secondary minerals are variable but mostly include carbonate minerals, chlorite, sericite, propylite, potassium feldspar, zeolites, and chalcedony; rhyolite is bluish to greenish gray, weathered to shades of yellow, red, or white, particularly in areas of strong alteration; locally contains porphyritic and trachytic textures; stretched vesicles, flow banding, flattened and (or) stretched pumice fiamme define a strong primary foliation, particularly in welded tuffs. Mineral-filled vesicles are common and forceful conduit-neck emplacement is suggested by strong local vesicle flattening. Clasts in pyroclastic deposits are mostly rhyolitic pumice lapilli, rarely with xenoliths and xenocrysts of Chuckanut affinity. Rhyolites are mostly pyroclastic ash flow (vitric, crystal-vitric, or crystal-lithic tuff ±lapilli) tuffs, but also include flows, domes, and dikes. Flow, intrusive, or hydrofractured breccias are locally evident.

New logging roadcuts have exposed medium to thickly bedded volcanic sandstones, siltstones, and conglomerates (lahars) interbedded with rhyolitic tuffs, breccias, and very thin coal beds (sites 8–9 on plate). These volcaniclastic rocks are compositionally and texturally variable, but most contain subangular to angular grains of volcanic quartz, plagioclase, and potassium feldspar, with rhyolite and andesite volcanic clasts and minor sedimentary lithic clasts. We speculate that the rhyolitic pyroclastic flow and dome rocks in the fault-bounded blocks encompassing sites 8 and 9 (on plate) may have been a caldera formed in a releasing bend of the DDMFZ.

In the Walker Valley area (site 10 on plate), andesite dikes, sills, and flows are conspicuous. Compared to the rhyolite, andesite in this area is relatively texturally homogenous and typically contains intergranular pyroxene microphenocrysts in a glassy matrix containing abundant plagioclase microlites ± interstitial quartz. Calcite- or opal-filled vesicles are typical. Geochemical, field, and mineralogic relations demonstrated to Mustoe and others (1996) that the shallow intrusion of andesite into an active fault zone was responsible for the extensive shallow Tertiary alteration and mineralization, some of which is gem quality, evident in the Walker Valley area. See Dragovich and others (2003a,b, 2002c) and Mustoe and others (1996) for andesite geochemistry and petrology.

Whetten and others (1988) obtained zircon fission-track ages of 38.1 ±1.8 and 43.5 ±2.2 Ma from rhyolite directly east of the study area. Also, Lovseth (1975) dated zircon from rhyolite from the Hendricks quarry near Big Lake, directly north of the study area, at 41.5 ± 3.4 Ma by the same method. In the study area, Whetten and others (1988) reported a zircon fission-track ages from rhyolite of 39.9 ±2.4 Ma (age site 2 on plate) and 44.1 ±2.4 Ma (age site 3 on plate). Several other zircon fission track ages around the study area indicate that rhyolitic volcanism occurred in the middle to latest Eocene (~35–45 Ma). Andesite dikes typically intrude rhyolite or intrude faults that cut rhyolite (Lovseth, 1975; Dragovich and others, 2002b,c, 2003a,b). Age and field relations indicate that andesites are Late Eocene or earliest Oligocene and contemporaneous with the Bulson Creek volcanic lithic-rich sandstone facies (unit ΦEc_{bs}). (this study; Lovseth, 1975; Dethier and Whetten, 1980; Tabor and others, 2002; Dragovich and others, 2002a,b, 2003a,b, 2004)

SEDIMENTARY ROCKS

Rocks of Bulson Creek

The rocks of Bulson Creek of Lovseth (1975) occur south of the DDMFZ main strand. Marcus (1981) concluded that the conglomerate facies was deposited in alluvial fan to braided river environments. Clast size variations, paleocurrents, and facies trends in rocks of the Bulson Creek indicate a west- to southwest-directed fluvial system subparallel to the DDMFZ. It seems likely that Tertiary vertical or oblique offset along the DDMFZ produced the relief necessary to create this fan-fluvial environment. The sandstone facies was deposited in a nearshore shallow marine setting (beach, deltaic, littoral, neritic) as indicated by stratigraphy and megafossil content. The presence of shallow marine fossils and terrestrial plant fossils requires a transition from a fluvial to an estuarine or nearshore marine environment in the upper portion of the sandstone facies. Marcus (1981) contended that the conglomerate facies was folded along an east–west axis prior to the deposition of the younger sandstone facies, and therefore the two facies are separated by an angular unconformity. Conversely, this study and Whetten and others (1988) suggest that the contact between the facies is largely faulted or locally interfingering. It seems likely to us that the tighter folding of the conglomerate facies is the result of its proximity to the main strand of the DDMFZ. Although further study is warranted, we also differ from Marcus (1981) in that we contend that the marine facies is generally older than the conglomeratic facies and contemporaneous with middle to late Eocene or perhaps earliest Oligocene (andesitic) volcanism in the area.

ΦEc_{bcg} **Rocks of Bulson Creek, conglomerate facies (Oligocene to Eocene)**—Conglomerate with local interbeds and lenses of pebbly sandstone, feldspathic litharenitic sandstone, lesser coal and siltstone, and rare paleosols and diamictite; rare Eocene(?) basalt dikes (sites 11–13 on plate). Conglomerate is greenish gray, weathered to yellowish brown; typically poorly indurated and crumbly; clasts are subangular to subrounded and subspherical to elongate; moderately to well sorted; typically displays very thick multistory bodies of massive imbricated conglomerate with thin to thick interbeds of sandstone; locally crudely normally graded and locally contains log casts; maximum clast diameter is 28 cm (11 in.), but commonly ranges from 1 to 9 in. (2–22 cm); clasts dominantly chert with lesser greenstone, sedimentary and metamorphic lithic clasts (phyllite and gneiss), and locally sparse serpentinite and granite; volcanic-clast poor (typically 0–5%; rarely up to 20%) with andesite and rhyolite clast types. Sandstones are massive to graded with channeling and cross-bedding locally observed; carbonized leaves and branches occur in the fine sand and silt interbeds. Sandstones are composed of chert, sedimentary and volcanic lithic fragments, polycrystalline and monocrystalline quartz, and plagioclase, with minor pyroxene, amphibole, garnet, and rare serpentinite and olivine. Some sandstone beds contain significant potassium feldspar (up to 15%), suggesting either a more distant source for some of the sandstone detritus or recycled Chuckanut (unit Ec_{c}) detritus. The conglomerate facies is compositionally more mature than the sandstone facies and contains more chert, quartz, and feldspar and fewer lithic clasts. Paleosols and basal beds of very coarse conglomerate unconformably overlie Trafton sequence basement, such as unit ₽l (for example, site 14 on plate) and metachert. Elsewhere, the rocks of Bulson Creek are faulted over the Trafton along low-angle faults. (this study; Jenkins, 1924; Danner, 1957; Lovseth, 1975; Marcus, 1981; Frizzell, 1979; Dethier and Whetten, 1980; Whetten and others, 1988; Dragovich and others, 2002c, 2004)

ΦEc_{bs} **Rocks of Bulson Creek, sandstone facies (Oligocene to Eocene)**—Sandstone with interbeds of siltstone, pebbly sandstone, coal, shale, and rare lenses of conglomerate; weathered to a yellow brown; moderately to well sorted with angular to subrounded clasts. Sandstones are massive, but locally display well-developed cross-beds and rare channel fill structures. Siltstone and shale are laminated, locally with flaser beds and current ripple marks. Siltstones and sandstones are feldspatholithic or lithofeldspathic arenites or wackes that are volcanic rich and mostly texturally immature. Volcanic lithic sandstones at sites 15–17 (on plate) contain volcanic fragments and crystals totaling 90 to 98 percent of the rock, with few exotic clasts. The volcanic clasts appear to be predominantly augite-bearing andesite with some rhyolite. Crystals include angular to subangular plagioclase, quartz, and minor augite. Site 18 (on plate) is an iron-oxide-stained tuff or tuffaceous siltstone consisting of angular microlitic volcanic fragments, plagioclase, quartz, and highly weathered grains of volcanic glass. Marcus (1981) also reported tuffaceous siltstones from the sandstone facies. Directly west of the study area, volcanic sandstones are locally composed of over 90 percent volcanic detritus, including substantial augite-bearing volcanic fragments of probable andesitic composition (Dragovich and others, 2002c). This is similar to Marcus (1981) who reported appreciable volcanic detritus in sandstones (20–66% volcanic clasts). These volcaniclastic sands were likely originally deposited as sandy lahars or hyperconcentrated flood deposits in a fluvial-deltaic setting. Subsequent fluvial or nearshore reworking of the volcaniclastic deposits resulted in the range of volcanic fragment abundances we now observe. Marcus (1981) and Lovseth (1975) reported scattered rhyolite clasts in the conglomerate facies; however, the conglomerate facies does not have the distinct volcanic provenance of the sandstone facies. It appears that the conglomerate facies: (1) is generally younger than the sandstone facies and contains minimal andesitic clasts due to its age, or (2) is partly contemporaneous with volcanism, but lacks a strong volcanic provenance as a result of the low preservability of laharic terraces in fluvial environments. The observation that much of the marine facies has been uplifted along faults within the broad DDMFZ suggests an age difference between the facies. For the most part, this tectonic exhumation placed older shallow marine rocks against or over the younger fluvial rocks with some contacts being low-angle faults. Although more work remains on the nature of the contact between the facies, the structural block west of the McMurray fault zone and south of the prominent reverse fault near sites 11–13 (on plate) contains distinctly volcanolithic sandstone facies rocks. This block is likely older than most of the Bulson rocks north and east of this structural wedge. This structural arrangement also suggests that DDMFZ transpression has tectonically juxtaposed different parts of an originally much wider Bulson basin. Danner (1957), Lovseth (1975), and Marcus (1981) report middle Eocene to earliest Oligocene shallow-water marine fossils of late Narizian or early Refugian age (~37–45 Ma) from the sandstone facies. This is similar to the Eocene age (~35–45 Ma) of rhyolites and associated (but probably somewhat younger) andesites. Therefore, the deposition of the marine facies and volcanism were roughly contemporaneous as indicated by the similarity of the radiometric ages and sandstone facies fossil ages. (this study; Danner, 1957; Lovseth, 1975; Dethier and Whetten, 1980)

Chuckanut Formation

The Chuckanut Formation was deposited in a fluvial sedimentary environment. Johnson (1982) divided the Chuckanut into the Bellingham Bay, Slide, and several younger members. Mustoe and Gannaway (1997) and Dragovich and others (1997) include the Bellingham Bay and Slide members in their informally named lower Chuckanut Formation. The lower Chuckanut was named the Coal Mountain unit east of the study area by Evans and Ristow (1994) and contains conspicuous potassium-feldspar (sparse potassium feldspar occurs in overlying members) derived from the Omineca Crystalline Complex basement in north-central Washington (Johnson, 1982). Chuckanut feldspathic arenite (arkose) in the study area contains 5 to 15 percent potassium feldspar (this study; Marcus, 1981; Lovseth, 1975; Frizzell, 1979). This content, combined with the provenance and stratigraphic style, indicates that the Chuckanut in and around the study area is the Coal Mountain unit. (this study; Dragovich and others 2002b,c, 2003a,b, 2004)

Ec_c **Coal Mountain unit (Eocene)**—Feldspathic sandstone, locally with pebbly sandstone, siltstone, mudstone, and coal; light gray, weathered to yellowish brown; micaceous; coarser grained beds (channel deposits) vary from massive to very thickly bedded sandstone and pebbly sandstone to thickly bedded to laminated sandstone and siltstone, locally with trough cross-bedding and ripple or plane laminations; fine-grained beds (overbank deposits) contain ripples, flutes, load casts, and plant fossils. Pebbles are mostly chert and polycrystalline quartz. The Chuckanut Formation is in fault contact with the rocks of Bulson Creek and in fault, intrusive, or depositional contact with Eocene volcanic rocks. Although further work is warranted, lithofeldspathic sandstones rich in angular quartz fragments that locally underlie unit Evr (site 19 on plate) are possible tuffaceous sandstones. This suggests that younger Chuckanut units may locally underlie or interfinger with the base of the Eocene volcanic rocks. The Chuckanut Formation unconformably overlies and may locally be thrust over the Helena–Haystack mélange basement as indicated by the geometry of overturned folds and inferred map patterns. DDMFZ deformation has resulted in overturned folding of the Chuckanut and protomylonitic to cataclastic texture along the main strand of the DDMFZ. Chuckanut fold geometry is complex and may locally contain some refolding as a result of shifting deformational regimes (transpression, transtension, and pure reverse faulting) within the DDMFZ. Eocene dikes and sills appear to have intruded fault strands of the DDMFZ, resulting in locally intense hydrothermal alteration of the nearby Chuckanut. Regional plant-fossil ages, as well as the ages of volcanic rocks that are intrusive into (for example, unit Eib) or overlie (unit Evr) the Coal Mountain unit, indicate an early Eocene age (49–55 Ma) for the lower Chuckanut Formation. Johnson (1982) obtained a zircon fission-track age of 49.9 ±1.2 Ma from a tuff bed near the top of the Bellingham Bay Member northwest of the study area. Also, the Coal Mountain unit near Mount Vernon contains a tuff bed with a zircon fission track age of 52.6 ±4.8 Ma (R. W. Tabor, pers. commun., 1993, to Evans and Ristow, 1994). This is similar to the zircon fission-track age of 52.7 ± 2.5 Ma obtained by Whetten and others (1988) from a tuff bed interbedded with sandstone on the eastern edge of the study area (age site 4 on plate). We were unable to locate this outcrop, but propose that the bed is one of the rare tuff beds found in the lower Chuckanut and thus not a Barlow Pass equivalent tuff. This correlation is supported by (1) the age of the other rare tuff beds in the lower Chuckanut, and (2) the restriction of Eocene volcanics lacking mature feldspathic arenite (unit Evr) to a younger age range (~35–45 Ma) in and around the study area. (this study; Jenkins, 1924; Hopkins, 1931; Lovseth, 1975; Frizzell, 1979; Dethier and Whetten, 1980; Marcus, 1981; Whetten and others, 1988; Dragovich and others, 2002b,c, 2003a,b, 2004)

Mesozoic to Paleozoic Low-Grade Metamorphic and Intrusive Rocks

HELENA–HAYSTACK MÉLANGE

The Helena–Haystack mélange of Tabor (1994) has a serpentinite matrix. Resistant blocks of greenstone erode out of mélange matrix as steep hillocks. Regional greenstone geochemistry indicates a mid-oceanic-ridge to oceanic-island-arc ophiolitic origin. Whetten and others (1980, 1988) obtained U-Pb zircon ages of 160 to 170 Ma (Jurassic) from greenstone near the map area. Blueschist facies metamorphism of the mélange likely accompanied subduction of these oceanic rocks during the Cretaceous. Complex mélange structural relations are the result of structural dismemberment during subduction, late-metamorphic thrusting and exhumation, and deformation within the broad DDMFZ. The mélange is faulted against the Chuckanut in the northeastern part of the study area, and probably is basement to the Chuckanut Formation in the northern part of the study area as suggested by geomagnetics, structural relations, and nearby mapping. The contact between the mélange basement and the Chuckanut is inferred to be a low-angle fault contact locally. Most intraformational contacts in the mélange are faulted. (Tabor, 1994; Whetten and others, 1988; Dragovich and others, 1999, 2000a, 2002b,c,d, 2003a,b, 2004)

Jmv_h **Greenstone (Jurassic)**—Metabasaltic greenstone with minor metagabbro, metadacite, metarhyolite, and minor slate, phyllite, and metasandstone (site 20 on plate); relict phenocrysts in greenstone include augite, sausuritized plagioclase, and rare hornblende; metamorphic minerals include albite, chlorite, acicular actinolite, pumpellyite, prehnite, stilpnomelane, aragonite, and calcite; grayish green metabasalt flows locally contain amygdules, breccia, and relict pillows. Greenstones are non- to weakly foliated. Metasedimentary rocks are subsumed into this unit and are characterized by strong first-generation phyllitic to slaty cleavage with local second- and third-generation folds, kinks, and crenulations. Rocks are fractured, veined, or mylonitized near faults. Rocks were locally hydrothermally altered under static post-metamorphic conditions, resulting in the growth of secondary potassium feldspar, white mica, and carbonate, particularly near faults and Eocene volcanic bodies. (this study; Dethier and Whetten, 1980; Dragovich and others, 2002c, 2004)

Ju_h **Ultramafite (Jurassic)**—Serpentinite with minor partially serpentinized dunite, peridotite, and pyroxenite; serpentinite is locally altered to talc-tremolite rock or silica-carbonate rock, particularly near faults; serpentinite is composed of serpentine minerals such as antigorite or chrysotile, locally with relict pyroxene and (or) olivine and accessory picotite, magnesite, magnetite, and chromite; serpentinite is greenish gray to greenish black and weathered to a dark yellowish orange. Ultramafite ranges from massive to locally intensely fractured or strongly foliated. (this study; Dragovich and others 2002c, 2003a,b, 2004; Dethier and Whetten, 1980)

TRAFTON SEQUENCE

The Trafton sequence of Danner (1966) is a tectonic mixture composed of tectonic blocks of mostly chert and greenstone in an argillite-phyllite mélange matrix. The mélange matrix is only rarely observed in the study area. This is due to poor exposure or maybe to less mélange-style internal disruption than observed elsewhere in the Trafton sequence. The Trafton sequence is likely correlative with the Eastern mélange belt (Tabor and others, 2002). Both belts underwent prehnite-pumpellyite facies metamorphism. However, the probable lack of metamorphic lawsonite suggests that the Trafton sequence and the Eastern mélange belt have not undergone the high-pressure blueschist facies metamorphism typical of the Northwest Cascades System north of the DDMFZ (for example, Helena–Haystack mélange). Even though the mélange belts may have been thrust over rocks of the Northwest Cascades System in the Cretaceous (Tabor, 1994), Tertiary DDMFZ displacement has modified any primary thrust-fault contacts. The Eastern mélange belt and Trafton sequence are submarine-fan to deep-oceanic deposits. Volcanic sandstone provenance and the occurrence of tuff and flows are suggestive of deposition near a volcanic edifice. This is consistent with the basalt geochemistry (Dragovich and others, 2004; Tabor, 1994), which indicates an intraplate seamount (hotspot) volcanic setting. (Dethier and Whetten, 1980; Tabor, 1994; Tabor and others, 2002; Dragovich and others, 2004)

JTRmc$_t$ **Metachert (Jurassic to Triassic)**—Metamorphosed chert and cherty argillite; locally includes minor argillite, siltstone, feldspatholithic sandstone or wacke, greenstone, tuff, and limestone; chert contains micro- and polycrystalline quartz (88–95%), with minor chlorite, disseminated organic material, and white mica, with veins of quartz common; chert is banded red, black, and gray and is very thinly bedded to riboned with thin laminae of argillite, less commonly occurring as thin laminae in meta-argillite. Metasedimentary rocks are nonfoliated to weakly foliated and locally complexly boudinaged and folded; protomylonitic, cataclastic, and brecciated near faults. The rocks of Bulson Creek unconformably overlie the Trafton sequence. Elsewhere the Trafton sequence is faulted over the rocks of Bulson Creek. This relation is particularly well-exposed along Pilchuck Creek (site 21 on plate) where a thick reverse-fault cataclasite zone separates the Trafton and Bulson. Fossil ages in the study area include Middle Jurassic radiolarians from metachert (age site 5 on plate; D. L. Jones, written commun., 1977, to Whetten and others, 1988), Early Triassic conodonts from a tectonic block or bed of limestone (age site 6 on plate; A. S. Harris, written commun., 1980, to Whetten and others, 1988), and Early and Middle Pennsylvanian conodonts from a tectonic block or bed of limestone (age site 7 on plate; A. S. Harris, written commun., 1980, to Whetten and others, 1988). These ages are consistent with fossil ages (Mississippian–Early Jurassic) elsewhere in the Trafton sequence. For example, Danner (1966) has identified Permian Tethyan fusulinids in limestone pods south of the study area. Regionally, most Trafton metachert yields radiolarian ages ranging mostly from Triassic to Jurassic. Although the critical contact relations are typically concealed, the generally Mesozoic age of the Trafton metacherts contrasts with the mostly Paleozoic age of Trafton limestones and suggests that at least some of the limestones are olistostromal (that is, ancient submarine landslide deposits that have chaotically juxtaposed blocks of various ages as a result of sliding). Alternatively, limestones are exotic sedimentary blocks of disparate age that have been tectonically mixed with metachert during mélange formation. (this study; Danner, 1957; Dethier and Whetten, 1980; Marcus, 1981; Tabor and others, 2002; Dragovich and others, 2004)

JTRmv$_t$ **Greenstone (Jurassic to Triassic)**—Metabasalt and green metatuff with minor thin interbeds of metachert locally; greenstones contain phenocrysts of plagioclase and clinopyroxene; metamorphic minerals include chlorite, pumpellyite, epidote, prehnite, and calcite; contains amygdules and forms pillows or massive flows. (this study; Dethier and Whetten, 1980; Dethier and others, 1980)

PzI **Meta-intrusive (Paleozoic)**—Medium to coarse-grained hornblende metaquartz diorite, metadiorite with minor pyroxene metagabbro, and rare hornblendite; (quartz) diorite typically contains hornblende (locally actinolized), blocky plagioclase ± pyroxene and minor quartz; metamorphic minerals include well-formed actinolite, epidote, chlorite, and pumpellyite (in veins); massive to weakly foliated, commonly with zones of veining, (proto)mylonitization, or cataclasis, particularly near faults. Discriminant diagram analyses of two coarse-grained diorites (SiO_2 51–52%; sites 22–23 on plate) indicate a subalkaline volcanic (island) arc intrusive setting. This differs from the intraplate oceanic island basalt geochemistry of the Eastern mélange belt (Dragovich and others, 2004; Tabor, 1994) and implies that these meta-intrusives are fault-bounded tectonic blocks unrelated to most or all of the volcanic rocks in the Eastern mélange belt or Trafton Sequence. A nearly concordant U-Th-Pb zircon age of 315 to 320 Ma indicates a Pennsylvanian intrusive age for this body (age site 8 on plate; R. E. Zartman, written commun., 1980, to Whetten and others, 1988). Similar quartz diorite associated with the Trafton sequence (Danner, 1966) southeast of the study area has been dated as middle Paleozoic (R. E. Zartman, written commun., 1978, to Whetten and others, 1988).

Tertiary to Recent Tectonic Zones

tz **Tectonic zones (Tertiary to Recent)**—Protomylonite, mylonite, cataclasite, fault breccia, and slickensided and fractured rocks in fault zones. Contains exotic tectonic blocks of protomylonitized and altered quartz diorite in the DDMFZ near Devils Lake (sites 24–25 plate). These exotic blocks are petrographically variable but typically contain plagioclase ± hornblende, and metamorphic or secondary xenomorphic epidote, potassium feldspar, chlorite, and quartz. On the basis of geochemistry and petrography, we suggest that these bodies are fault slices of the Helena–Haystack meta-intrusives and (or) altered Tertiary hypabyssal intrusive bodies related to unit Evr. These quartz diorites are not likely unit ₽l as suggested by Dethier and Whetten (1980). Site 26 is one of the notable areas of mylonitization and silicification (76% SiO_2) found along the informally named McMurray fault zone. Probable sheared Quaternary sediment in the DDMFZ main strand is included in unit tz. (See 'Darrington–Devils Mountain Fault Zone'.) (this study; Lovseth, 1975)

DARRINGTON–DEVILS MOUNTAIN FAULT ZONE

Introduction

The Darrington–Devils Mountain fault zone (DDMFZ) has likely been active in the Holocene. We first describe the general age and structural attributes of the DDMFZ and then offer some indirect and direct evidence for Holocene fault offset in the DDMFZ. See plate for age and other site locations.

Tertiary Bedrock Structures

The DDMFZ extends from southwest of Darrington to west of Whidbey Island where it may become the Leach River fault on Vancouver Island, B.C. The fault zone divides the Northwest Cascades System on the north from the Eastern and Western mélange belts on the south (Dragovich and others, 2002b,c,d, 2003a,b, 2004; Tabor, 1994) and has a complex displacement history beginning in the mid-Eocene (or perhaps the mid-Cretaceous) and continuing to the Recent (Tabor, 1994; Johnson and others, 2001). Tertiary left-lateral strike-slip offset is well demonstrated for the DDMFZ by the geometry of boudins, extensional veins, stretched clasts, slickenlines, and S-C intersections in gouge and sheared rocks along the main strand (Dragovich and others 2002c, 2003a,b, 2004; Lovseth, 1975; Tabor, 1994). The Tertiary DDMFZ is up to 8 mi wide and contains many antithetic and synthetic faults and en echelon fold axes. The curvature of the DDMFZ antithetic faults and en echelon fold axes, where they merge with the main strand, also indicates left-lateral Tertiary offset (plate; Dragovich and others, 2002c, 2003a,b, 2004). Left-lateral master faults such as the Rock Creek, Pilchuck Creek, and Day Lake fault zones parallel the main strand of the DDMFZ (this study; Dragovich and others, 2004). These antithetic and synthetic faults partition the DDMFZ into numerous imbricate tectonic blocks with various structural attributes. For example, some blocks appear to be dominated by flower or strike-slip thrust duplex structures (this study; Dragovich and others, 2000b, 2002, 2003a,b, 2004, 2005). Some upright to overturned fold axes in blocks near the main strand have geometries consistent with oblique to pure reverse faulting or thrusting. However, the overall style of most faults and folds is consistent with a left-lateral transpressional fault zone in the Tertiary.

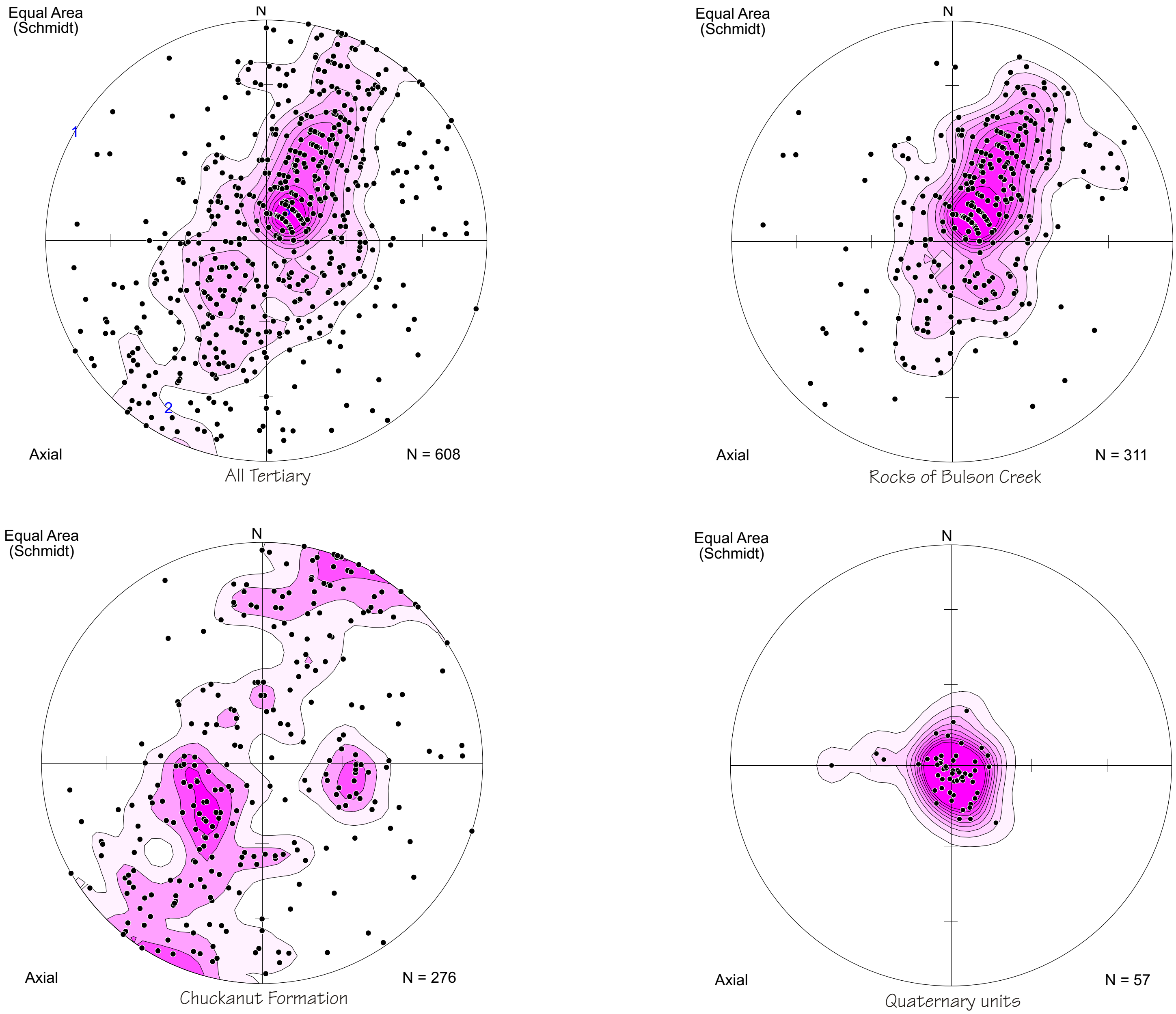
Right-lateral antithetic faults, such as the Mount Washington and McMurray fault zones in the McMurray quadrangle, are subparallel to the generally northwest-trending en echelon fold axes (Fig. 1). The McMurray fault zone (named herein) follows the valley southeast of Lake McMurray and is locally characterized by zones of mylonitization and cataclasis. This structural zone appears to be a family of major and minor right lateral-reverse slip faults that separate older and younger rocks of Bulson Creek. The McMurray fault zone terminates into a zone of reverse faulting; this reverse fault is part of a family of east–west trending reverse faults that uplifted pre-Tertiary bedrock and older marine Bulson Creek rocks (see plate). (See unit ΦEc$_{bs}$.) We suspect that the northwest-trending Lake McMurray fault is a major Cascade Mountains bounding fault that may extend considerably south of the study area; perhaps as far as the Skykomish River where the structure may correlate with the Lake Chaplain fault (for example, Cheney, 1987).

The Eocene and Oligocene stratigraphic record indicates that the broad DDMFZ has a complex Tertiary strike-slip history. The stratigraphic relations around the main strand of the DDMFZ suggests that this master fault has been dominantly both a compressional and extensional structure in this area. For example, there was no obvious active Tertiary DDMFZ offset during the Early Eocene deposition of the easterly derived Coal Mountain unit into an open meandering-river basin. The lack of Chuckanut strata between the pre-Tertiary bedrock and the rocks of the Bulson Creek south of the main strand in the study area is tentatively ascribed to early Middle Eocene erosion of the Chuckanut as a result of the uplift and emergence of mélange belt highlands south of the main strand; these up-thrust blocks became sediment sources. Emergence was contemporaneous with the deposition of the upper (Middle Eocene) Chuckanut units, which have a local provenance and paleocurrent indicators consistent with initiation of basin-bounding partition faults along the DDMFZ (Evans and Ristow, 1994; Dragovich and others, 1997, 2004, 2003a,b). This implies strike-slip transpressional faulting with an oblique south-side-up component. Middle Eocene to earliest Oligocene volcanic rocks are preserved in local strike-slip basins formed at this time. Deposition of the Bulson Creek conglomerate facies only south of the main strand suggests oblique south-side-down transtensional strike-slip faulting along the main strand in the later Eocene to Early Oligocene. Subsequent DDMFZ reverse faulting, evident in the McMurray quadrangle (see plate), uplifted older volcanolithic marine facies of the Bulson Creek unit as well as pre-Tertiary bedrock of the Trafton sequence. This faulting post-dates deposition of the younger conglomerate facies of the Bulson Creek and is interpreted to be the result of renewed transpression in the DDMFZ in post-Eocene time. Several unknowns remain in this model for Tertiary movement. For example, what are the ages and kinematic roles of the many synthetic and antithetic fault strands in the broad DDMFZ? Was there a stress change on the DDMFZ in the middle Eocene? Alternatively, perhaps the evidence for a change in vergence in the Tertiary record a more local response of various blocks in this broad strike-slip system to local stress-strain conditions such as transpressional step-overs and similar types of transfer structures along the length of the fault.

Evidence for Holocene Offset

MISCELLANEOUS EVIDENCE

Although further work is required, we offer some indirect and direct stratigraphic, structural, geophysical, and geomorphic evidence for Holocene offset in the DDMFZ. (Also see Table 1.) Recent activity along the DDMFZ has been concentrated along the main strand of the fault, with perhaps some additional offsets along nearby antithetic and synthetic segments (this study; Dragovich and others, 2003a,b, 2004, 2005). Available stratigraphic and geophysical evidence is most consistent with reverse fault offset of the main strand, with perhaps some transpressional left-lateral strike-slip or oblique movement. For example, the map distribution of Holocene and Pleistocene deposits suggests that lower stratigraphic levels have been uplifted along and south of the main strand and indirectly implies overall south-side-up reverse faulting (Table 1). In the present study



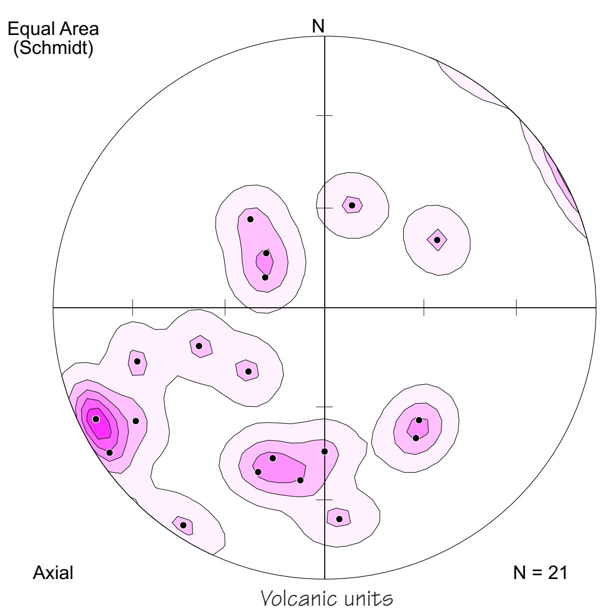


Figure 1. Stereonet plots of bedding orientation for Tertiary rocks and Quaternary glacial deposits in the study area. Data is contoured using the Gaussian (k=100) method with contour intervals of 0, 2, 6, 8…12 percent/1 percent area. Tertiary rock bedding attitudes are derived from this study, Marcus (1981), Dethier and Whetten (1980), Jenkins (1924), and Hopkins (1931). We plotted bedding for the Chuckanut Formation, rocks of Bulson Creek, and Quaternary deposits. The “All Tertiary” net combines bedding attitudes for the Chuckanut Formation and rocks of Bulson Creek, as well as the Eocene volcanics (unit Evr). “Quaternary” includes bedding from Fraser glacial and Olympia nonglacial deposits (see plate). Tertiary rocks are folded along northwest- to west-northwest-trending fold axes (see plate). Tertiary bedding adjacent to the main strand of the DDMFZ parallels this east–west structure as a result of strike-slip displacement and (or) later reverse-fault compressional folding. The rocks of Bulson Creek mostly dip gently or moderately to the southwest but are more tightly folded near the main strand of the DDMFZ. Northwest-trending, steeply dipping bedding also occurs in rocks and tectonic zones (unit tz) adjacent to faults that are antithetic to the DDMFZ, such as the McMurray fault zone.

Table 1. Some of the evidence for Holocene offset along the Darrington–Devils Mountain fault zone (DDMFZ) observed regionally. The Oak Harbor, Crescent Harbor, McMurray, Stimson Hill, Conway, Oso, and Mount Higgins quadrangles are the 7.5-minute scale geologic maps cited in the references column (see map index on plate). Most evidence is consistent with an overall south-side-up offset for the DDMFZ main strand (for example A, B, and D). Some evidence implies general vertical tectonism with significant strike-slip movement (for example, C). Other evidence is ambiguous or implies general uplift (doming) of the broad DDMFZ and (or) an overall north-side-up offset for the DDMFZ main strand (for example, uplift terraces north of the main strand cited in A).

Stratigraphic, geophysical, or geomorphic evidence	Reference
A. Uplifted(?) older alluvium (unit Qoa) in the Stimson Hill quadrangle north of the DDMFZ main strand may indicate overall uplift across parts of the DDMFZ. Older alluvium in the Pilchuck Creek drainage may be related to overall uplift of the basin south of the DDMZ main strand. Radiocarbon-dated unit Qoa peat from an inset Holocene terrace in the Stimson Hill quadrangle suggests mid-Holocene or younger uplift north of the DDMFZ main strand. More widespread unit Qoa south of the DDMFZ in the Oso and Mount Higgins quadrangles may also be due to uplift and incision of the valley south of the DDMFZ. Latest Pleistocene laharic valley-fills thin abruptly where the DDMFZ crosses the North Fork Stillaguamish River area, indicating south-side-up Holocene uplift and erosion after about 5 ka. (Compare the Darrington, Fortson, Oso, Mount Higgins, and Stimson Hill quadrangles.) Holocene uplift and erosion are implied by the absence of laharic valley fills where the DDMFZ crosses the North Fork Stillaguamish River, despite occurrences of latest Pleistocene lahar deposits on both sides of the fault zone.	Dragovich and others, 2002a,b, 2003a,b, 2004 (site 21); this study
B. Direct observation of outcrop-scale sheared Pleistocene strata along the DDMFZ main strand in the Oso, Stimson Hill, and McMurray quadrangles. Moderate to poor outcrop exposure at these sites typically precludes a definitive assignment of the deformation with Holocene DDMFZ displacement.	Dragovich and others, 2003b (site 8), 2004 (site 29); this study (sites 29 and 31)
C. A high-resolution seismic survey by previous workers imaged about 10 to 16 ft of vertical offset of Holocene and late-glacial recessional lake sediments across the DDMFZ main strand at the bottom of Lake Cavanaugh in the Stimson Hill quadrangle. The study suggested that a significant amount of strike-slip offset accompanied Holocene DDMFZ deformation.	Naugler and others, 1996; cross sections B and C of Dragovich and others, 2004
D. Hypocenter and focal-mechanism geometry in the Darrington seismic zone implies an active south-side-up thrust-fault zone striking N80°W ±20°, dipping south at 40° ±15°, with a strike length of at least 6 to 12 mi. The dip of the main strand probably shallows at depth (Fig. 4).	Zollweg and Johnson, 1989; cross section C of Dragovich and others, 2003a
E. The occurrence of sand dikes in glacial deposits indirectly implies liquefaction in the study area. Liquefaction features in Vashon and Everson glacial deposits are also observed in the Stimson Hill, Oso, and Mount Higgins quadrangles. Differential erosion of Everson Interstade recessional deposits south of the DDMFZ main strand and resultant exposure of older Pleistocene deposits may hypothetically have been aided by earthquake-generated liquefaction and landsliding, including laterally spreading. Resultant low-density deposits would be highly susceptible to accelerated surface erosion and removing by a variety of mass-wasting agents, including rilling.	this study (critical sites 5, 32–35); Dragovich and others, 2003a,b, 2004

area, we regard the occurrence of both ancient Pilchuck Creek alluvium (unit Qc_o) and older alluvium (unit Qoa) as evidence for episodic, south-side-up DDMFZ faulting. These deposits occur in terraces as erosional remnants of old Pilchuck Creek alluvium (site 6 area on plate). Anomalous elevated advance lake deposits directly south of the main strand (for example, site 27 on plate) are also consistent with regional map data implying Holocene reverse faulting and uplift (Table 1). This uplift is associated with tilting of Pleistocene strata on Whidbey Island; Dragovich and others (2005) related this deformation to Holocene growth folding within the DDMFZ. (See tilted Quaternary bedding on plate and Figure 1.) Similar uplift and anticlinal folding of Olympia beds directly south of the main strand are inferred by Dragovich and others (2004) directly east of the current study area. Holocene offset is also consistent with the subtle but apparent truncation of lidar-defined glacial fluting in the study area (Fig. 2). Although flutes are not as definitively offset as documented for some other active faults in the Puget Lowland, the observation that glacial flutes or drumlins do not cross the DDMFZ main strand indirectly implies active faulting. Other probable indirect evidence for Holocene movement along the main strand includes an anomaly along the Pilchuck Creek river profile where the main strand crosses the river (Fig. 3).

Regional earthquake focal mechanisms indicate that the DDMFZ is likely currently under almost pure north–south compression (Ma and others, 1996; Van Wagoner and others, 2002). Zollweg and Johnson (1989) defined the active Darrington seismic zone east of the study area using a local portable seismometer array (Table 1). Their hypocenter and focal-mechanism data imply an active south-side-up thrust fault for the main strand. Dragovich and others (2003a) correlated the Darrington seismic zone and Pacific Northwest Seismic Network (PNSN) data with the main strand and inferred that the main strand shallows southward into a gently south-dipping regional décollement. Using relatively poor quality PNSN hypocenter data, we also infer that the main strand shallows into a regional décollement in the current study area (Fig. 4). The high-angle Mount Washington seismic zone of Dragovich and others (2004) includes a tight cluster of recent shallow earthquakes directly east of the current study area. The Mount Washington fault intersects the DDMFZ main strand in the study area (see plate). We speculate that translational Mount Washington fault zone motion has resulted in some active transfer of offset to the DDMFZ. This activity appears to have resulted in the shallowing of the DDMFZ into thrust geometry; note the shallowing of the main strand on plate from a reverse structure east of the Mount Washington fault to a thrust west of the fault. We note here that some hypocenters may also cluster around the similarly oriented, high-angle McMurray fault zone.

TRENCH EVIDENCE

Direct evidence for Holocene offset of the main strand is obtained from our reinterpretation of the trench data acquired by Puget Power (1974). (See Crosby and others [1986] and Adair and others [1989] for an alternative interpretation.) Puget Power excavated ten trenches (totaling 2137 linear ft) to a depth of 13 to 22 ft. Trenches are located at sites 28, 29, and 30 (see plate), as well as around Cross Section B. The "cell tower trench" (site 29 on plate) traversed the main strand and exposed 15 ft of mas-

Figure 2. Lidar image of the McMurray quadrangle (vertical exaggeration 6x). The main strand of the DDMFZ forms a distinct geomorphic lineament in the study area. Note the occurrence of Pilchuck Creek fluvial terraces directly south of the DDMFZ along the eastern edge of the study area. We suggest that some of stranded alluvium is the result of uplift south of the DDMFZ as a result of Holocene reverse faulting. Lidar was not available for the entire quadrangle—rectangles with lower resolution in the lower right and upper left corners are areas filled in with a digital elevation model (DEM) elevation data. Lidar is a bare-earth digital elevation model (DEM) available from the Puget Sound Lidar Consortium (http://pugetsoundlidar.ess.washington.edu/).

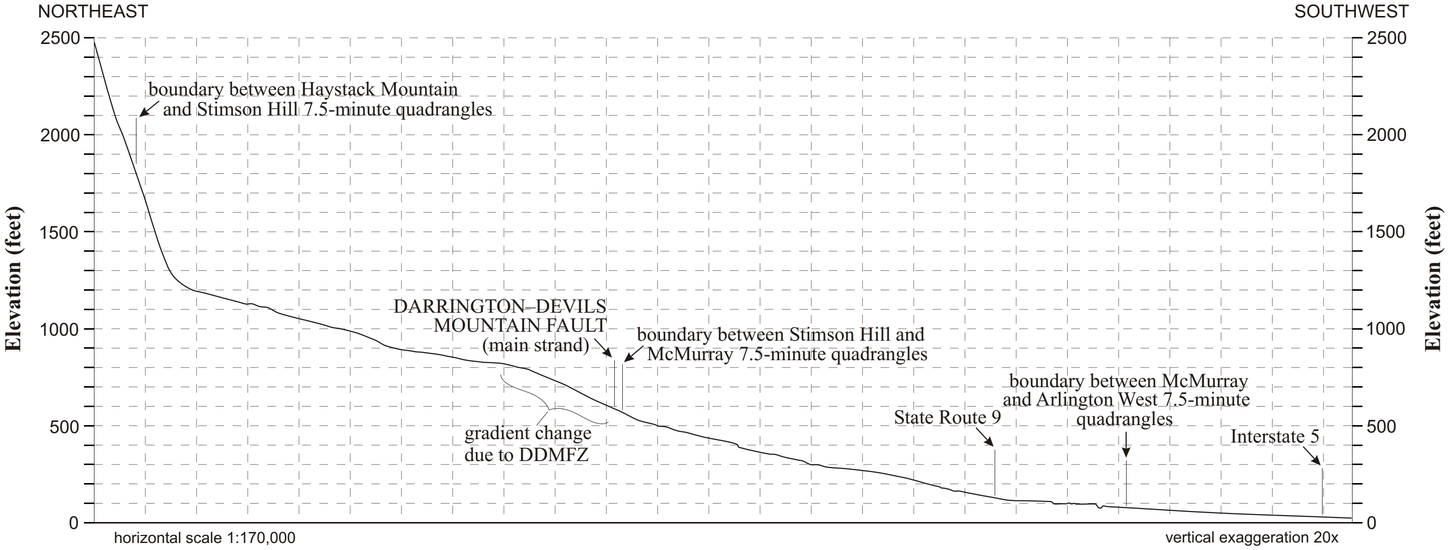


Figure 3. Topographic profile (down-channel) of Pilchuck Creek constructed using lidar elevation data. Grid cells are 5280 ft horizontally by 100 ft vertically; profile is about 24.5 mi long. The Pilchuck Creek headwaters are steep first-order streams of the southernmost Haystack Mountain quadrangle. Pilchuck Creek then passes through the Stimson Hill, McMurray, and Arlington West quadrangles. The profile ends at the confluence of Pilchuck Creek and the Stillaguamish River. The main strand of the DDMFZ is spatially associated with a distinct increase in the gradient of Pilchuck Creek. Although multiple variables affect river gradient, the change in river gradient is consistent with our finding that the main strand has been active in the Holocene. It is unknown what influence potential activity along the Mount Washington fault zone has on the river gradient near the DDMFZ main strand (see plate).

sive bouldery gravelly silty clay (diamicton) with sandstone, greenstone, mottled clay, granite, phyllite, conglomerate, and siltstone clasts. The trench site is located on a bedrock ridge with thin patches of Vashon till. Excellent bedrock exposures around the ridge indicate that main strand is a south-dipping reverse or oblique-slip fault that separates rocks of Bulson Creek from the Chuckanut Formation. Puget Power recovered three organic samples from the trench. One sample was insufficient for dating. However, the other two samples were dated at 22,610 ±800 and 31,500 +2400/–1800 ^{14}C yr B.P., from depths of 8 and 10 ft, respectively. The trench diamicton is not a glacial deposit as indicated by (1) the softness of the diamicton, including the report of void spaces; (2) the occurrence of organics; and (3) the trench position on a bedrock ridge. That is, the lack of compaction indicates that the diamicton is post-Vashon in age and not lodgment till. A recessional glacial origin for the diamicton (for example, flow till) is also unlikely given the organic-rich nature of the diamicton as well as the lack of field evidence for Everson recessional deposits, such as a flow till, on this steep bedrock ridge. (Organic materials are rare in glacial deposits, but common in nonglacial sequences due to the relatively high organic productivity during nonglacial intervals.) Also, the deposit is not a landslide, due to the lack of Olympia-age source materials near or above the trench; that is, there is no nearby source for the ancient organics in the deposit. The trench diamicton is similar to soft silty clay diamicton that we excavated with hand tools from a roadcut on the main strand directly east of the cell tower trench (site 31 on plate). Site 31 contains similar subrounded gravel clasts of granite, quartzite, and greenstone, with angular sandstone and conglomerate fragments. The occurrence of exotic clasts suggests a glacial deposit source, such as Vashon glacial till. We interpreted this soft diamicton as tectonically mixed fault gouge and Vashon till. The interpretation that the nearby trench diamicton is likewise fault-related explains both the anomalous “occurrence of two samples 9,000 yrs apart in age at the same elevation, and only 5 ft apart” as noted by Puget Power (1974). It also explains the spatial correspondence of this unusual diamicton with the main strand. The trench diamicton is similarly interpreted to be a tectonic mixture of sheared glacial till, organic-rich fault colluvium or paleosol of Olympia nonglacial age, and Tertiary sedimentary-rock fault gouge. This interpretation provides direct evidence for post-Pleistocene offset along the main strand of the DDMFZ similar to our direct observation of deformed Fraser glacial deposits in moderately to poorly exposed areas along the main strand (Table 1).

Puget Power (1974) also dug seven trenches and bored eight exploratory drill holes (55–89 ft depth) across the DDMFZ main strand in the north-central part of the study area. Cross Section B is our interpretation of this information. The main strand is well constrained in this area by the trench, drill hole, and lidar (LIght Distance And Ranging) information as well as our local mapping. Recent lidar images of the area show two east–west-trending scarps along the main strand that we interpret to be fault scarps (Fig. 5). The trench logs show a prominent offset of the glacial and nonglacial deposits where the most prominent scarp meets the trenches. This offset was interpreted as a Holocene slump by Puget Power (1974). However, a landslide origin is unlikely given the linearity of the scarps, combined with the near coincidence of the lineaments with the main strand. Also, the scarps are oblique to, and far removed from, the closest steep slopes and thus are not easily related to downslope movement. We reinterpret these features as Holocene fault (graben) scarps. Although unrecognized by Puget Power (1974), Vashon advance lake deposits widely occur in this area (see unit Qgl_v and plate). We correlate dense, massive to thinly bedded silt, clayey silt, fine sand, and sandy silt with scattered gravel, described in the trench and drilling logs, with advance lake deposits, including the distinctive dropstone diamictons of this facies. Puget Power (1974) obtained a ^{14}C age of 14,725 ±470 yr B.P. from faintly bedded silty sand with occasional (dropstone) pebbles (age 1, Cross Section B). The age likely directly dates the advance lake sediments and is not an “anomalous” age as forwarded by the original investigators. The age also implies that unfaulted Olympia deposits do not overlie the main strand of the DDMFZ as undisturbed, onlapping strata as suggested by Crosby and others (1986) and Adair and others (1989). Puget

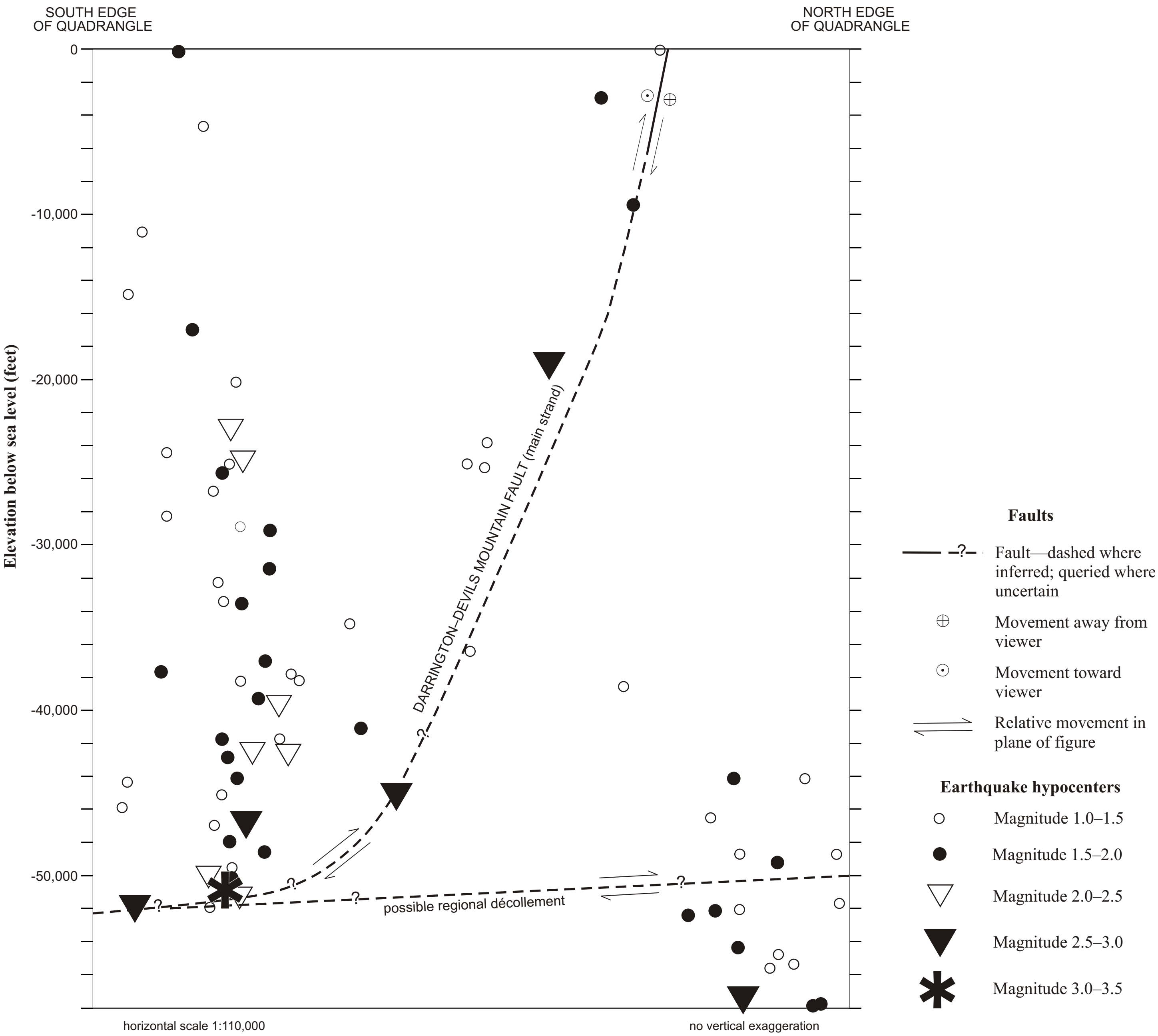


Figure 4. Schematic cross section showing the DDMFZ main strand and the location of 74 recent hypocenters (1978–2004) obtained from the Pacific Northwest Seismic Network (PNSN). The cross section traverses the whole study area along a central north–south axis from the northern and southern edges of the quadrangle and evenly divides the study area into east and west halves. The hypocenters are projected onto this north–south cross section plane. The DDMFZ main strand is a south-dipping fault, as demonstrated by the trace of the DDMFZ main strand across topography in the present study area (see plate). Using the higher quality hypocenter and focal mechanism data of Zollweg and Johnson (1989), Dragovich and others (2003a) suggested that the DDMFZ main strand to the east shallows southward into a gently south-dipping regional décollement. This décollement was inferred to extend to Whidbey Island by Dragovich and others (2005). We similarly hypothesize that some local seismicity is related to DDMFZ main-strand activity. The main strand may be actively interacting with some right-lateral, antithetic fault strands of the DDMFZ. (See discussion of the Mount Washington fault zone and McMurray fault zone under 'Darrington–Devils Mountain Fault Zone'.) Some of the scatter of the data we attribute to interaction with antithetic faults oblique to this cross section and poor determination of hypocenter depth by current PNSN instrumentation. The depth of the décollement is about 52,000 ft (16 km), similar to the regional Puget Lowland décollement depth of 46,000 to 65,500 ft (14–20 km) hypothesized by Pratt and others (1997) south of the DDMFZ.

Power (1974) also directly dated Olympia beds in the trenches. They obtained ^{14}C ages of 35,030 +3340/–2350 yr B.P. from a paleosol and >37,000 yr B.P. from a decayed wood fragment in dense sand and silt (ages 2 and 3, Cross Section B). The wide zone of bedrock fault gouge found along the main strand in the trenches (unit tz on Cross Section B) is common along the main strand elsewhere (this study; Dragovich and others, 2002c). Stratigraphic relations in the trenches, such as the V-shaped contacts in the pre-Vashon geologic units, indicate that the main strand here was a paleovalley formed as a result of erosion into the soft fault gouge prior to the last glaciation (Cross Section B). The Olympia beds that were dated are ancient stream sediments and paleosols deposited in this paleovalley. Vashon Stade glacial deposits subsequently buried this ancient basin. Our interpretation of the stratigraphic relations across the main strand here suggests an overall south-side-up reverse offset along the

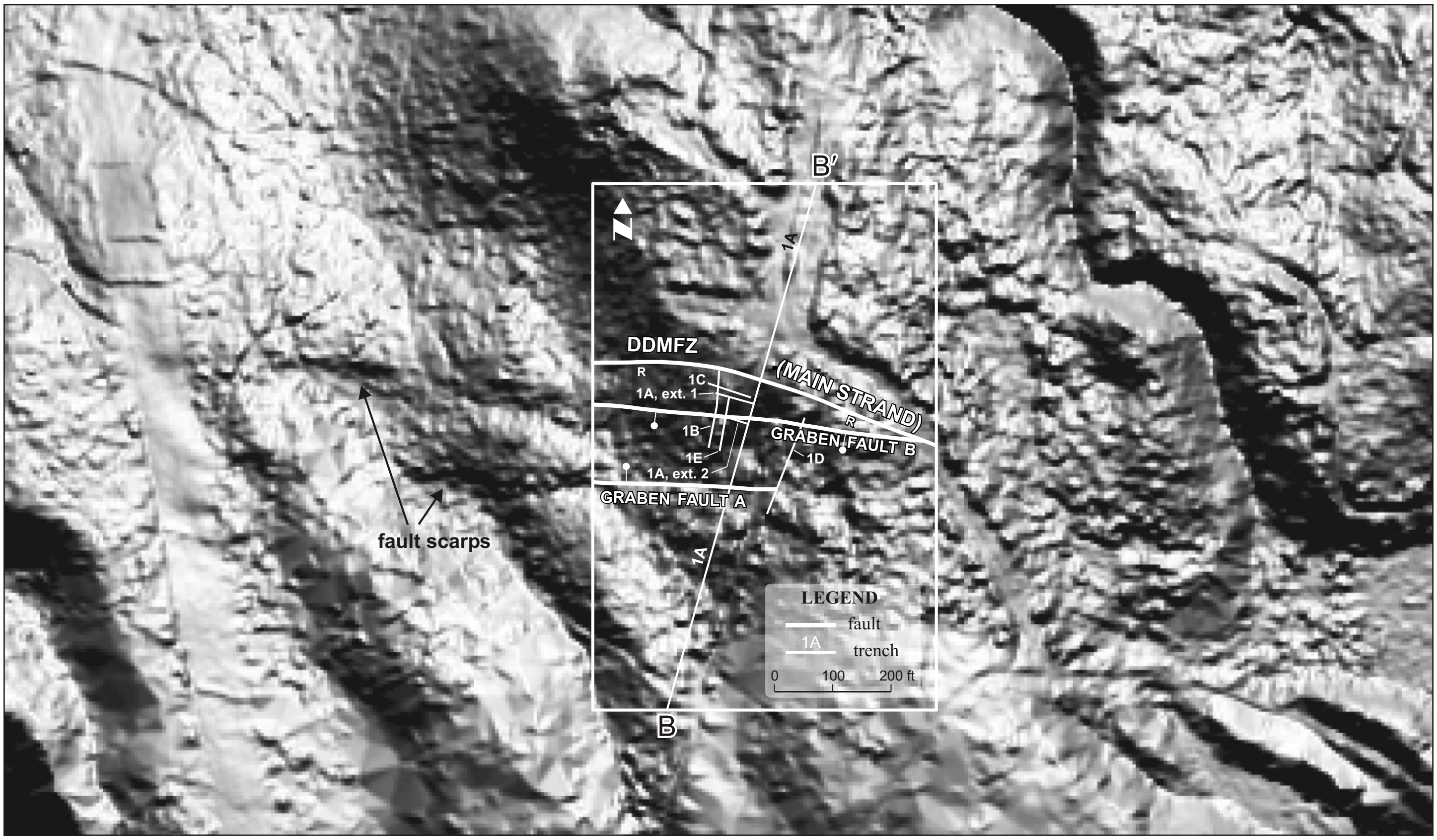


Figure 5. Lidar image of Cross Section B area showing the location of the trenches and mapped faults. See Cross Section B and the index map on plate for location of this image. See Figure 2 for a lidar image of the whole study area. Graben faults A and B were mapped on the basis of the geomorphically prominent fault scarps that are apparent along and west of the Cross Section B area as well as the truncation of stratigraphy documented in the trench logs. We suspect that these faults largely record extensional strain behind the DDMFZ main strand reverse fault. Also note that glacially sculpted features such as subtle fluting do not appear to cross the main strand of the DDMFZ.

DDMFZ main strand; some strike-slip offset is suggested by the stratigraphic thickness variations evident in Cross Section B. Reverse fault compression resulted in the formation of a graben structure in the hanging wall. Such secondary extensional faults in the hanging wall of active thrusts and reverse fault systems are mapped elsewhere in Washington State (West and others, 1996). When all the data are considered, our conclusion is that the DDMFZ is an active and long-lived fault zone.

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