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Geologic Map of the Oak Harbor, Crescent Harbor, and Part of the Smith Island 7.5-minute Quadrangles, Island County, Washington

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June 2005

DESCRIPTION OF MAP UNITS

Our mapping was supplemented by information that was compiled from the sources listed at the end of each description. Our classification systems are described in Dragovich and others (2002d).

Quaternary Sedimentary and Volcanic Deposits

HOLOCENE NONGLACIAL DEPOSITS

Qf — **Artificial fill and modified land (Recent)**—Mixed earth materials including engineered and unengineered fill at major construction sites (highways, airports, saltwater dikes). Locally includes graded or otherwise disturbed land surfaces.

Qb — **Beach deposits (Holocene)**—Sand, gravel, pebbly sand, and boulder gravel. Locally contains shells and organic debris, such as logs.

Qn — **Nearshore deposits (Holocene)**—Estuarine mud and the fine-sand tidal flat deposits with little or no marsh component. Locally organic-rich and shell-bearing (cross sections A–D). Includes tide-dominated Skagit River delta deposits in the northeastern portion of the map. (Pessl and others, 1989; Dragovich and others, 2002c, 2000d)

Qm — **Saltwater marsh deposits (Holocene)**—Organic-rich silt and mud, commonly with lenses and layers of peat at or above highest high tide, covered with salt-tolerant vegetation. Saltwater marsh, nearshore (unit Qn), and beach deposits (unit Qb) in active fault zones may have been uplifted to their present elevations. (Pessl and others, 1989; WDOE, 1979)

Qp — **Peat (Holocene)**—Fibrous to woody peat and organic sediments of fresh-water bogs and swamps; occurs in kettles and other depressions, including depressions possibly formed by active faulting; poorly stratified to unstratified. From limited data, peat and saltwater marsh deposits (unit Qm) are distinguished on the basis of saltwater versus fresh-water plant species content (for example, tree stumps). Williams and Hutchinson (2000) note that Swantown Marsh peats were deposited in a low-salinity marsh near high tide limits. They report ^{14}C ages of 1,230 ±50, 1,630 ±50 (^{14}C site 19-20), 1,970 ±50, and 2,010 ±50 yr B.P. (^{14}C site 21-22) from marine-microfossil-bearing "sand sheets" in the peats, which they interpret as tsunami deposits. Near Rocky Point, Johnson and others (2001) obtained a ^{14}C age of 1,750 ±50 from a tree branch in a woody peat exposed at very low tide (^{14}C site 23). Considering the terrestrial nature of this peat deposit, we interpret the current marine setting as evidence for local late Holocene down-dropping of the beach south of Strawberry Point fault no. 1.

Qd — **Dune deposits (Holocene)**—Wind-deposited, well-sorted, and well-rounded sand and silty sand, locally on paleosols (buried organic layers representing former soil horizons) and buried stumps; typically structureless or moderately stratified with broad planar cross-beds. Dunes are common near beach level and along western bluff tops where barren slopes are exposed to strong onshore winds. (Thorsen, 2001; Pessl and others, 1989; WDOE, 1979; Polenz and others, 2005)

Qls — **Landslide deposits and scarps, undivided (Holocene–latest Pleistocene)**—Poorly sorted and unstratified diamicton (debris flows or fans) or partially intact to severely disrupted, slid, or rotated blocks with relict stratigraphy (debris or rock slumps); heterogeneous in composition and structure, reflecting sources in complexly layered Quaternary strata. Landslide deposits were not mapped in bluff areas prone to large-block toppling or superficial sliding. See WDOE (1979) for study area hazard zonation. (Thorsen, 2001; Pessl and others, 1989)

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Relative stratigraphic position, organic content, ^{14}C ages, and particularly provenance data were used to separate glacial from nonglacial deposits. Provenance was determined using sand-clast composition as observed in thin-sections and gravel-clast composition as determined in the field (columnar sections 1–5). Glacial deposits have northern provenance (Fidalgo Island to Coast Mountains of British Columbia), whereas the nonglacial deposits (Olympia beds and Whidbey Formation) have eastern or Skagit River provenance (Dragovich and others, 2000c, 2002c,d). The key nonglacial provenance clast-type indicators are Glacier Peak dacite (>5%) and hypersthene. Conversely, glacial sand and gravel deposits have a little or no Glacier Peak detritus (0–5%) and contain significant granitic and metamorphic lithic clasts (Dragovich and others, 2000c,d, 2002c).

Deposits of the Fraser Glaciation of Armstrong and others (1965)

EVERSON INTERSTADE

Glaciomarine Facies

$Qgdm_{fed}$ — **Glaciomarine drift**—Clast-rich diamicton with abundant dropstones (unit $Qgdm_{fed}$, >5% dropstones) and mud with few or no dropstones (unit $Qgdm_{fec}$, <5% dropstones); locally contains very thin to very thick interbeds of shallow marine sand and (or) gravel outwash; locally has desiccation joints or cracks. Glaciomarine drift is generally brown and stiff when dry, and grayish blue and soft when moist or wet. Diamicton unit consists of silty sandy gravelly clay to clayey gravel and is typically massive or forms several-meters-thick, structureless or crudely stratified beds with varied gravel dropstone content. Mud unit is structureless, varved, or laminated. Marine shell ^{14}C ages reported include 12,300 ±180 yr B.P. (^{14}C site 24, Easterbrook, 1969) and 13,595 ±145 and 13,650 ±350 yr B.P. (^{14}C sites 25 and 26, Dethier and others, 1995). (Easterbrook, 1966; Dragovich and others, 1998, 1999, 2000c, 2002c, unpub. data; Dethier and others, 1995)

$Qgos_g$ — **Glaciomarine sand deposits**—Sand, pebbly sand, and silty fine sand with local thin interbeds of silt and rare cobbly sand; mostly structureless to locally plane bedded, laminated, or rarely cross-bedded; locally complexly interlayered with glaciomarine drift; includes minor glaciofluvial deposits. Facies relations, including fining trends, and sedimentary structures suggest deposition in a shallow glaciomarine setting as foreshore deposits or submarine fan turbidites. (Johnson and others, 2001, 2004; Domack, 1982; Dethier and others, 1995)

$Qgom_{fe}$ — **Emergence (beach) deposits**—Pebbly sand or sand and gravel, locally with boulders; mostly structureless, but may be stratified, laminated, or ripple cross-bedded with rare boulder lag deposits. Many Pleistocene stratigraphic sections below the glaciomarine limit of ~220 to 240 ft are capped with as much as 3 ft of reworked beach or shoreface substrate deposited during Everson isostatic emergence. Longer sea-level stands produced distinctive wave-cut strandlines (Sheet 1). (Dethier and others, 1995; Dragovich and others, 2000d, 2002c)

Ice-Contact Facies

Qgi_d — **Diamicton**—Sandy, silty pebble gravel to bouldery, gravelly sandy silt; typically structureless, locally has a faint friable primary fabric. Diamicton is poorly exposed and represents melt-out, ablation, or flow tills associated with kettles or partially closed depressions. We infer a recessional depositional environment from the spatial association of this unit with other moderate to low-density ice-contact deposits and its stratigraphic position above dense (subglacial) Vashon lodgment till (cross sections A–D).

$Qgim_d$ — **Moraine deposits**—Bouldery cobble gravel with interbeds of sand or pebbly sand and minor diamicton (flow till?); typically structureless and poorly to moderately stratified with poorly sorted, clast-supported bouldery gravel (critical sites 1–3). Moraines form topographically prominent features near or below the glaciomarine limit. They commonly grade laterally to glaciomarine drift or sand and may be submarine debris fans or outwash deposited adjacent to grounded ice. (Dethier and others, 1995; Domack, 1982; Polenz and others, 2005)

$Qgis_d$ — **Stratified ice-contact deposits**—Bouldery cobbly gravel, diamicton, pebbly gravel locally, pebbly sand, and sand; moderately to well sorted, moderately to well stratified, and medium to very thickly bedded. Ice-contact primary structures include syndepositional slumping and collapse features (oversteepened and contorted bedding). These deposits occur mostly in kettles or controlled moraine(?) geomorphic settings. Interstratified soft diamictons and granular meltwater deposits are interpreted as melt-out-till and flow-till deposition punctuated by supraglacial, englacial, and subglacial meltwater deposition. The unit is locally divided into subglacial tunnel(?) deposits (unit $Qgics_d$) composed of stratified gravel-diamict similar to unit $Qgis_d$. The areal distribution of the deposits in a WSW-trending swath (critical sites 4–7) suggests recessional subglacial excavation along Crescent Harbor, Dugualla Bay, and Clover Valley. These swaths are mostly subparallel to the secondary but dominant WSW–ENE fluting direction (see unit $Qgfs_d$), border present topographic lows such as modern marine embayments, and may terminate in grounded submarine outwash embankments. The deposits typically contain abundant and locally very large (≤30 ft diameter) rip-up clasts of Vashon till and older glacial and nonglacial units. This subglacial scour appears to be coincident with removal of Vashon advance outwash deposits (Booth and Hallet, 1993) (cross sections A–D).

$Qgik_d$ — **Kame deposits**—Sandy gravel, sand, and cobble gravel, locally with laminated silt pods and lenses of diamict (mostly melt-out till from buried ice blocks); medium to very thickly bedded, moderately to well stratified. Rip-up clasts, cross-bedding, cut-and-fill structures, and ice-contact features, such as oversteepened and slumped bedding, common. Lateral ice buttressing is required to produce these elevated fluvial deposits. The unit is locally divided, from youngest to oldest, into units $Qgik_{d1}$, $Qgik_{d2}$, $Qgik_{d3}$, and $Qgik_{d4}$. Relative age is indicated by terrace height and inset relations, terrace age increasing with terrace elevation. Kame deposits are well exposed in several study area gravel mines (for example, critical sites 8–9).

Qgl_d — **Lake deposits**—Silt, silty clay, silty fine sand, and fine sand, rarely contains scattered dropstones; typically laminated to thinly bedded with bedding locally folded or tilted. Most of these deposits occur above the Everson glaciomarine limit and interfinger with kame deposits, indicating that they were deposited in ice-dammed lakes.

Terrestrial, Deltaic, and Undivided Facies

$Qgof_g$ — **Fluvial deposits**—Cobble and sandy pebble gravel, pebbly sand, and rare silt; mostly structureless to moderately stratified with medium to very thick beds. Mostly occurs above the glaciomarine limit as valley-train deposits between WSW-trending flutes. These deposits lack ice-contact features or other evidence for lateral constraint from ice.

$Qgod_g$ — **Deltaic deposits**—Sandy and cobbly pebble gravel, pebbly sand, and sand with thin beds of silt; well stratified and thinly to thickly bedded; high-amplitude foreset beds are characteristic; locally contains rip-up clasts of till or compact silt several feet across, plane-bedded sand, rare flame structures, and marine fossils; locally interfingers with Everson glaciomarine drift, recessional fluvial deposits, or kame deposits. A kame delta, well exposed in a gravel pit (critical site 10), represents the western termination of kame terrace fluvial deposits at the edge of the glaciomarine environment.

$Qgog_g$ — **Gravel deposits**—Pebble cobble (boulder) gravel to pebbly cobbly sand with minor beds and lenses of sand; structureless to moderately stratified. May include any of the gravelly Everson facies described above. Where gravel occurs as a thin mantle over older glacial deposits (cross sections A–D), it probably represents emergence facies.

Vashon Stade

Qgt_g — **Till**—Dark yellowish brown to bluish gray diamicton consisting of clay, silt, sand, and gravel in various proportions, with scattered pebbles, cobbles, and boulders and local thin to thick lenses of sand, gravel, or rarely silt; structureless and nonstratified; commonly has a friable (shear) fabric and a silty sand matrix; locally contains subglacial ice-shear structures, such as aligned, striated clasts and shear-folded sand and gravel interbeds (critical site 11). Till mantles topography and rests unconformably on a wide variety of older deposits. Mantling is well displayed where till descends from the uplands to below sea level (critical site 11). Bedrock glacial striae, ice-shear structures, and fluted till shapes indicate a late WSW ice-shear direction formed in zone a few miles wide behind the retreating ice margin. This direction strongly overprints the regional north–south fluting trend observed along the axis of the Puget Lowland and may be the result of a late ice surge toward the ice-free Juan de Fuca glaciomarine embayment. Regional ^{14}C dates indicate lodgment till deposition in the study area between about 15,200 and 13,600 ^{14}C yr B.P. (Booth and Hallet, 1993; Dragovich and others, 2000c, 2002d; WDOE, 1979; Porter and Swanson, 1998; Pessl and others, 1989)

Qga_v — **Advance outwash**—Sand, pebbly sand, and sandy gravel with lesser layers and lenses of pebble-cobble gravel, silty fine sand, and sandy or clayey silt; mostly well stratified, well sorted, and very thinly to very thickly bedded; contains plane and graded beds, localized cut-and-fill structures, and trough and ripple cross-beds; mostly fluvial meltwater sediments deposited during advance of the Puget lobe. Using provenance data, we include some sand and pebbly sand, previously included as Vashon advance outwash by Easterbrook (1968), in the channel facies of the Whidbey Formation (unit Qc_{wc}) (columnar sections 1–2). Regional ^{14}C dates indicate advance outwash deposition in the study area between about 16,000 to 15,200 ^{14}C yr B.P. (Polenz and others, 2005; Porter and Swanson 1998; Pessl and others, 1989; Thorsen, 1983)

Deposits of the Olympia Nonglacial Interval

Qc_O, Qc_{Ow} — **Olympia beds**—Sand, silt, silty clay, peat, pebbly sand, organic sand, and silt, and minor lenses and layers of pebble gravel; also contains rare pebble cobble gravel of fluvial channel origin and rare diamicton of probable mass-flow origin. Olympia beds along Blowers Bluff and West Beach that also contain a 1- to 25-ft thick bed of "West Beach silt" too thin to depict at map scale are mapped as unit Qc_{ow}. The West Beach silt of Thorsen (1983, 1985) is massive, well-sorted, gray wind-blown silt (loess) that weathers a yellow-tan. A 1- to 3-ft-thick paleosol at the base of the silt is generally oxidized but locally olive colored. Olympia beds are typically well sorted, well stratified, and laminated to thickly bedded, and display plane bedding, scour-and-fill, trough cross-bedding, flame structures, and (or) ripples. They also contain rare terrestrial fossils (gastropod, pelecypods, vertebrate remains) and, more commonly, wood, peat, and other plant remains. Like the Whidbey Formation, the Olympia beds in the study area are ancient Skagit River channel and flood-plain deposits. Sand thin-section data demonstrate that the Olympia beds have a provenance comparable to modern Skagit alluvium. Olympia beds contain 3 to 15 percent dacitic lithic fragments, significant hypersthene and hornblende, and minor augite, all of Glacier Peak volcano origin (columnar sections 1–5). Some beds are rich in vesicular or pumiceous dacite clasts and represent lahar runout or volcanic alluvium. The present Skagit River delta channels carry only pebble and sand detritus as bedload, whereas the ancient Skagit River channel deposits in the Olympia beds contain *cobble* gravel consistent with a lower-than-present sea level during this nonglacial time. Substantial post-Olympia uplift is implied by the maximum elevation of the Olympia beds around active fault zones in the study area. (See Figure 1 and Active Faulting in the Study Area.) The Olympia nonglacial interval occurred between about 16,000 and 60,000 ^{14}C yr B.P. (Easterbrook, 1994). We obtained ^{14}C ages of 23,060 ±140 yr B.P. from sticks (^{14}C site 27) and 35,900 ±1,100 yr B.P. from wood (^{14}C site 28) (Fig. 1 on Sheet 1). Previously reported ^{14}C ages include 15,190 ±220, 21,100 ±150, and 29,270 ±340 yr B.P. (^{14}C sites 29, 30, and 34; Johnson and others, 2001), 26,850 ±1,700, and 34,900 ±3000 yr B.P. (^{14}C site 31-32; Easterbrook, 1969). Additional previous ^{14}C ages from Strawberry Point are shown on measured section 4. Disseminated organics from a West Beach silt paleosol overlying Possession Drift yielded a ^{14}C age of 37,610 ±380 yr B.P. (G. W. Thorsen, written commun., 2004; ^{14}C site 33; columnar section 2). (WDOE, 1979; Dragovich and others, 2000c, 2002, unpub. data; Pessl and others, 1989; Johnson and others, 2001; Easterbrook, 1994; Hansen and Easterbrook, 1974; Blunt and others, 1987; Polenz and others, 2005)

Deposits of the Possession Glaciation of Armstrong and others (1965)

$Qgdm_p$ — **Glaciomarine drift**—Silty clay and clay with scattered gravel dropstones, locally with minor laminated silt and fine sand and rare gravel lenses and scattered shell fragments. Amino acid analyses of *Nuculana* and *Clinocardium* in this unit suggest an age of about 80,000 ±22,000 yr B.P. (Blunt and others, 1987, AA site 35). This age is consistent with the accepted age of 60,000 to 80,000 yr B.P. for the Possession glaciation, which is based on regional age relations and oxygen isotope data. (Thorsen, 1983; Pessl and others, 1989; Easterbrook, 1994)

Qgt_p — **Till**—Diamicton consisting of clay, silt, sand, and gravel in varied proportions, with scattered cobbles and boulders. Locally includes thin beds and lenses of dense gravel and sand. (Easterbrook, 1994; Easterbrook and others, 1967)

Qga_p — **Advance outwash**—Sandy gravel, sand, pebbly sand, and scattered lenses of cobbly gravel with rare silt and clay interbeds; mostly cross-bedded to structureless and moderately stratified. Sand thin-section provenance data combined with field gravel-clast counts, subsurface data, and Olympia nonglacial deposit ^{14}C ages indicate that Possession outwash occurs between the nonglacial deposits of the Olympia interval and the Whidbey Formation. In the study area, it forms a distinct thin but discontinuous stratum in several bluffs (columnar sections 1–5).

Whidbey Formation

The Whidbey Formation of Easterbrook and others (1967), like the Olympia beds in the study area, is an erosional remnant of the ancient Skagit River fluvial-deltaic system that prograded west of the study area for an unknown distance. This fluvial-deltaic system was graded to a sea level near or slightly higher than present during this interglacial interval (Johnson and others, 2001, and global oxygen isotope data). We divide the Whidbey Formation into three fluvial depositional facies including: (1) flood-plain facies (unit Qc_{wf}), (2) channel facies (unit Qc_{wc}), and (3) lahar runout facies (unit Qc_{wl}). A slight to distinct disconformity or angular unconformity is common at the top of the Whidbey Formation. Regional age considerations as well as global oxygen isotope data indicate that the Whidbey Formation is about 80,000 to 140,000 ^{14}C yr B.P. old and corresponds to global interglacial marine isotope stage 5. We obtained three ^{14}C ages (>43,960 yr B.P. [peat; ^{14}C site 36], >44,770 yr B.P. [sticks, ^{14}C site 37], and >44,790 yr B.P. [sticks, ^{14}C site 38]) from the formation. Johnson and others (2001) obtained a finite age of 44,740 ±910 yr B.P. (^{14}C site 39) but concluded that it was an infinite age and the result of sample contamination with modern carbon. Several other ^{14}C ages previously obtained from the Whidbey Formation were all >42,000 ^{14}C yr B.P. (^{14}C sites 40–46 and columnar section 4.) and thus "infinite" (Johnson and others, 2001; Easterbrook and others, 1967; Easterbrook, 1968, 1969; Hansen and Easterbrook, 1974; Blunt and others, 1987). D. P. Dethier (Williams College, written commun., 2005) obtained an infinite ^{14}C age from probable Whidbey Formation on Smith Island (inset map, ^{14}C site 47). Berger and Easterbrook (1993) report thermoluminescence dates from clay in the formation at the base of Blowers Bluff (98,000 ±16,000 to 107,000 ±17,000 yrs; TL site 47) and West Beach (142,000 ±10,000, TL site 48).

Qc_{wf} — **Whidbey Formation**—Fluvial flood-plain facies deposits (unit Qc_{wf}) consisting of silt, clay, peat, silty sand, sand, and rare pebbly sand; sand, silt, and clay commonly organic and rarely ashy; mostly well stratified and thinly laminated to thickly bedded; encompasses general overbank, oxbow-lake, swamp, and levee depositional environments; logs (flattened), bark, sticks, leaves, sedge, and vertebrate (for example, bison molar or mammoth tusk) and other terrestrial fossils are common. Fluvial channel facies deposits (unit Qc_{wc}) consist of sand and pebbly sand, with lesser silt and clay, and rare peat and pebbly gravel (with rare cobble-size pumice clasts); mostly well stratified and thickly laminated to very thickly bedded; encompasses point bar, channel, and levee depositional environments; contains several fluvial cross-bed forms, lenticular beds, rip-up silt clasts, and lag deposits. Scour-and-fill structures and erosional unconformities within the Whidbey Formation are mostly the result of lateral stream-channel migration across the flood plain. Fluvial sedimentary structures for both the flood-plain and channel facies include ripple marks, graded beds, flutes, flames, and convolute bedding. Liquefaction features, such as sand dikes, are evident near some active fault strands. Rare shells reported in well logs may be deltaic or marine facies of the formation at depth. Locally mapped as: (1) undivided channel and flood-plain facies (unit Qc_{wcf}) where map scale does not allow differentiation between these facies, and (2) undivided Whidbey Formation (unit Qc_{wu}, cross sections only). The channel and flood-plain facies have a Skagit River provenance (columnar sections 1–5). Pebbles in these facies are 5 to 55 percent vesicular dacite with a Glacier Peak geochemical and petrographic signature. (See Table 1 and lahar runout of Oak Harbor below.) Sand thin-section data demonstrate that the channel and flood-plain sands contain 6 to 50 percent dacite lithic clasts with significant detrital hypersthene, hornblende, oscillatory-zoned plagioclase, and some augite, all of Glacier Peak origin. The deposits strongly resemble Skagit River alluvium directly east of the study area (Dragovich and others, 2000a,b,c,d, 2002c; unpub. data); this alluvium contains detrital dacite and crystal fragments of Glacier Peak origin, including microlitic dacite fragments (16–30%), hypersthene (2–3%), hornblende (2–3%), and augite (0–1%). Whidbey Formation sand also contains significant biotite and muscovite similar to Skagit River alluvium. (WDOE, 1979; Johnson and others, 2001; Easterbrook and others, 1967; Easterbrook, 1968, 1969; Heusser and Heusser, 1981)

Qc_{wl} — **Lahar runout of Oak Harbor**—Dacite-rich pebbly sand and sand, locally overlain by a thick bed of water-laid ashy silt; locally includes overlying stratified silt and sand, mostly of the flood-plain facies (unit Qc_{wf}); structureless to crudely graded and locally cross-bedded. Abundant rip-up clasts of silt are common along the base of the lahar. This informally named lahar runout is correlated with Glacier Peak volcano on the basis of dacite-clast petrographic and geochemical characteristics (Table 1), sand composition, and geographic position. Pebble clasts are 65 to 95 percent homogeneous dacite, hypersthene-hornblende ±augite phyric, and moderately vesicular to locally pumiceous with trachytic and glomerocrystic textures typical of Glacier Peak dacite. Thin-section analyses show that the lahar runout sand contains 55 to 90 percent dacite fragments with significant hypersthene and hornblende ±augite crystals (columnar sections 1, 3). These characteristics correspond well to those of younger Glacier Peak volcanic deposits from the edifice to the lower Skagit River valley (Dragovich and others, 2000a,b,c,d, 2002a,b,c, 2003a, 2004; unpub. data). The occurrence of volcanic sediments in much of the Whidbey Formation implies that Glacier Peak had eruptive episode(s) between ~80,000 and 140,000 ^{14}C yr B.P.

Deposits of the Double Bluff Glaciation

Qgt_d — **Till**—Diamicton with rare lenses of sand and gravel; occurs as discontinuous, very dense outcroppings along the base of coastal bluffs or in the subsurface below the Whidbey Formation (cross sections A–D). (Also see unit oo.) The Double Bluff glaciation is thought to have occurred between about 250,000 and 140,000 yr B.P. and corresponds to marine isotope stage 6. (Blunt and others, 1987; Easterbrook, 1994)

Undivided pre-Double Bluff Glaciation (Glacial and Nonglacial Deposits)

Qgn_{pd} — **Glacial and nonglacial deposits (Pleistocene–Pliocene?) (cross sections only)**—Dense sand, silt, clay, gravel, peat, and diamicton older than the Double Bluff till; commonly organic rich and thus may include substantial composite stratigraphic thicknesses of nonglacial deposits (cross sections A–D). Locally divided into:

oo — **Older outwash (Pleistocene) (cross sections only)**—Dense sand and gravel. Occurrences of unit oo directly below unit Qgt_d may be advance outwash of the Double Bluff glaciation.

ot — **Older till (Pleistocene) (cross sections only)**—Dense diamicton including clayey gravel and silty sandy gravel.

Tertiary Sedimentary Rocks

ΦEc_{bcg} — **Rocks of Bulson Creek (Oligocene–Eocene)**—Pebble and cobble conglomerate and lesser pebbly sandstone, with minor siltstone and rare coal. Conglomerates are typically structureless to normally graded; clasts subangular to subrounded, moderately spherical to elongate, and locally imbricated. Sandstone interbeds range from structureless to thickly bedded with rare graded bedding and cross-bedding; clasts are angular to subrounded. Carbonized leaves and branches occur in the sandstone and siltstone interbeds. Unit occurs directly south of the main strand of the Devils Mountain fault zone as fault-controlled fluvial and alluvial-fan basin deposits. East of the study area, Bulson Creek rocks fine to the south and grade to shell-bearing marine rocks. Inferred Bulson Creek rocks in the subsurface of the study area (cross sections A–D) may similarly fine southward and are likely partly shallow-water marine in origin. (Whetten and others, 1988; Dragovich and others, 2002c)

Ec_c — **Chuckanut Formation (Eocene) (cross sections only)**—Sandstone with lesser conglomerate, mudstone, siltstone, and coal. Walsh (1984), citing vitrinite reflectance and BTU content data, reports that bituminous coal samples from between 634 and 800 ft below the surface in boring B1-USGS (cross section D) are likely of the Chuckanut Formation.

Jurassic to Cretaceous Metamorphic Rocks

GOAT ISLAND TERRANE

The Goat Island terrane of Whetten and others (1988) is a structurally disrupted serpentinite-matrix mélange. Symmetamorphic static recrystallization (blueschist facies) is common in the metavolcanic rocks of the terrane. The terrane occurs as imbricate slices in the Devils Mountain fault zone (DMFZ). Thus, many major contacts are east–west-trending, high-angle faults. Metasedimentary rocks typically contain lineated-foliated (L–S) tectonites and two or three generations of folding. These complex deformational structures are related to both mid-Cretaceous thrusting and to later, lower strain, semiductile to brittle, transpressional strike-slip deformation along the DMFZ. Both deformational episodes have resulted in localized development of S-C mylonites. These structures are well displayed in the Fidalgo Igneous Complex directly north of the study area. There, mid-Cretaceous thrust structures with north-vergence are common and overprinting effects of the DMFZ disappear. Bedrock structures associated with the DMFZ include cataclasite, lineated protomylonite, and folds, all with a strong east–west strike or trend. Bedding, foliation, and fold trends in the terrane are subparallel to the DMFZ. Rocks are locally hydrothermally altered as a result of fluids permeating deformational zones in the DMFZ (Whetten and others, 1988; Dragovich and others, 2000d, 2002c, 2004, unpub data.)

KJu_{tg} — **Metavolcanic greenstone (Jurassic–Cretaceous)**—Greenstone with local thin interbeds of metachert and rare pods of serpentinite. Greenstones are composed of plagioclase phenocrysts in a chloritized and sauseritized matrix, with interstitial quartz and microphenocrysts of pyroxene occurring locally. Metamorphic minerals are fine-grained and include Fe-chlorite, epidote, and albite ±actinolite, with accessory calcite and opaque minerals. Some volcanic beds contain quartz- or chlorite-filled vesicles, breccia fragments, and pillows. Rocks are structureless to moderately foliated or strongly fractured or mylonitized. (Whetten and others, 1988; Dragovich and others, 2000d, 2002c, unpub. data.)

KJu_{ug} — **Ultramafic (Jurassic–Cretaceous) (cross sections only)**—Serpentinite and silica carbonate bodies too small to show at map scale. Ultramafites occur as foliated tectonic pods, locally with unusual strontium mineralization, and are likely the cause of high magnetic anomalies over the terrane. (Johnson and others, 2001; Dragovich and others, 2000d, 2002c)

$KJmt_{sg}$ — **Metasedimentary rocks (Jurassic–Cretaceous)**—Metasandstone with lesser metagraywacke, slaty or phyllitic metasiltstone, and metaconglomerate, with local thin to very thick beds of tuffaceous meta-andesitic greenstone, (ribboned) metachert, rare metadiamictite, and marble pods or concretions; typically well stratified and thinly to locally very thickly bedded; siltstones locally siliceous with radiolarians or radiolarian ghosts. Sand-size relict clasts in subquartzose metasandstones include abundant monocrystalline and polycrystalline quartz (including abundant chert), with lesser volcanic lithic clasts, plagioclase, sedimentary lithic clasts, and local detrital(?) chlorite and white mica. Metasiltstone rip-up clasts are typical. Metamorphic minerals include quartz, plagioclase, muscovite, and Fe-chlorite, with locally some pumpellyite, prehnite, calcite or aragonite, epidote, stilpnomelane(?), white mica, and rare lawsonite. Local systematic veins and stretched detrital grains are filled with pumpellyite, prehnite, and minor aragonite. The rocks are well foliated with cross-cutting brittle to ductile shear zones common; primary foliation is mostly subparallel to bedding. Geometric relations between relict bedding, crenulations, folds, and foliation orientations define large overturned folds (cross section D). These folds are refolded around shallow east–west-trending fold axes. (Whetten and others, 1988; Dragovich and others, 2000d, 2002c)

METAMORPHIC ROCKS OF ROCKY POINT

$KJhmt_{fp}$ — **Mixed metasedimentary and metavolcanic rocks (Jurassic?–Cretaceous)**—Phyllitic meta-argillite, metaconglomerate, and metasandstone with lesser tuffaceous greenschist, metabasaltic greenstone, and minor metachert; moderately to well stratified. Strongly foliate and crenulated, as well as ductilely to brittlely sheared, with S-C mylonites and subhorizontal stretching lineations locally prominent. Two syn- to post-metamorphic semiductile to penetrative deformations are evident. The deformational style of these rocks is likely due to Tertiary and (or) pre-Tertiary deformation near a major strike-slip fault zone.

METAMORPHIC ROCKS OF THE SAN JUAN ISLANDS–NORTHWEST CASCADES SYSTEM

$KJmm$ — **Lopez structural complex (Jurassic–Cretaceous) (cross sections only)**—Mostly metachert, metabasalt, and metagraywacke. We infer that the Lopez complex (Dragovich and others, 2002d) occurs below Quaternary strata (cross sections B, C) north of the main strand of the Devils Mountain fault zone and southeast of our informally named San Juan Margin fault in the northernmost part of the study area. We regard the San Juan Margin fault as a major structure due to two geophysical observations: (1) the low gravimagnetic anomaly signature southwest of the San Juan Margin fault (Johnson and others, 2001), which suggests that this concealed bedrock block is unit $KJmm$, not the geomagnetically prominent Goat Island terrane rocks, and (2) seismic reflection data of Johnson and others (2001) that imagine a series of tightly spaced Quaternary(?) faults and folds co-linear with the San Juan Margin fault directly north of the study area and west of Whidbey Island.

ACTIVE FAULTING IN THE STUDY AREA

The map area has several active faults that are regionally significant. Johnson and others (2001) recently mapped active strands of the Devils Mountain, Strawberry Point, and Utsalady Point fault zones. Although we modify some fault locations, geometries, and inferred offsets, we concur with a majority of their conclusions. We map and name the Oak Harbor fault and add it as a possible Holocene active structure.

Our mapping (Sheet 1) confirms that most previously mapped fault zones are associated with significant tectonic fracturing, tilting, and folding of Pleistocene strata. Whereas, Pleistocene strata outside the fault zones are subhorizontal or only gently warped (cross sections A–D). It is unlikely that Pleistocene glacial shear caused Quaternary deformation (Johnson and others, 2001; this study) because the local deformation style is consistent with the high-angle deformation observed in the strata near the active fault structures, not thrust-style glacial shear deformation. Also, the deformation in the fault zones is not easily related to deep-seated landsliding—tilted Pleistocene strata are deformed over areas too broad to be attributed to landsliding. Where deep-seated landslides are mapped, disrupted Pleistocene strata have bluff-parallel strikes as a result of slide-block rotation (NT site 1). Further evidence for these faults includes offset stratigraphy and subtle topographic lineaments or risers, particularly for Strawberry Point fault no. 1 (for example, NT sites 2–5). Our subsurface analysis also supports significant Quaternary deformation. For example, data from boring logs demonstrate apparent late Pleistocene to Holocene(?) offset of Strawberry Point fault no. 1 north of Oak Harbor (cross section C, wells B-USGS8 to B-USGS9). Stratigraphic offset between these borings indicates a south-side-up movement consistent with fault offset relations to the east (this study, Johnson and others, 2001). Conversely, offshore seismic reflection data of Johnson and others (2001) from west of the island implies an opposite offset sense for Strawberry Point fault no. 1, suggesting that it may be a scissor fault.

We mapped inferred compressional or transpressional active growth-folds within active fault zones in the map area. Quaternary growth folding is suggested by the reduction of stratal deformation with age and the local occurrence of angular unconformities (particularly between the Whidbey Formation and younger strata). We conservatively show major Quaternary fold axes as concealed by latest Pleistocene and Holocene strata. However, ongoing fold tightening may be occurring near the most active fault structures, particularly those that apparently involve deformation and uplift of Vashon glacial deposits and Olympia beds (cross sections A–D, Fig. 1).

We offer a new geometric arrangement for the Devils Mountain fault zone (DMFZ) in the study area. The main strand of DMFZ in the eastern half of the area is defined by a steep east–west geomagnetic lineament that juxtaposes high magnetic anomalies to the north (Goat Island terrane) with low magnetic anomalies to the south (Tertiary rocks of the Everett basin). However, we contend that the main strand of the DMFZ is directly south of all the geomagnetic highs (see unit $KJmm$ and Johnson and others, 2001). This results in a main strand that parallels Clover Valley, a pronounced east–west topographic feature suggestive of past faulting. An east–west fault in this location is also consistent with our surface and subsurface map data, including the probable vertical juxtaposition of Holocene nearshore deposits with older glacial deposits below the naval air station and other stratigraphic relations across the fault zone (cross sections A–D). South-side-up reverse offset across the DMFZ is also suggested by the offset of the seafloor west of Whidbey Island (Johnson and others, 2001; NT site 13), stratigraphic uplift indicators and earthquake focal location and mechanism data along the DMFZ east of the study area (Dragovich and others, 2003, 2004), and the difference in elevation of Olympia beds (Fig. 1). We also note here that radiocarbon-dated Everson Interstade beach deposits on Hope Island, directly north of the DMFZ and the study area, are anomalously low and may be indicative of an overall northside-down offset of the DMFZ directly north of this broad structural trend (Dragovich and others, 2000d, unpub. data).

We traced the top of the Olympia beds using surface and subsurface mapping. It may be useful as a marker for estimating both the amount and rate of recent deformation (Fig. 1). The local elevation of the Olympia beds suggests substantial uplift across the active fault zones during the last 60,000 years. Most compelling is the interpretation that the local Olympia beds are ancient Skagit River fluvial and deltaic deposits (see units Qc_O and Qc_{ow}). If sea level during this nonglacial interval was below that of the present and this ancient fluvial-deltaic system was graded to sea level (an observation supported by the current geographic and geomorphic position of northern Whidbey Island adjacent to the modern Skagit River delta), then the Olympia beds should have maximum stratigraphic elevations near or below present sea level. The anomalously high Olympia beds are likely the result of tectonic uplift within the Utsalady, Strawberry Point, and Devils Mountain fault zones. Given the geographic position of northern Whidbey Island, it is not likely that local damming or other river-gradient perturbations can explain the anomalous height of the Olympia beds in the study area. One caveat regarding this model pertains to the distribution of Olympia bed ages. It appears likely that growth folding associated with active faults has uplifted older Olympia beds, leaving younger, less deformed Olympia beds at lower altitudes. This suggests an inset relationship between younger and older Olympia beds and topographically inverted stratigraphic ages. South-side-up reverse offset across the DMFZ is further supported by the elevation (above present sea-level) of Olympia beds of 20 to 30 ka age (Sheet 1) relative to elevated 23 ka Olympia deposits south of Clover Valley (^{14}C site 27). Dated wood-bearing silts at this site are interbedded with Skagit River–provenance sands containing significant detrital dacite and crystals of Glacier Peak origin. The elevation of this critical age-date site implies significant uplift of the Olympia beds south of the main strand of the DMFZ during the late Pleistocene and Holocene (Fig. 1).

We offer a few observations related to vertical Holocene tectonism in the map area. First, subsurface data and some surface mapping suggest that estuarine (unit Qn) and shell-bearing beach deposits (unit Qb) have been uplifted in the Holocene (NT sites 6 and 7). Second, geomorphic relations and paleoecology suggest that some marsh (unit Qm) and stump-bearing peat deposits (unit Qp) have been down-dropped in the Holocene (NT sites 8–10). Third, geologic mapping suggests a southerly tilt of some Everson Interstade strandlines (NT site 11). Finally, we note here that Utsalady Point fault no. 4 probably occurs directly north of Polnell Point, as indicated by liqu