# GEOLOGIC MAP OF THE LILLIWAUP 7.5-MINUTE QUADRANGLE, MASON COUNTY, WASHINGTON

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# Geologic Map of the Lilliwaup 7.5-minute Quadrangle, Mason County, Washington

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## INTRODUCTION

The map area straddles Hood Canal north of the 'great bend' in the western Puget Lowland and is predominantly covered by glacial sediment from both alpine glaciers of the Olympic Mountains and continental glaciers coming down out of Canada. This mapping was undertaken to delineate the glacial stratigraphy and hydrologic characteristics of the Hood Canal area for scientists working on the Hood Canal dissolved oxygen problem, and to identify the geologic hazards of the area, including active faults and landslides. Active faults in the Puget Lowland are important and poorly understood. Both the Seattle and Tacoma faults have been traced into this area. Other active faults are known to exist, including the Saddle Mountain faults, Dow Mountain faults, and Lucky Dog structure (Polenz and others, 2010a,b). Massive landslides, such as the Alderwood landslide (Sarikhan and others, 2007), and smaller active slides have damaged property and infrastructure in the area. Debris torrents from the December 2007 storm covered shellfish beds with gravel and damaged and destroyed homes and roads.

Apparent structural complexity at the intersection of the Tacoma fault, Seattle uplift, and Dewatto basin suggests that statements about the depth and character of bedrock beneath the area may be speculative. Jones (1994) estimated unconsolidated sediment thickness above Tertiary bedrock at greater than 600 ft throughout most of the map area, with bedrock outcrops only in the northwest corner of the map. These outcrops of bedrock were mapped by Carson (1976) as Crescent Formation basalt and volcaniclastic sedimentary rock of the Twin River Group(?). Tabor and Cady (1978) later mapped the sedimentary rocks as Lincoln Creek Formation. Logan (2003) correlated these rocks to the Lincoln Creek Formation based on appearance, location, stratigraphic position, and other nearby rocks that were correlated with the Lincoln Creek type section (Rau, 1966, 1967). We continue this assertion based on Logan's work; however, new research casts doubt on previous biostratigraphic age correlations of sedimentary rocks of the Olympic Peninsula and makes this assertion problematic (Liz Nesbitt, Burke Museum of Natural History and Culture, written commun., 2010).

Repeated Pleistocene glacial incursions into the map area deposited most of the unconsolidated sediment. Glacial drift deposited by continental (Cordilleran) glaciers (hereinafter 'northern-source') generally contains abundant clasts of granitic and metamorphic rock. Alpine glaciers of the Olympic Mountains (hereinafter 'Olympic-source') deposited sediment that is rich in clasts of basaltic or volcaniclastic origin. The Cordilleran ice sheet overrode and incorporated sediment shed from the Olympics, resulting in deposits with mixed provenance. Green and Gold mountains, a few miles northeast of the map area, introduced additional basalt to the northern drift (Reeve, 1979; Clark, 1989; Yount and Gower, 1991; Haeussler and Clark, 2000). Further complicating interpretation, the Cordilleran ice sheets deposited northern-source sediment in the foothills of the Olympic Mountains, which mixed with dominantly basalt- and sandstone-rich alpine drift.

A supplemental report (Polenz and others, 2010b) accompanies this map. It contains additional data, descriptions, and discussions pertaining to this map and mapping in the adjacent Skokomish Valley and Union quadrangles completed during the 2009 field season.

## STRUCTURE

### Tacoma Fault and Dewatto Basin

While strands of the Tacoma fault may cross through the map area, and previous mapping by Derkey and others (2009) extends the fault to within 2.5 mi of this quadrangle, direct field evidence of Quaternary faulting was not found in this study. However, deformed glaciolacustrine deposits in the southern portion of the map area may imply tectonic tilting of 9 to 21 degrees to the north. This is consistent with regional tectonic and geophysical models (Blakely and others, 2009; Johnson and others, 2004; Lamb and others, 2009) that indicate that the Dewatto basin exists below the map area. The Tacoma fault may cross the basin or splay northward toward the Seattle fault. Lamb and others' (2009) updated tectonic model includes a queried Tacoma fault continuing west across the southern portion of the map along a very faint east–west magnetic anomaly. The tilted beds may be evidence of deformation and confirm the models. The tilted beds consist of two units of different ages: (1) unit Qpd (Double Bluff?) in the southeastern corner of the map, and (2) unit Qapo in the southwest corner. Unit Qapo is correlated with the reversely magnetized Clark Creek Drift and IRSL samples from it are likely greater than 300 ka (Table 1).

Southeast dips on older Pleistocene glaciolacustrine deposits along the eastern shore of Hood Canal and the sparse (and likely less reliable) southwest-dipping measurements along the eastern edge of the map may support Lamb and others' (2009) folding of the Dewatto basin. However, further age dates and structural analysis are necessary to confirm this, as some dips are shallow enough that they may represent depositional dips, and some southwest dips may not be reliable due to the nature of the deposit (that is, glaciotectonically affected or ice-contact deposits), and they appear to be steeper than those measured by Lamb and others' seismic reflection lines.

### Hood Canal Fault

The Hood Canal fault (Gower and others, 1985) is shown on the map as 'existence questionable, location inferred or concealed'. It was digitized from Lidke and others (2003). We found no convincing evidence for the existence of this fault or fold, but chose to include it based on the work of others, specifically Haug (1998). We suspect that Hood Canal was filled with sediment prior to the Vashon Stade because older units appear continuous across the canal.

## DESCRIPTION OF MAP UNITS

Most of the surficial deposits of the fluted upland are relatively unweathered, but variations in weathering of clasts, both within units and across units are common and increase lower in the stratigraphic section. Weathering and secondary interstitial clay content also tend to increase in coarse-grained units with higher permeability, in sediments derived from the Olympics, and those found either at or beneath paleosols. The weathered units range in color from red to brown and yellowish brown. Some exposures include a mix of unweathered and weathered sediment. Such mixing can result from in-place weathering but also appears to reflect the presence of northern-source clasts alongside proximally sourced clasts of the Olympic Mountains. We attribute the mixing to incorporation of altered sediment previously shed off the Olympic Mountains and ophiolitic Tertiary bedrock from Green and Gold mountains into the northern-source material. While northern-source sediment can thus contain sediment of Olympic provenance, sediment derived from the Olympic Mountains also contains as much as 5 percent northern-source granitic and metamorphic clasts. Because of these relatively subtle distinctions, determining the source of glacial drift was aided by petrographic examination of thin sections. Northern-source drift has a greater abundance of polycrystalline quartz and high-grade metamorphic rocks, whereas drift from the Olympic Mountains is rich in angular sands of plagioclase feldspar, clinopyroxenes, and predominantly monocrystalline quartz (chert or vein filling). Consequently, deposits attributed to northern provenance typically include 5 to 9 percent clasts with a diagnostic Cordilleran provenance, whereas Olympic-provenance rocks tend to

**Table 1.** Age control data. Radiocarbon "greater than" age statements (for example, >43,500 B.P.) include a 2-sigma variance against background radiation. Uncertainty statements reflect random and lab errors; errors from unrecognized sample characteristics or flawed methodological assumptions (for example, $^{14}C$ sample contamination from younger carbon flux; incomplete pre-depositional re-setting of luminescence samples) are not known. $^{14}C$, radiocarbon analysis; IRSL, infrared stimulated luminescence analysis. $^{14}C$ ages stated in ka are in calendar years before 1950. Elevations are in feet (as estimated in this study using Puget Sound Lidar Consortium lidar grid elevations projected to State Plane South, NAD 83 HARN, supplemented by visual elevation estimates on bluffs; lidar elevation statements were not adjusted to account for systematic projection differences relative to base map).

| Age-date site | Site name | Analytical method | Age estimate ($^{14}C$ yr B.P. or ka) | $^{13}C/^{12}C$ (o/oo) | Material dated | Geologic unit | Lab no. | Elev. (ft) | Notes |
|---|---|---|---|---|---|---|---|---|---|
| T455 | Capstan Rock Road | $^{14}C$[1] | >43,100 yr B.P. | -26.2 | peat | Qpd | Beta 272799 | ~347 | Lab cautions that "$^{14}C$ activity was extremely low" and the "most conservative interpretation of age is infinite". |
| T1071 | North Rendsland Creek | $^{14}C$[1] | >43,050 yr B.P. | -28.2 | peat | Qpd | Beta 272800 | ~256 | Lab cautions that "$^{14}C$ activity was extremely low" and the "most conservative interpretation of age is infinite". |
| T1244 | Redbluff | IRSL[2] | >50 ka, but likely much older | – – – | sand from slackwater channel or floodplain | Qapo | T-1244 | ~121 | Sample likely much older (Shannon Mahan, USGS, written commun., 2010), probably >300 ka. This unit was found to be magnetically reversed (Easterbrook and others, 1988). |
| T1245 | Summertide Resort | IRSL[2] | >245 ka, but likely much older | – – – | glacial outwash | Qapo | T-1245 | ~60 | Taken 700 ft south of the map area in the Union quadrangle. Sample likely much older (Shannon Mahan, USGS, written commun., 2010), probably >300 ka. This unit was found to be magnetically reversed (Easterbrook and others, 1988). |

[1] Analysis by Beta Analytic.
[2] Analysis by Shannon Mahan (U.S. Geological Survey).

contain less than 2 percent of those rock types. Deposits with 2 to 5 percent diagnostically Cordilleran-provenance clasts are common and were generally assigned to Olympic- or northern-source units based on stratigraphic field relations rather than lithologic composition.

Nonglacial units are present throughout the map area but are relatively thin and cannot be shown at map scale. There are multiple locations of peat and (or) paleosols that likely represent nonglacial periods. These peats and paleosols can be found at contacts such as the Vashon advance outwash (unit Qga) and underlying Olympic-source drift (unit Qad) contact, which may be evidence of Olympia age or Whidbey Formation deposits. There is also organic material at the contact of pre-Vashon drift (unit Qpd) and Olympic-source outwash (unit Qapo), and there is locally a significant paleosol within unit Qapo that in some places contains organic material. These peats may represent previous interglacial periods and are not broken out as separate units, with the exception of a line unit depicting a paleosol in unit Qapo.

We sought to show deposits that form a sufficiently thick surficial cover to be of geotechnical significance, generally requiring a thickness of at least 5 ft, although where stiff, impermeable, or geotechnically challenging (for example, till or peat), we locally mapped thinner deposits. In most areas, we relied considerably on geomorphology, field relations, or, where available and helpful, subsurface records. We used the Udden-Wentworth scale (Pettijohn, 1957) to classify unconsolidated sediments and estimated consistency and apparent density using suggested guidelines of the American Association of State Highway and Transportation Officials (1988). A U.S. Geological Survey 7.5-minute topographic map was used as a base map, but contact locations other than marine shorelines were generally refined by reference to lidar, aerial photos, and field observations.

## Quaternary Unconsolidated Deposits

### HOLOCENE NONGLACIAL DEPOSITS

ml **Modified land**—Sediment ranging from clay to gravel and diamicton; mixed and reworked by excavation and (or) redistribution that notably modifies topography; shown where relatively extensive, masking underlying geology, and geotechnically significant (>5 ft); excludes roads (except along North Shore Road where significant road building and development has obscured shoreline geology) and abandoned pits where underlying units can be identified.

Qa **Alluvium**—Sand to cobble gravel, locally includes clay and peat; typically gray and generally unweathered; loose; clasts subrounded to rounded; moderately to well sorted; stratified to massively bedded; deposited in stream valleys and estuaries, includes some lacustrine and beach deposits, and may include unrecognized older glacial outwash channels; derived from reworked glacial and nonglacial deposits.

Qb **Beach deposits**—Sand to boulder gravel with shells; gray to brown-gray; clasts typically moderately to well rounded and spherical; may be well sorted; loose; derived from shore bluffs, streams, and underlying deposits. Unit is often too small to show at map scale and unrepresented in favor of mapping more geologically significant units.

Qmw **Mass wasting deposits**—Pebble to boulder gravel and diamicton, with minor sand and gravel beds where modified by stream processes; loose or soft; clasts subrounded to well rounded; poorly to moderately sorted; shown along mostly colluvium-covered slopes and includes debris fans, alluvial fans, and landslides. This unit was mapped along the eastern shore of Hood Canal where debris flows dominate and does not include the unstable area that provided the material. Many mass wasting deposits are too small to be shown at this scale. The unit is mostly Holocene but may include some late Pleistocene deposits.

### HOLOCENE TO LATEST PLEISTOCENE NONGLACIAL DEPOSITS

Qp **Peat**—Organic-rich sediment, including peat, muck, silt, and clay; dark brown to black; very soft to medium soft; typically in closed depressions. Unit Qp includes upland wetland areas and flat surfaces in closed depressions, unless a different unit or standing water was specifically identified (identification of some polygons is therefore tentative) or the deposit was too small to show at map scale. Where field data were unavailable, peat was mapped on the basis of topography, aerial photos, or prior mapping (Washington Department of Natural Resources, GIS soils data layer, 2010). Unit Qp overlies Vashon Drift and is Holocene but may include some late Pleistocene deposits.

Qls **Landslide deposits**—Unsorted mixture of clay, silt, and gravel (diamicton); clasts angular to rounded; loose or soft; unsorted to poorly sorted and nonstratified, but may locally retain primary bedding; includes exposures of underlying units in scarp areas. Absence of a mapped slide does not imply absence of sliding or hazard, as some slides are too small to show at map scale. Many previously mapped slides were not included in order to show underlying geology or because of lack of evidence of movement or different interpretation of landforms. It is difficult to distinguish landslides from slumped features in ice-contact deposits (unit Qgic). An example of this is at the mouth of the Dewatto River—on the south side is a feature made of ice-contact deposits that may not be a landslide but is conservatively mapped as one. Also not shown are the numerous debris flow chutes evident in lidar (light detection and ranging). This unit is mostly Holocene but may include some late Pleistocene deposits.

Qaf **Alluvial fan deposits**—Debris-flow diamicton and alluvial sand and gravel; gray, weathering to brownish-orange; loose; clasts subrounded to rounded; typically poorly to moderately sorted and massive to weakly stratified; forms concentric lobes where streams emerge from confining valleys and reduced gradient causes sediment load to be deposited. Unit Qaf is predominantly Holocene but likely includes some late Pleistocene deposits. Debris flow and debris torrents may be a geologic hazard on some alluvial fans. The December 2007 storms added northern-source material to most fans in the area. These deposits damaged homes and infrastructure and covered beaches and shellfish beds.

## PLEISTOCENE GLACIAL DEPOSITS

### Recessional deposits of the Vashon Stade of the Fraser Glaciation (northern source)

Mapped deposits of the Vashon Stade of the Fraser Glaciation include units Qga, Qgt, Qgo, and Qgic. The basal part of the advance outwash locally consists of advance glaciolacustrine silts with dropstones and diamicton and grades to sandy gravel beneath Vashon till (unit Qgt) or stagnant-ice sediment and outwash deposits. The base of unit Qga may actually be older than Vashon age and include thin deposits at least as old as Olympia age, based on new $^{14}C$ age dates (Table 1), but at the time of mapping it was mapped as Vashon advance outwash.

Haugerud (2009a,b) noted that deglaciation at the end of the Vashon Stade in the southern Puget Lowland probably began with stagnation of the ice sheet, which resulted in preservation of subglacial drainage features. This is consistent with this map and recent mapping by Polenz and others (2009a,b) and Derkey and others (2009) in adjacent and nearby quadrangles that shows stagnant-ice features throughout the map areas.

Qgo **Vashon recessional outwash (late Pleistocene)**—Fluvial cobble to pebble gravel and pebbly sand and minor silt beds; gray, weathering to tan; clasts rounded to subangular, from both northern and local sources; loose and generally less compact than advance outwash (unit Qga); moderately to well sorted; crudely stratified beds typical; few feet to tens of feet thick; stratigraphically above Vashon till (unit Qgt). Unit Qgo was deposited by glacial meltwater in outwash channels or isolated basins on the fluted upland surface, but some deposits are ice-proximal and difficult to separate from unit Qgic, resulting in gradational boundaries between units Qgic and Qgo.

Qgic **Vashon ice-contact deposits**—Cobbly pebble gravel, diamicton, silty sandy till (between flutes on upland surface), silty pebbly gravel, and pebbly sand, with lesser sand and silt; yellow-tan to gray; clasts subangular to rounded; loose to very dense; variably sorted; massive to well stratified; formed in the presence of meltwater alongside, in, on, or above ice. Unit Qgic includes steeply dipping beds that typically reflect sub-ice flow, but their dip and small-scale shears may have developed as collapse features or due to glaciotectonic deformation such as ice shove or melting of ice buttresses. Ice-contact deposits are accompanied by stagnant-ice features, such as kettles, hummocky topography, eskers (separately mapped as unit Qge where distinct), and subglacial or subaerial outwash channels. Where mapped between fluted topography that lacks more recognizable stagnant-ice features, unit Qgic is commonly a friable melt-out till, includes poorly consolidated till with lesser amounts of fines sediment, and is commonly accompanied by underlying sand noted as "sub-glacially reworked till" by Laprade (2003) (see unit Qgo and Polenz and others, 2010b). Unit Qgic ranges in thickness from a few feet (common where mapped on upland surfaces between drumlins) to a few hundred feet along the flanks of large basins, where it forms kame terraces. Unit Qgic is mapped within troughs and low-lying areas of the uplands throughout the map area, in the drainages of the Dewatto River, Rendsland Creek, Lilliwaup Creek, Eagle Creek, and Tahuya River, and along Hood Canal. Although it is not thick enough to show at map scale, there may be a bed of lodgment till under unit Qgic. Previous geological mapping showed these deposits as large landslide complexes north of the mouth of the Dewatto River (O'Neal, 2004) and along the western shore of Hood Canal, including the drainages of Eagle and Lilliwaup Creeks (Carson, 1976). Some landslides do occur in this unit (typically where underlain by lacustrine deposits or where dip-slope contacts occur), but not all features that have landslide geomorphology are active. Locally divided into:

Qge **Vashon esker deposits**—Gravel and sand; tan to brown; clasts moderately to well rounded; loose; typically well sorted; high porosity and permeability; forms low, elongate, sinuous hills; deposited subglacially or englacially by Vashon meltwater in areas occupied by stagnant ice; mapped in adjacent quadrangles (Polenz and others, 2009a,b, 2010a; Derkey and others, 2009).

Qgik **Vashon kame deposits**—Gravel and sand; yellow-gray; clasts rounded; loose; moderately to well sorted; moderately to well stratified; medium to very thickly bedded or massive; commonly contain localized delta foreset beds, crossbedding, cut-and-fill structures, and oversteepened or slumped bedding. Because the unit drapes older topography, determining unit thickness is difficult, but some areas reach a thickness of more than 300 ft. Stagnant ice occupied the Hood Canal during ice recession, resulting in perched ice-contact deposits, including kames, veneering parts of the valley walls.

**Advance Proglacial and Subglacial Deposits of the Vashon Stade of the Fraser Glaciation**

Qgt **Vashon lodgment till**—Mixture of sand, pebbles, cobbles, silt, and clay (diamicton); gray, weathering to yellow-orange; clasts subangular to rounded, from both northern and Olympic sources, striation and faceting common; very compact; unsorted and unstratified; may contain angular clasts where directly overlying local bedrock. Lodgment till is typically supported by a sandy-silty matrix and is unweathered, but near the surface is slightly oxidized and jointed as a result of weathering and desiccation. It is typically covered by 1 to 6 ft of loose ablation till or rounded outwash gravel. Some exposures include beds and lenses of sand and gravel, locally with an ice-shear foliation. Unit Qgt thickness ranges from 1 to 20 ft, but is commonly less than 5 ft thick. Till typically comprises the fluted upland surfaces. Individual drumlins measure 0.1 to 0.3 mi wide by 0.5 to 1.3 mi long, with the long axis aligned with the direction of ice flow. Unit Qgt is typically in sharp, unconformable contact with underlying units, most commonly advance outwash gravels (unit Qga). Unit Qgt may include unrecognized exposures of older till.

Qga **Vashon advance outwash**—Gravel, sand, silt, and dropstone diamicton; gray to tan, with some orange oxidized zones; clasts well rounded, northern source; mainly well sorted; stiff or dense; typically stratified; typically thinly to very thickly bedded; contains planar, graded beds, cut-and-fill structures, and crossbeds; thickness 100 to 200 ft, average 150 ft. The base of unit Qga contains glaciolacustrine silt, sandy silt with scattered dropstones, and beds of massive diamicton 20 to 40 ft thick throughout the map area, and is prone to mass wasting. The base may include older deposits at least as old as Olympia age and discontinuous alpine drift that is not shown. Unit Qga is typically overlain by unit Qgt along a sharp, unconformable contact.

**Pre-Vashon Glacial Deposits**

Prior to the Vashon Stade of the Fraser Glaciation, both Cordilleran and Olympic glaciers deposited sediment in the map area. We obtained a few Infrared Stimulated Luminescence (IRSL) and Carbon 14 ($^{14}C$) age dates, but were largely unable to constrain the ages of the units. Previous mapping suggests that stratigraphic relations are important, because it is difficult to determine age using weathering alone (Deeter, 1979). We used advance glaciolacustrine silts of the Vashon Stade (or possibly older) as a stratigraphic marker to differentiate between Vashon and older drifts. At the contact of the silts and the older northern drift (likely Double Bluff) are discontinuous peat layers, which when analyzed were radiocarbon infinite (see age dates T455 and T1071 in Table 1).

We tentatively correlate the oldest glacial deposits with the Annas Bay and Clark Creek Drifts (Easterbrook and others, 1988). They consist of an alpine till (unit Qapt) on the east side of the canal at the north end of the map and unit Qpu, not exposed in the map area but shown in the cross section. Unit Qapt is tentatively correlated with the reversely magnetized Clark Creek till found at Capstan Rock (~0.4 mi north of the map boundary along the east side of Hood Canal). We also speculate that the glaciolacustrine silts (unit Qpl) deposited on Crescent basalts near Lilliwaup correlate with the Annas Bay Drift, but they could be significantly younger. Unit Qpl could not be constrained in age by stratigraphic relationships, because contacts were obscured by more recent glaciations. R. J. Carson (Whitman College, unpub. report, 1980) draws similar conclusions.

Qad **Uppermost Olympic-source drift, undivided**—Outwash consisting of sandy pebble gravel, till, and diamicton; light brown to buff; clasts rounded to angular, dominated by basalt and sandstone (>95%) from core and peripheral rocks of the Olympic Peninsula; well sorted to unsorted; compact. Sands are predominately pyroxene and monocrystalline quartz, but include basalt and sandstone clasts. These largely unweathered deposits overlie pre-Vashon northern-source drift (unit Qpd) and underlie Vashon glacial deposits (units Qga and Qgt). Unit Qad is found in discontinuous exposures along the eastern and northern shores of Hood Canal, mapped only where large enough to show at map scale. Unit Qad extends as far east as the east side of the Tahuya River in the Union quadrangle. We concur with Jessica Hellwig (Univ. of Illinois at Urbana-Champaign, written commun., 2010) that the deposits are older than Evans Creek Drift of the Fraser Glaciation and likely from a mid-Wisconsinan alpine glaciation or glaciations. A $^{14}C$ age from peat below an exposure of this unit north of Rendsland Creek is radiocarbon infinite, meaning it is too old to be reliably dated by the radiocarbon method (Table 1, age-date site T1071).

Qpd **Pre-Fraser northern-source drift, undivided**—Gravel, sand, till, and diamicton; tan to orange-brown; clasts well rounded to angular; compact; varies from well sorted sand and gravel outwash to poorly sorted diamicton. Outwash gravels typically have an orange-brown iron-oxide staining or cementation. Tills are typically lightly weathered. Sand grains are variable but diagnostically include granitic and metamorphic rocks of northern origin. Compared to Olympic-source glacial deposits, unit Qpd contains more polycrystalline quartz sand and granitic and metamorphic clasts and fewer pyroxene and monocrystalline quartz sands and basalt and sandstone clasts. Unit Qpd is 125 to 170 ft thick, overlies unit Qapo, and is overlain by a discontinuous paleosol with organic fragments and laminated clay and silt. Throughout the map area, unit Qpd occurs either directly under Vashon advance glaciolacustrine deposits (unit Qga) or under undivided pre-Vashon alpine drift (unit Qad). Although absolute age constraints are poor, we tentatively concur with Deeter (1979), who maps deposits of similar stratigraphic position and weathering as Double Bluff Drift.

Qapd **Pre-Vashon Olympic-source drift, undivided—**Undifferentiated glacial outwash and till (silt to boulder gravel); orange-brown to gray; outwash gravels appear weathered, but till appears unweathered; clasts subangular to rounded, primarily basalt and sandstone from peripheral and core rocks of the Olympic Peninsula; compact; outwash deposits moderately to poorly sorted; at least 100 ft thick, but full unit thickness not entirely exposed. Unit Qapd is found in discontinuous exposures along the northern shores of Hood Canal at the southern map boundary and extends east of the Tahuya River in the Union quadrangle. It was deposited as glacial outwash and till in an ancestral Skokomish River valley. Unit Qapd appears to be under pre-Vashon northern-source drift (unit Qpd). Where exposed near Summertide Resort in the Union quadrangle (Polenz and others, 2010a), the unit has an alpine till top and bottom; elsewhere we only found only one till at its base. Sample T1245 (Table 1), taken from outwash in the Union quadrangle, is older than 245 ka. We speculate that unit Qapd can be broadly correlated with the magnetically reversed Clark Creek Drift (Easterbrook and others, 1988).

Qapo **Pre-Fraser Olympic-source outwash**—Sandy pebble gravel and cobble gravel, with minor interstitial alteration clay and minor beds of sand and paleosols; orange-brown with buff interstitial clay; clasts mostly subrounded, primarily Crescent Formation basalt and sandstone (~95%) with minor weathered granitic and metamorphic clasts (<5%); dense; predominately poorly stratified to massive and poorly to moderately sorted. Unit Qapo varies from moderately weathered to saprolitized. It is fully exposed at the top of the map on the east side of Hood Canal, where it is approximately 350 ft thick. It is also well exposed on the eastern shore of Hood Canal, along the Tahuya peninsula, and in limited exposures north of Lilliwaup and south of Miller Creek. It is conformable on the alpine till (unit Qapt) and lies beneath unit Qpd. A brick-red paleosol up to 7 ft thick separates older, more weathered outwash from younger outwash in the north-central part of the map and is depicted by a line on the map where the location is well constrained. This paleosol dips 4 degrees to the southeast at the mouth of the Dewatto River (south side, in exposures along Dewatto Bay Road). Other paleosols are poorly exposed and thus not shown on the map. Overall, unit Qapo dips gently to the southeast (4–5°) along the eastern shore of the canal in the northern and central portions of the map. This tilting may reflect tectonic deformation or be a result of primary deposition. At the bottom of the map, unit Qapo dips to the north near the mouth of Rendsland Creek, where rhythmically bedded sands and silts dip 9 to 19 degrees. This unit is interpreted as an outwash deposit because (1) there is sparse alpine till associated with this deposit, (2) it is poorly sorted, (3) there are occasional layers of boulders, and (4) it is widely deposited throughout the quadrangle so that proximal alpine glaciers are required as a sediment source. We suspect that unit Qapo represents multiple alpine glaciations because of the widespread occurrence of intraformational unconformities (paleosols) and association with underlying alpine tills at two locations. These tills are exposed at the top of the map on the east side of Hood Canal (unit Qapt) and in unit Qapd in the ditch east of Summertide Resort, just south of the map border in the Union quadrangle. Unit Qapo is susceptible to mass wasting in drainages where the upper 10 to 15 ft tend to weather and lose strength. A sample (Table 1, age-date site T1244) taken from between the Dewatto River and Rendsland Creek is >50 ka. A sample (Table 1, age-date site T1245) from a correlative unit (Qapd), taken just outside the map area in the Union quadrangle, is older than 245 ka. Both samples are likely much older than 300 ka (Shannon Mahan, USGS, written commun., 2010). This unit is correlated with Carson's Clark Creek Drift in Easterbrook and others (1988), where it was found to be magnetically reversed. We also speculate that unit Qapo may be correlated with parts of unit Qpu$_{op}$ in the Union and Skokomish quadrangles (Polenz and others, 2010a).

Qapt **Pre-Fraser Olympic-source till**—Nonstratified, unsorted mixture of pebbly silt and diamicton; brown-gray and orange-brown; clasts rounded to subangular, commonly faceted, either basalt or sandstone (exclusively) derived from the Olympic Mountains; very dense, massive and matrix supported; commonly in 3 to 10 ft thick layers of lodgment till. Unit Qapt crops out on the eastern shore of Hood Canal at the top of the map. It appears to be stratigraphically under unit Qapo. Outcrops of pre-Fraser alpine till at the bottom of the map are included in unit Qapd because they were too small to show at map scale and may be younger. Unit Qapt may be correlated with Carson's Clark Creek Drift (Easterbrook and others, 1988), which was found to be magnetically reversed.

***Pre-Fraser northern-source glacial and nonglacial deposits***

Qpl **Pre-Fraser fine-grained glaciolacustrine sediments**—Silt and fine sand; light buff, gray when wet; clasts subangular to rounded; well sorted; dense; typically thinly bedded to thickly laminated with a pervasive set of near vertical joints. Well logs and exposures suggest that unit Qpl is as much as 300 ft thick. Unit Qpl is exposed in the northwest quarter of the map near Lilliwaup. Due to draping of younger units, stratigraphic relationships could not be precisely determined, so this unit could be much younger and might be of Vashon age.

Qpu **Pre-Fraser sediments, undivided (cross section only)**—Composite unit of glacial and nonglacial sediments below unit Qapt; not exposed in map area; likely contains northern-source sediment of Carson's Annas Bay Drift (Easterbrook and others, 1988) and other sediment.

## Tertiary Sedimentary and Volcanic Rocks

ΦEm$_{lc}$ **Lincoln Creek Formation(?) (Oligocene to Eocene)**—Marine tuffaceous siltstone, sandstone, and feldspathic sandstone; light gray to dark olive-gray; fine- to coarse-grained; clasts subangular; moderately to poorly sorted; indistinctly bedded to massive. The siltstone outcrops typically have hackly joints and exhibit onion-skin weathering. Unit ΦEm$_{lc}$ was deposited unconformably on the Crescent Formation (unit Ev$_{c}$). It is exposed near the center of the western border of the map. At the type section, the Lincoln Creek Formation is estimated to be about 2500 ft thick (Beikman and others, 1967). It was deposited in an offshore marine environment and contains foraminiferal faunas referable to the Refugian and Zemorrian Stages (Rau, 1966, 1967). Alternatively, this unit might be correlated with the Blakeley Formation.New research suggests that previous biostratigraphy on the Olympic Peninsula may need to be reexamined (Liz Nesbitt, Burke Museum of Natural History and Culture, written commun., 2010). More work is needed to sort this out.

Ev$_{c}$ **Crescent Formation (lower to middle Eocene)**—Basalt; black to greenish black in unweathered exposures, gray and medium yellow-brown in weathered exposures; commonly occurs as fine- to coarse-grained blocky sills and submarine or possibly subaerial flows that commonly include amygdules of zeolite and chlorite-group minerals. Flows are locally pillowed and fine grained and include palagonitized breccias. Mineralogy typically includes plagioclase with intergrowths of augite and disseminated opaque minerals. Replacement of interstitial glass by chlorite and oxidation products is also common. Unit Ev$_{c}$ appears in gorges in the northwest corner of the map. It contains rare interbeds of laminar basaltic siltstone or fine sandstone with foraminiferal faunas referable to the Ulatisian Stage (Rau, 1981).

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