GEOLOGIC MAP OF THE QUILCENE 7.5-MINUTE QUADRANGLE, JEFFERSON COUNTY, WASHINGTON

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WASHINGTON STATE DEPARTMENT OF
Natural Resources
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INDEMNIFICATION

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WASHINGTON STATE DEPARTMENT OF NATURAL RESOURCES

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Geologic map of the Quilcene 7.5-minute Quadrangle, Jefferson County, Washington

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INTRODUCTION

The map area is located in the western Puget Lowland at the base of the Olympic Mountains on the Olympic Peninsula. It includes the eastern portion of the community of Quilcene and contains Dabob and Quilcene Bays on Hood Canal (Fig. M1 on map sheet). Most of the map area is covered by Quaternary sediment, including sediment deposited by the Puget lobe of the Cordilleran ice sheet, which advanced from Canada several times during the Pleistocene Epoch. Also included is sediment deposited by alpine glaciers of the Olympic Mountains and nonglacial sediment deposited during interglacial periods. The western half of the map area has outcrops of Tertiary basalt and sedimentary rocks.

Previous researchers have mapped multiple aspects of the geology of this region, including geologic units (Birdseye, 1976a; Hanson, 1976; Tabor and Cady, 1978; Yount and Gower, 1991; Yount and others, 1993), sedimentary bedrock biostratigraphy (Hamlin, 1962; Spencer, 1983a,b; 1984), and hydrogeology (Grimstad and Carson, 1981; Simonds and others, 2004). Previous studies have also documented the glacial recessional lake history of the area (Bretz, 1913; Thorson, 1989). Both Bretz (1913) and Carson (1980) suggested deformation on the Bolton and Toandos Peninsulas. Beale (1990) studied relative sea level rise in the area to determine the post-glacial tectonic activity.

As indicated by these works and the current study, the map area is seismically active and structurally complex. Segments of many intersecting faults have been mapped in or near the area. These faults include the Dabob Bay fault zone, the questionable Hood Canal fault, and the Seattle Fault to the southeast (Blakely and others, 2009; Polenz and others, 2013; Lamb and others, 2012)(Fig. M1). Geophysical models by Lamb and others (2012) and Blakely and others (2009) suggest that the Seattle fault zone extends across Hood Canal south of the map area and connects with the Dabob Bay and Saddle Mountain fault zones (along the eastern edge of the Olympic Mountains). The map area also contains other large-scale structural features, including the Olympic–Wallowa lineament (OWL), mapped by Raisz (1945) through the northern half of quadrangle, and the Kingston arch, an anticline that trends toward the northern half of the quadrangle. In the northwest portion of the map area, previous mapping by Yount and Gower (1991) suggests an east-plunging anticline where Pratt and others (1997) and Brocher and others (2001) map the Seattle basin; how these faults and structures interact is not well understood.

In addition to this large-scale deformation, geomorphic benches and scarps, as well as buried tree stumps and accumulations of boulders along the shores of Dabob and Quilcene Bays, indicate historic mass-wasting events along steep coastal bluffs. Landslides are common and continue to damage property and infrastructure in the area, particularly along these erodible shorelines. Many of these slides initiate in the silts and clays of the Olympia and Whidbey nonglacial intervals.

This mapping was undertaken to identify the area's geologic hazards, including active faults and landslides, in greater detail and to delineate the glacial stratigraphy and hydrologic characteristics of the area. These new data and interpretations are intended to assist local government, property owners, and scientists working on the problem of low concentrations of dissolved oxygen in Hood Canal.

Throughout the text, we refer to significant sites numbered S1 to S9 (see Table C1), indicated by orange diamonds on the map. Many of these sites are connected with additional data found on the map sheet or in the appendices, including radiocarbon (14C) and infrared stimulated luminescence (IRSL) dates (Table M1 on map sheet) and passive seismic soundings (Appendix D). Water well or boring logs that were used to inform this

mapping project are depicted on the map as gray circles labeled W1 to W72. They can be cross referenced with Washington State Department of Ecology (WADOE) well tags in Table M2 on the map sheet.

GEOLOGIC OVERVIEW

Bedrock units in the southwestern portion of the map are dominantly submarine or subaerial basalt flows, breccia, and minor sedimentary interbeds of the Eocene Crescent Formation (Arnold, 1906). The basalt flows were erupted approximately 50.5 ±1.6 Ma from a rift along the continental margin and then accreted to the continent (Hirsch and Babcock, 2009; Babcock and others, 1992). The Crescent Formation is overlain and locally interfingers with sediments of the Aldwell Formation (Spencer, 1984; Yount and Gower, 1991). These formations are heavily faulted and deformed. In the northwest corner of the map area, along Center Road, sandstone and interbedded siltstone of the overlying sandstone of Snow Creek (Spencer, 1984) are well exposed. Mudstones of the Townsend Shale (Durham, 1944) are exposed along Tarboo Creek and Tarboo Bay in the north-central portion of the map and at the southwest tip of the Bolton Peninsula. The exposures on the Bolton Peninsula are strongly faulted and deformed; outcrops are characterized by abundant calcareous concretions containing glendonite crystals. Glendonite crystals, a calcite replacement of the mineral ikaite, form in alkaline marine settings at near-freezing temperatures and indicate that this locality is a fossilized methane seep (Elizabeth A. Nesbitt, Burke Museum of Natural History, written commun., 2014, and Nesbitt and others, 2013).

Above the Tertiary bedrock, the geology consists of sediment deposited by rivers draining the Olympic and Cascade mountain ranges during nonglacial intervals and by glacial drift from both Olympic and Cordilleran glaciers that advanced during the Quaternary period (the past 2.6 million years). Most of this unconsolidated material is likely less than 1 million years old.

Previous work described the Pleistocene stratigraphy in the map area and provided subsurface information relating to groundwater (Bretz, 1913; Birdseye, 1976a,b; Grimstad and Carson, 1981; Hanson, 1976, 1977; WADOE, 1978; Yount and others, 1993). These authors documented thick sequences of nonglacial fluvial and lacustrine deposits interbedded with glacial drift from both Olympic and Cordilleran glaciers.

In many of the exposed glacial units, general sediment provenance can be determined by lithologic characterization of clasts. To the west, the Olympic Mountains are primarily basalt of the Eocene Crescent Formation overlain by Eocene to Oligocene sandstone and siltstone. North of the map area, the bedrock of the North Cascades and British Columbia is a variety of volcanic, granitic, and metamorphic rocks. Based on these distinctly different basement lithologies, we broadly classify the various drifts as 'Olympic-sourced' or 'northern-sourced'. Drift deposited by alpine glaciers of the Olympic Mountains contains basalt and sandstone with rare phyllite and reworked granitic and metamorphic clasts; northern-sourced drift, deposited by the Cordilleran ice sheet, generally contains abundant granitic and high-grade metamorphic clasts. However, northern-sourced drift in the map area may also contain abundant locally derived basalt clasts because the Cordilleran ice sheet incorporated sediment shed from the Olympic Mountains before depositing material in the Olympic foothills.

Nonglacial deposits are distinguished primarily by the presence of organic matter, a higher degree of sorting throughout, and ages coincident with inferred nonglacial intervals (Fig. M2 on map sheet). While some nonglacial units contain alluvium that was likely eroded in part by alpine glaciers and their meltwater, the Puget Lowland was ice-free at the time of their deposition. A modern example of this process southwest of the Quilcene quadrangle is the sediment deposited into Hood Canal by the Dosewallips River (Fig. M1), which includes a minor amount of sediment derived from the Eel Glacier. Although this sediment came from an alpine glacial setting, it is being deposited in the Puget Lowland during a nonglacial interval.

Figure M2 depicts the glacial history of the Puget Lowland and related Marine Isotope Stages (MIS) using variations in the ratio of 18O/16O. This ratio is used to differentiate between warm and cool climatic intervals and thus the changes in climate over the past 800,000 years. We refer to the various marine isotope stages in our discussion and description of the geologic units.

POSTGLACIAL LANDFORMS

Landslides

Unstable slopes are prevalent along Hood Canal where shoreline processes erode and undermine over-steepened bluffs. Slope instability is also increased where relatively impermeable beds of silt and clay perch water above the main water table; the perched water contributes to landslides by adding weight and reducing the strength of the

unconsolidated sediment. The nonglacial Whidbey Formation and Olympia deposits (units Qc_W and Qc_O) often contain layers of clay and silt that prevent water drainage. These units also contain thick sequences of well-sorted, unconsolidated sands that lose strength when saturated. Since 1997, significant damaging landslides have occurred east of Red Bluff on the Bolton Peninsula (significant site S8, sec. 32, T27N R1W), creating large translational slides that appear to have failed within the nonglacial deposits. In 2009, one such slide compromised a home above the bluff. The home was built on pre-Vashon glacial till, which is generally assumed to be stable. However, it appears that the top of the underlying nonglacial deposits provided a slip surface for the till to slide over the face of the bluff.

Birdseye (1976a,b), WADOE (1978), and Ana Shafer (Wash. Dept. of Natural Resources, unpub. database, 2012) identified numerous landslides along the bluffs of Hood Canal. We have mapped three main areas as landslides along the shoreline, based on morphology and signs of instability observed in the field and in historic photos. These areas are the south end of the Bolton Peninsula and the east and northwest shores of Dabob Bay; all appear to fail in and upon fine-grained nonglacial sediments. There are other smaller landslides outside these three main areas. Additionally, there are undoubtedly unmapped landslides and areas prone to mass wasting in unit $Qgic$ between the uplands and Hood Canal throughout the map area. Due to the hummocky nature of both landslides and stagnant-ice deposits, we were occasionally unable to differentiate between the two. Where we had additional information suggesting instability, we mapped the features as landslides.

We have mapped unit Qmw in many drainages surrounding Dabob Bay where it appeared that material had moved downslope and been deposited in drainages graded to a base level approximately 100 to 200 ft above modern sea level. We suspect that much of this material was deposited at the end of the Fraser Glaciation, but some deposits may be younger. We were unable to differentiate the modern mass-wasting deposits from relict deposits. Because unit Qmw is made of unconsolidated material derived from the surrounding hillslopes, we mapped it all as mass-wasting deposits, even though much of it may not be active.

Based on the proximity to active faults and the presence of stratigraphy conducive to liquefaction, additional slope failure and modification of the topography likely occurred during past earthquakes. However, determining the nature and origin of individual landforms is beyond the scope of this project; site-specific analysis is required to adequately assess slope stability.

Nonglacial Sand Deposits

Extensive sand deposited during the Olympia nonglacial interval (unit Qc_O) and reworked by glacial recessional meltwater and modern stream and beach transport provides abundant sediment to beaches along the northern shores of Hood Canal. This sand is easily eroded from cliffs and bluff and continuously replenishes the extensive sandy beaches within the Quilcene quadrangle. This contrasts with the predominantly gravelly beaches encountered along the southern Hood Canal (Contreras and others, 2012a,b; Polenz and others, 2013, 2012a,b. In many places along the bluffs of Dabob Bay, exposures of nonglacial sand with interbedded silt extend from sea level to 400 ft elevation. In previous studies, these exposures were generally mapped as advance deposits of the Vashon Glaciation (Birdseye, 1976a; Yount and others, 1993), however, age data from this mapping and adjacent mapping suggests that this sand was deposited during nonglacial intervals. This interpretation isn't universal because there is a change in age of deposits directly under the Vashon Till between this quadrangle and the northern end of the adjacent Center quadrangle. Polenz and others (2014) provided age data from sand deposits below the Vashon Till that coincide with ages expected from Vashon advance deposits. (See additional information under Pre-Fraser Glacial and Nonglacial Deposition.)

STRUCTURE

Determining precisely how the Seattle, Hood Canal, Dabob Bay, and southern Whidbey Island fault zones interact is impeded by dense vegetation, thick cover of glacial and nonglacial deposits, and relatively minor changes in geophysical properties. This map provides additional field evidence for the Dabob Bay fault zone and its possible connection with the Bon Jon Pass fault zone (Tabor and others, 2011; Haugerud and Haeussler, 2000) to the northwest at locations along the Olympic–Wallowa lineament (Fig. M1). Observed fault orientations and kinematic information generally fit with regional stress regimes expected for the area—southwest–northeast to north–south compression (McCaffrey and others, 2007). We observed northwest-trending right-lateral faults and east–west-

oriented folds, faults, and joints, suggesting north–south compression with a component of dextral transpression as observed and discussed in the adjacent Seabeck and Poulsbo quadrangles (Polenz and others, 2013).

To supplement the structural data obtained through geologic mapping, we plotted and interpreted seismic lines in Dabob Bay published by Dadisman and others (1997). The locations of these lines are depicted on the map by solid purple lines south of the Bolton Peninsula. The seismic profiles show complex structures in the Tertiary bedrock, and thus the map likely underestimates the structural complexity of the area. Using the regional stress regime as a framework, we interpreted the structural geology by incorporating both field observations and the data provided by the seismic profiles.

Olympic–Wallowa Lineament

The Olympic–Wallowa lineament (OWL), first described by Raisz (1945), is a 400-mi-long structural feature that trends northwest–southeast from Cape Flattery to the Wallowa Mountains. There is much debate as to what the lineament represents (Mann and Meyer, 1993; Mann, 1994; Reidel and Tolan, 1994). Raisz (1945, p. 481) noted that the OWL passes through the north and central portion of the map area at a "little sink hole two miles north of Quilcene." This site is presumably Rice Lake along the western map boundary (significant site S1, sec. 12, T27N R2W). Raisz suggested that the lineament may continue to the southeast across the northern Bolton Peninsula and Dabob Bay to the Toandos Peninsula shoreline at Camp Discovery. He also stated that the track of the lineament continued to the southeast of the map area across Bainbridge Island toward Seattle. Although we cannot directly connect the lineament to faulting in the Quilcene quadrangle, Haeussler and others (1999) and Tabor and others (2011) mapped the Bon Jon Pass fault as a right-lateral fault zone in the Uncas quadrangle northwest of the map area (Fig. M1). Haugerud and Haeussler (2000) also suggested that a right-lateral gouge zone in this area indicates the presence of a fault along the northwest-trending Little Quilcene River, which is on or near the line of the OWL.

We did not find any kinematic indicators in the north end of the map area to suggest that the OWL continues southeastward as a right-lateral fault system; however, we infer that the right-lateral faults mapped as the Bon Jon Pass and the Little Quilcene faults continue along the trajectory that Raisz suggested for the OWL. The inference is based on magnetic anomalies (Richard Blakely, U.S. Geological Survey, written commun., 2013) that roughly correlate with the absence of sedimentary bedrock exposures south of the fault along Dabob Bay. We depict these faults on the map as concealed, queried, right-lateral faults extending from Rice Lake toward Camp Discovery. We also infer a fault with a similar orientation at significant site S2 (northeastern Bolton Peninsula, sec. 17, T27N R1W), where (1) sedimentary bedrock exposures end abruptly and are deformed, and (2) the fault appears to deform sand of the Whidbey Formation. We map this fault across Dabob Bay to where we found deformed Whidbey Formation deposits in the bluffs northeast of photo site P1 (sec. 15, T27N R1W; Fig. 1). We infer that this fault folded and shifted bedrock down to the southwest, based on the lack of bedrock exposed to the south.

Dabob Bay Fault Zone

The Dabob Bay fault zone (DBFZ) was proposed by Blakely and others (2009), who noted "possible en echelon faults through Dabob Bay" based on geophysical anomalies and structural models for the area. Polenz and others (2013) found exposures and geophysical evidence of this right-lateral fault zone and continued it across the Toandos Peninsula toward the southwest corner of this quadrangle. The fault zone is expressed as a wide zone of dominantly high-angle right-lateral faults that suggest a positive flower structure on the Toandos Peninsula. Movement along these faults appears to have sheared volcanic and sedimentary bedrock on the Bolton Peninsula and at the base of Mount Walker (Fig. M1). Between Fishermans Point and Frenchmans Point, the fault zone appears to have sheared and juxtaposed sedimentary bedrock of the Aldwell Formation with younger Townsend Shale, omitting the section of Lyre Formation exposed farther northwest. Exposures of bedrock on both sides of Quilcene Bay are structurally complex, with wide zones of fault gouge within northwest-striking right-lateral faults and east–west-striking reverse faults. The relief between Mount Walker and the bottom of Quilcene Bay—as much as 240 ft—between these two areas suggests that the bedrock at this site was more susceptible to excavation by glacial processes than the surrounding bedrock, further strengthening our interpretation of a fault zone in this area. We infer that the northwest-striking fault zone in the southern half of the quadrangle continues to the northwest and steps north along locations coincident with the OWL. This step-over appears to have created a pull-apart basin (see Mann and others, 1983) between these right-lateral faults on the Bolton Peninsula; bedrock is absent along the shoreline, in subsurface wells, and geophysical soundings (Table M2 and HVSR sites 1, 3, and 4 on map sheet; Table D1). The
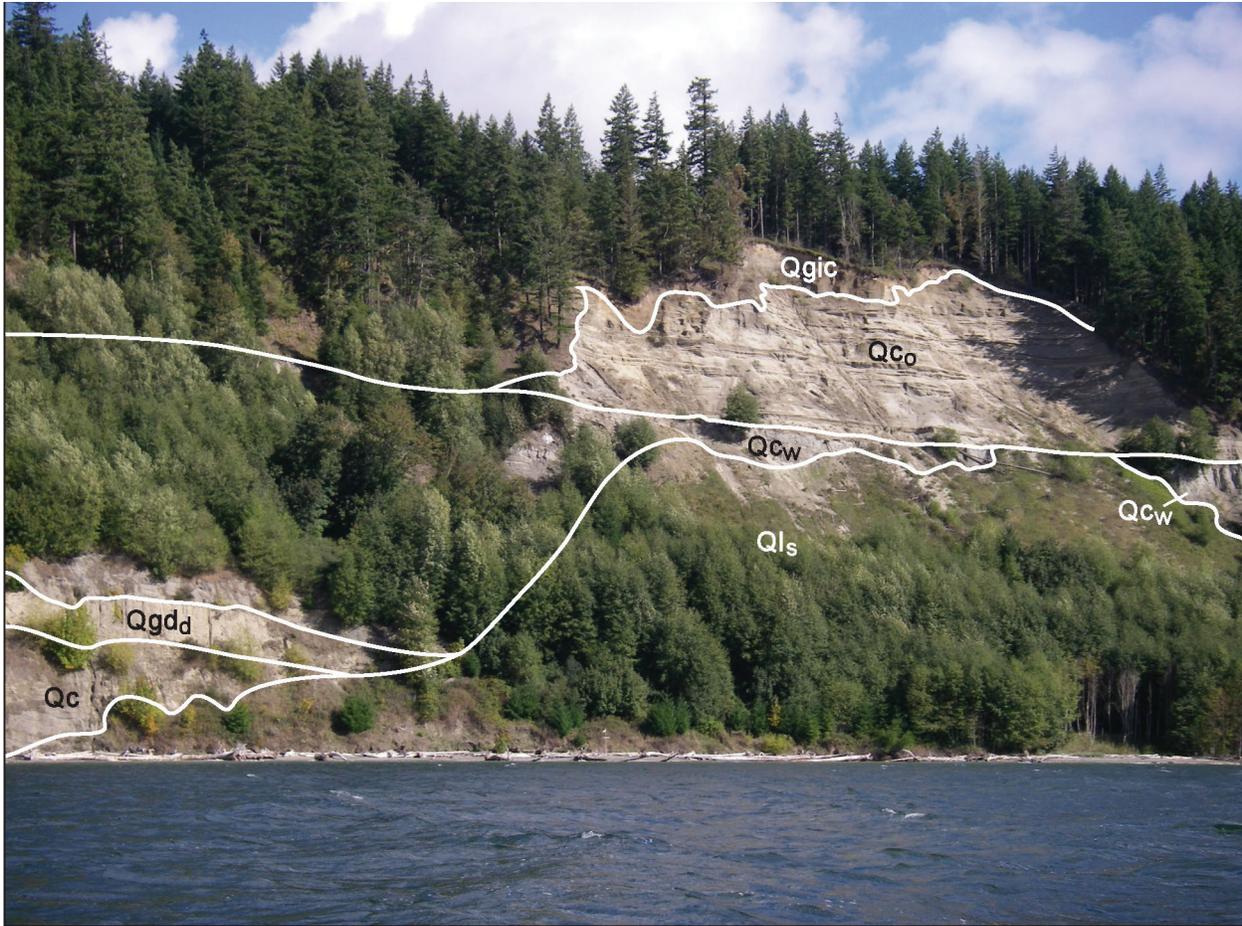
Figure 1. Mapped stratigraphy of glacial and nonglacial deposit at photo site P1 along the northeast shore of Dabob Bay. View is to the east.

absence of near-surface bedrock on most of the Bolton Peninsula and near the community of Quilcene supports the assertion that bedrock depth and distribution may be structurally controlled by the Dabob Bay fault zone.

J Harlen Bretz (1913) specifically discussed deformed outcrops on the Bolton Peninsula as the most severe deformation of Admiralty (pre-Vashon glaciation) deposits known in the Puget Lowland. His description of the location, at the south end of the Bolton Peninsula (sec. 6, T26N R1W), is consistent with exposures at age site GD17. Here the sedimentary bedrock disappears abruptly and glacial and nonglacial deposits are faulted and tilted to the northwest by at least 21 degrees. Local stratigraphy and degree of weathering suggest that these tilted deposits are Double Bluff or older in age. Similar deformation exists at significant site S6 (western Bolton Peninsula, sec. 31, T27N R1W), where exposure of sedimentary bedrock ends and the overlying nonglacial and glacial deposits are folded.

Dating Landslides and Land Level Changes

At age sites GD11 and GD15, along the west and southeast shores of Quilcene Bay (Fig. 2), buried tree stumps and the proximity to scarps at significant sites S5 and S7 (sec. 36, T27N R2W and sec. 36, T27N R2W) indicate large landslides and (or) ground subsidence events. Our radiocarbon results for wood sampled from the buried stumps at age sites GD11 and GD15, while poorly constrained, suggest that a rockslide and possible ground movement occurred in the past 500 years. Native American oral stories may also record an earthquake-related rockslide at age site GD11 (Elmendorf, 1992; Lee Stilson, Wash. Dept. of Natural Resources, oral commun., 2013). However, the suggestion that these two sites were subjected to sudden subsidence due to earthquakes is not supported by the work of Beale (1990), who studied relative sea-level changes in the lagoon at Fishermans Point (significant site S9, sec. 31, T27N R1W) and at the mouth of Donovan Creek in Quilcene Bay (significant site S4, sec. 18, T27N R1W). Beale concluded that there had probably been no crustal displacements of more than 3 ft in the past 3,000 years.
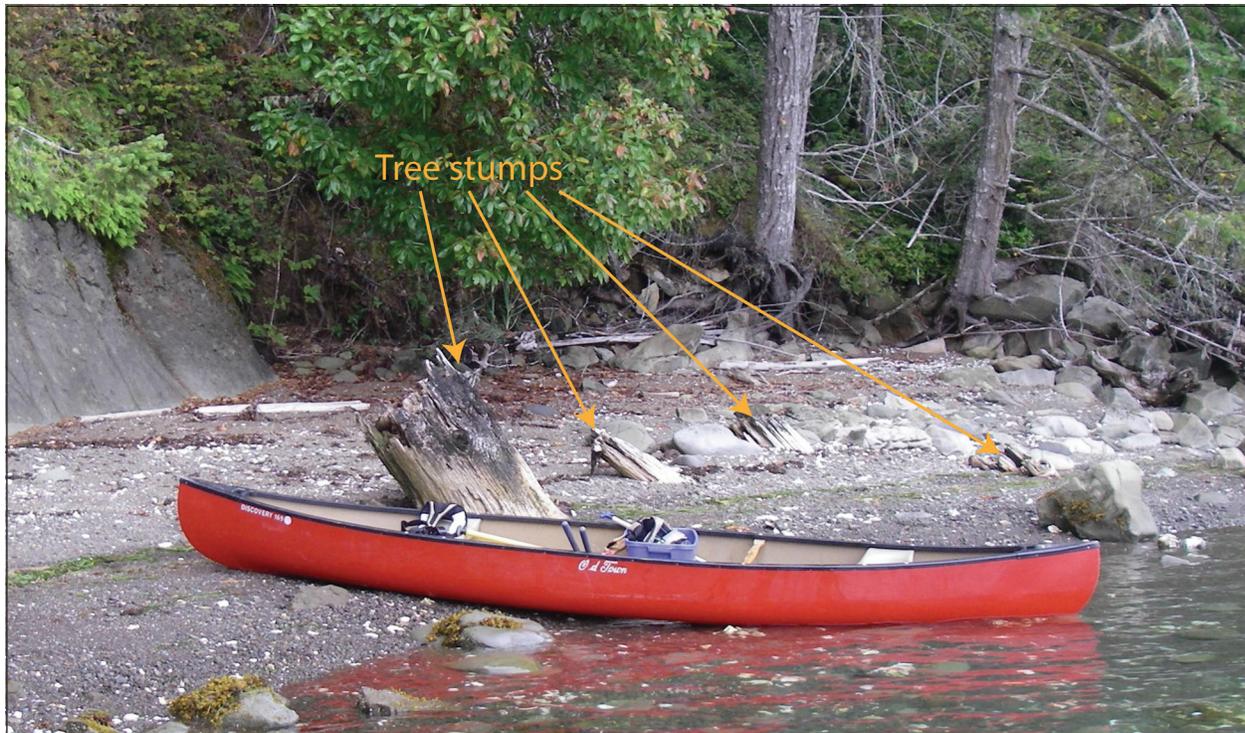
Figure 2. Preserved stumps in a landslide deposit at age site GD11 on the west side of Quilcene Bay (see Table M1 on map sheet). The stumps were buried in the landslide, which may have been caused by an earthquake. These events may have been recorded in the oral history of local Native American tribes (Elmendorf, 1992). View is to the northwest.

At age site GD11, at least four large stumps are preserved in a slide deposit at the base of a bedrock cliff (Fig. 2). The tree stumps are back-tilted toward the cliff, suggesting that they slid and tilted as one block. A radiocarbon sample was collected from the outer wood of one of the stumps but the calibrated age only constrains the landslide to within the past 300 years (Table M1). At age site GD15 on the southeastern shore of Quilcene Bay, submerged roots in beach deposits are found between exposures of sedimentary bedrock (unit Em_{2t}), suggesting that this site also experienced a landslide or subsidence between 500 to 319 yr BP, similar to but earlier than at site GD11.

Significant sites S5 and S7 (sec. 36, T27N R2W and sec. 36, T27N R2W), along the western border of the map, are locations where northwest- and northeast-trending, 25- to 100-ft-high scarps disrupt the glaciated surface, indicating a possible post-glacial faulting or mass-wasting event. The northwest-trending scarps have the same orientation as magnetic anomalies at the site and shear zones in basalt and sedimentary bedrock near the DBFZ. Movement along these shear zones may have triggered mass-wasting events. Figure 3 shows the orientation of northwest-striking high-angle fault planes measured for this study. Slickensides observed at significant site S5 (sec. 36, T27N R2W) exhibit right-lateral reverse-oblique movement. This is consistent with slickensides and other kinematic indicators observed in the bedrock within the DBFZ, suggesting that the scarps could be tectonic in origin. However, they may simply be landslide scarps.

Active Seismicity

A swarm of earthquakes recorded by the Pacific Northwest Seismic Network (PNSN)(http://www.pnsn. org/) that began in late November 2013 and continued into mid-2014, suggesting that the map area is seismically active. Most of the earthquakes were near the southwestern map border; historical earthquakes also show a broad band of seismicity in the southern half of the map area (Fig. 4). Earthquakes from the recent swarm were generally confined to depths of 10.5 to 13.5 mi (17–22 km).

The first motions recorded by seismographs provide information about the type and orientation of the fault plane that produced the earthquake—these are termed focal mechanisms. Locations of focal mechanisms from the recent swarm are shown on Figure 4 and tabulated in Table B1. Focal mechanisms provide two possible orientations for the fault responsible for the earthquake. We chose the northwest-oriented right-lateral strike-slip
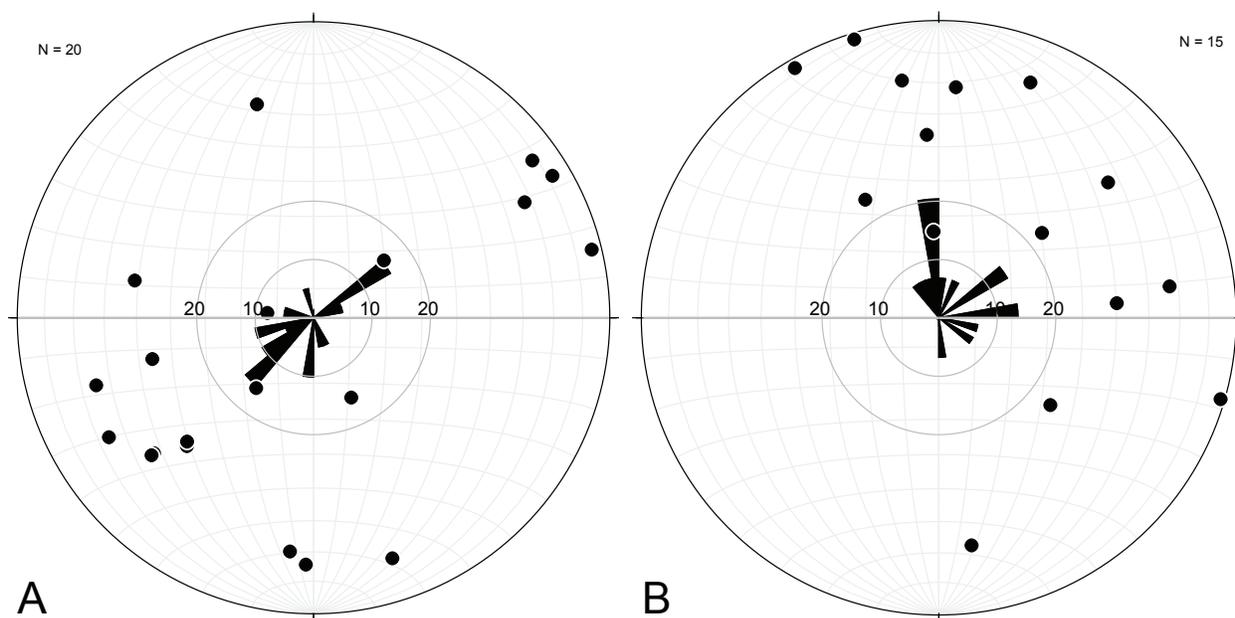
Figure 3. Equal-angle stereonet plots showing poles to planes and rose diagrams (with frequency-bin contours) of minor structures in deformed Tertiary bedrock in the southwest corner of the map area. Measurements of fault planes and joints were recorded using a Brunton pocket transit. A. Minor fault planes in Eocene sedimentary units delineate a series of NW–SE-striking faults (n=20). B. Joint planes in Eocene sedimentary units; these surfaces generally strike E to SW (n=15).

fault orientations and the east–west oriented faults plane solutions because they more closely resemble fault planes observed in the map area and nearby (Contreras and others, 2012a,c)(Fig. 3).

DESCRIPTION OF MAP UNITS

Our map shows the geologic units exposed at the surface, generally where the mapped unit has a thickness of at least 5 ft. In addition to field observations, we relied on geomorphology, field relations, subsurface records, and Landsat satellite images to infer lithology, particularly in areas with limited exposure. Gabriel Legorreta Paulín refined the Landsat data and applied a technique for supervised classification of Landsat images to determine lithology. Due to restricted access, our mapping of Naval Base Kitsap–Bangor in the southeast corner of the map relied heavily on satellite imagery and previous geological mapping by Birdseye (1976a) and Robert Carson (unpub. maps, 1976). As a result, contacts on the naval base are poorly constrained. We refined previous work based on lidar (light detection and ranging) shaded relief maps, our nearby mapping, and radiocarbon and luminescence dates.

We used the time scale of the U.S. Geological Survey (USGS) Geologic Names Committee (2010). Most radiocarbon age estimates are stated as conventional carbon-14 ages and have "yr BP" after the date. Where calibrated dates from other reports are included, "cal yr BP" is after the date. A USGS 7.5-minute topographic map of the Quilcene quadrangle was used as a basemap, but contact locations were refined by reference to a lidar shaded-relief maps, aerial photos, and field observations. Classification of unconsolidated sediments is based on the Udden-Wentworth scale (Pettijohn, 1957).

Quaternary Unconsolidated Deposits

HOLOCENE NONGLACIAL DEPOSITS

ml   **Modified land**—Clay to boulder gravel and diamicton; locally derived but mixed and reworked by excavation and (or) redistribution that notably modifies topography; shown where fairly extensive, masking underlying geology, and geotechnically significant (>5 ft); excludes roads except where connected to a larger modified area. Unit ml is found along the western shore of Quilcene Bay, the northwestern Bolton Peninsula, and the southeastern Bolton Peninsula.
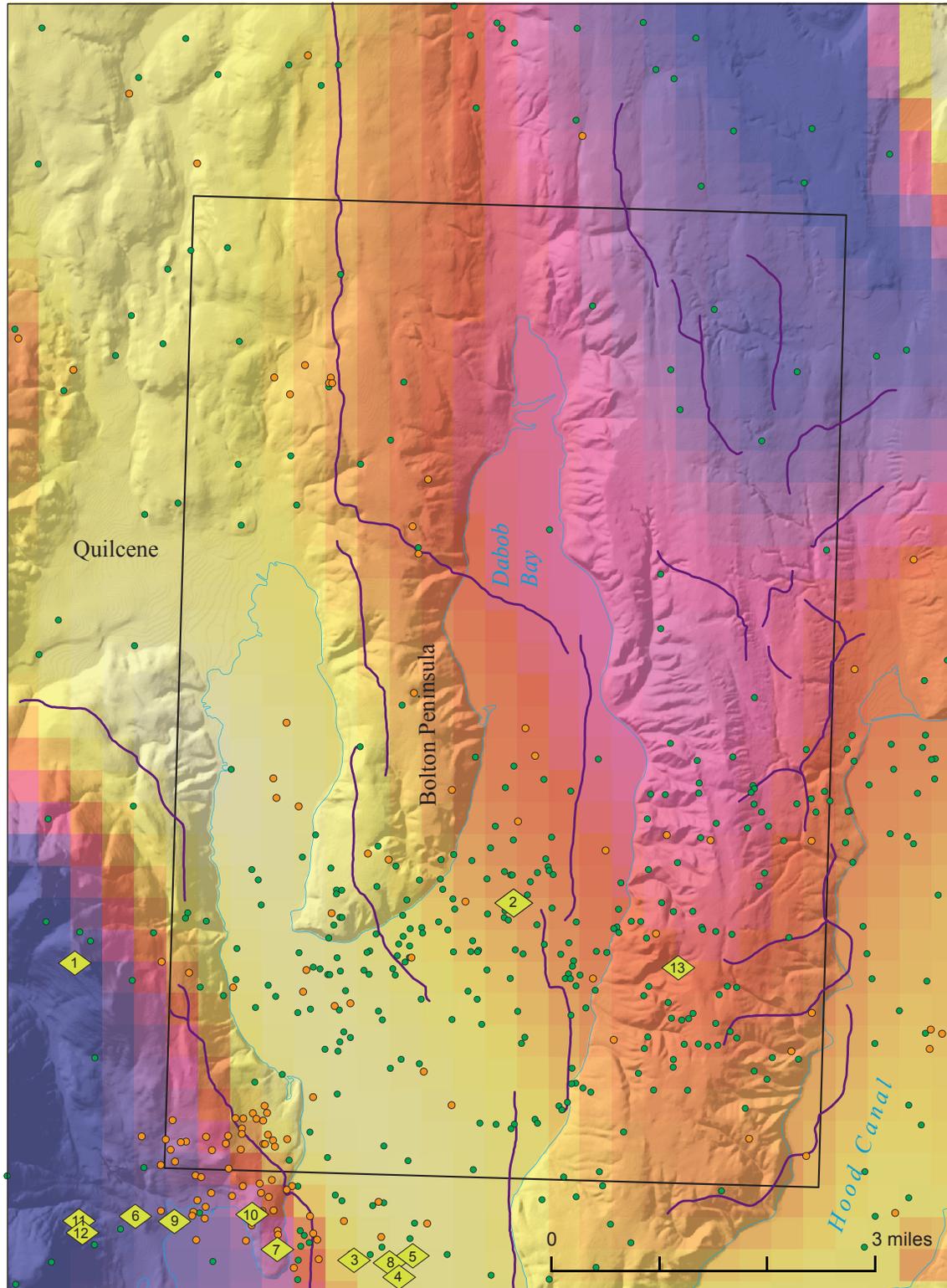
Figure 4. Earthquake epicenters showing active seismicity in and near the Quilcene 7.5-minute quadrangle (black rectangle). Orange circles indicate earthquakes that occurred from January 2013 to March 2014. Green circles indicate earthquakes that occurred from 1969 through 2012. Yellow diamonds indicate earthquakes in the 2013–2014 swarm for which focal mechanism solutions were calculated by the Pacific Northwest Seismic Network (PNSN); numbers correlate with focal mechanisms listed in Table B1. Aeromagnetic anomaly basemap and associated anomalies (shown as purple lines) adapted from data provided by Richard Blakely (USGS, written commun., 2012). Seismic data was obtained from the PNSN website on April 17, 2014.

Qa,   **Alluvium**—Sand to cobble gravel; locally includes silt, clay, and peat; typically gray and generally
Qoa   unweathered; loose; clasts subrounded; moderately to well sorted; stratified to massive; includes some
       lacustrine and beach deposits and may include unrecognized older glacial outwash; sediment consists
       of material from reworked glacial and nonglacial deposits. Unit may locally include recessional outwash
       (unit Qgo). Subunit Qoa resembles unit Qa but is older and forms elevated relict terraces that lack
       evidence to link them to a recessional glacial environment; however, unit Qoa likely includes some
       recessional glacial deposits.

Qb   **Beach deposits**—Sand to boulder gravel with shells and driftwood; gray to brown-gray; loose; clasts
       moderately to well rounded; may be well sorted; derived from shore bluffs, streams, and underlying
       deposits. Unit is commonly too small to show at map scale and unrepresented in favor of mapping more
       geologically significant units. We suggest that the extensive beach deposits in the northern Hood Canal
       area are derived from the easily eroded sand of extensive nonglacial deposits originating in the central
       Cascades (see additional information under unit Qc_o). This deposit is probably less than 6,000 years
       old, based on relative sea-level curves of Eronen and others (1987) and Dragovich and others (1994), and
       suggests aggradation of beach deposits as sea level rose.

HOLOCENE TO LATEST PLEISTOCENE NONGLACIAL DEPOSITS

Qp   **Peat**—Peat, muck, and organic-rich silt and clay; dark brown to black; very soft to medium soft;
       typically in closed depressions. Unit Qp is found in upland wetlands and flat surfaces in closed basins,
       except where standing water was identified. We mapped some peat deposits using topography and aerial
       photos. Unit Qp overlies Vashon Drift and older glacial deposits and is typically Holocene in age, but
       may include some late Pleistocene deposits.

Qls   **Landslide deposits**—Diamicton; loose or soft; clasts subangular to rounded; unsorted to poorly sorted;
       generally nonstratified, but may locally retain primary bedding; includes exposures of underlying units
       in scarp areas. This unit is mapped along shorelines where steep bluffs tend to be unstable. Where
       landslide deposits are mapped, there is additional evidence of landslide movement beyond geomorphic
       expression alone. This often included signs of instability observed in the field, damaged infrastructure,
       and historical accounts of movement. Many deep-seated landslides appear to initiate on fine-grained
       sand and silt of the Olympia or Whidbey nonglacial intervals. This unit is mostly Holocene but may
       include some late Pleistocene deposits. Queried landslides indicate some uncertainty about the landform
       or a site that was not field verified to confirm the existence of a landslide identified with other methods.
       Because some landslides have headscarps of sufficient size to map, but deposits that are too small to
       depict at 1:24,000 scale, we chose to map the headscarp but not the deposit. Similarly, some landslide
       scarps and deposits were too small to map, and therefore the absence of a mapped landslide does not
       imply the absence of a landslide hazard.

Qmw   **Mass-wasting deposits**—Sand, pebble to boulder gravel, and diamicton, with minor sand and gravel
       beds where modified by stream processes; loose; clasts subrounded; poorly to moderately sorted. Unit
       Qmw represents colluvium-covered slopes and includes debris fans, alluvial fans, and landslides where
       the landform cannot be more specifically identified and (or) where lidar suggests mass-wasting deposits
       not observed in the field. This unit is often mapped in valleys that appear graded to approximately 100 to
       200 ft above modern sea level, which suggests that these deposits may have formed at the end of the ice-
       age as ice was melting in an environment and climate different from today. This unit is mostly Holocene
       but likely includes late Pleistocene deposits.

Qaf,   **Alluvial fan deposits**—Sand, gravel, and debris-flow diamicton; gray, weathers to brownish-orange;
Qoaf   loose; clasts subrounded to rounded; typically poorly to moderately sorted; massive to weakly stratified.
       Unit forms concentric lobes where streams emerge from confining valleys. Debris flows and debris
       torrents may be a geologic hazard on some alluvial fans. For example, fan aggradation occurred at
       several locations in the quadrangle during storms in December 2007. This aggradation added significant
       material to fans in the area, damaged homes and infrastructure, and covered beaches and shellfish
       beds (Sarikhan and others, 2008). Unit Qaf is predominantly Holocene but likely includes some latest

Pleistocene recessional deposits of the Fraser Glaciation. Unit Qoaf is similar in form and composition, but lack of evidence for recent sediment delivery indicates that areas mapped as unit Qoaf are relict features.

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Vashon Drift of the Fraser Glaciation (MIS 2)

Work in the Hoodsport quadrangle to the southwest places the age of the Puget lobe of the Cordilleran ice sheet between about 17,000 and 15,700 cal yr ago (Polenz and others, 2012a). Ice filled the Puget Lowland to an elevation of 3,100 ft in the adjacent Brinnon quadrangle (Polenz and others, 2012b). Vashon Drift in the map area is mostly a thin, unweathered, discontinuous layer of melt-out till or ice-contact stratified drift (stagnant-ice deposits) with little lodgment till. An exception is along the crest of the Toandos Peninsula, between the projection of the Olympic–Wallowa lineament and the southern boundary of the map, where lodgment till is as much as 150 ft thick. The Puget lobe may have stagnated in the map area, causing the ice sheet to abruptly collapse into marine water north of the map area at the Strait of Juan de Fuca (Ralph Haugerud, USGS, oral commun., 2012). This event was inferred from the lack of recessional moraines and prevalence of stagnant-ice features, such as eskers and kame and kettle topography, in the central Puget Lowland. Porter and Swanson (1998) suggested that deglaciation occurred prior to 16,420 cal yr BP at Lake Carpenter (~5 mi east of the map area).

An extensive recessional lake system was first proposed by Bretz (1913) based on the presence of alluvial flats and shorelines formed as recessional meltwater was impounded in front of receding ice. Numerous lakes formed as ice melted and retreated from south to north. These lakes were graded to spillways at the south end of the Puget Lowland and eventually to outlets in the north. By the time the map area was ice free, Lake Russell (named by Bretz) had formed and was graded to the Black Lake spillway near Olympia. As ice continued to melt, recede, and uncover additional spillways, Lake Bretz (Waitt and Thorson, 1983) drained to the north at Port Discovery, resulting in progressively lower spillways (Haugerud, 2009a). Thorson (1981, 1989) studied the isostatic uplift of the area using the modern elevation of delta deposits formed in the recessional lakes as a proxy for prehistoric lake elevation. Thorson (1989) determined that these deposits were progressively uplifted to the north by isostatic rebound as the Puget lobe melted. He calculated a postglacial isostatic rebound gradient of approximately 0.85 m/km (4.5 ft/mi). Within the map area, isostatic rebound is approximately 120 ±4 m (394 ft) at the Quilcene delta (Thorson, 1989) since deglaciation (Dethier and others, 1995). In the nearby Seabeck and Poulsbo quadrangles, Polenz and others (2013) correlated shorelines found at elevations above 240 ft with Lake Russell and those below with Lake Bretz. We find numerous elevated shorelines within the map area at approximately 200 to 220 ft in elevation (see map sheet). We found additional shorelines at various elevations, but few that we could systematically correlate across the map area. See additional discussion of the recessional shorelines in the Results section.

Mapped recessional deposits of the Fraser Glaciation are units Qgoaf, Qgo, Qgog, and Qgic. Porter and Carson (1971), Porter and Swanson (1998), and Haugerud (2009b) noted that deglaciation following the Vashon Stade in the southern Puget Lowland probably began with stagnation of the ice sheet: the ice thinned, stopped moving, and melted in place, leaving behind subglacial drainages and other ice-contact features. We find consistent evidence of this in the Quilcene quadrangle; Polenz and others (2009a,b), Derkey and others (2009), and Contreras and others (2010, 2012a,c) depict stagnant-ice features throughout the region. Previous mapping assumed that the area is covered with Vashon-age lodgment till; however, lidar images and field work show that stagnant-ice deposits are more extensive at the surface than in previous mapping. The apparent roughness of topography on and near drumlins coincides with stagnant-ice deposits and a lack of lodgment till, although there are areas with a significant thickness of well-developed lodgment till and diamict (unit Qgt) on the Toandos Peninsula. These deposits are likely younger than ice retreat in the Puget Lowland or 16,420 cal yr BP (Porter and Swanson, 1998).

Qgo   **Vashon recessional outwash**—Sand and cobble to pebble gravel, pebbly sand, and minor silt; gray, weathering to tan; loose; clasts subangular to rounded; moderately to well sorted; typically crudely stratified; derived from both northern and local sources, including pre-Vashon nonglacial deposits; a few to tens of feet thick. Unit Qgo was deposited by meltwater outwash in channels and isolated basins on the fluted upland surface. It is difficult to distinguish from units Qgic and Qgog, resulting in approximate boundaries between units. Locally divided into:

Qgoaf   **Vashon alluvial fan deposits**—Sand and pebble gravel, silt, and cobbles; loose; clasts subrounded; moderately to poorly sorted; stratified; formed concentric lobes where outwash streams emerged from confining valleys. These relict fans do not appear to receive modern sediment and are often incised by modern streams. Unit is mapped on the west side of Tarboo Bay at a maximum elevation of 230 ft, where it was deposited into a recessional lake. These alluvial fans formed as the glacial ice melted, or shortly thereafter. Unit Qgoaf deposits have been smoothed by recessional lakes and have relict shorelines still evident.

Qgog   **Vashon recessional outwash gravel**—Pebble and cobble gravel, sand, and local silt; loose; gray to tan, locally iron-stained to red-brown and yellow, but typically unweathered; clasts moderately to well rounded; moderately to well sorted; typically 10 to 100 ft thick. Unit is mapped in outwash channels that were graded into a recessional lake at approximately 300 to 400 ft elevation. Unit Qgog rests on older nonglacial deposits and includes rip-up clasts of silt and peat eroded from these deposits. It was differentiated from unit Qgo where recent gravel mining has exposed extensive deposits dominated by pebble and cobble gravel, as in the northeast corner of the map area. Unit Qgog is locally mapped beyond such exposures on the basis of channel morphology.

Qgic   **Vashon ice-contact deposits**—Unsorted mixture of clay, silt, sand, and gravel (diamicton), silty pebble to cobble gravel, and pebbly sand; includes minor lenses of sand and silt; yellow-tan to gray; loose to very dense; clasts subangular to subrounded; variously sorted; massive to well stratified. Unit Qgic ranges in thickness from a few to tens of feet and is mapped on both sides of Hood Canal over a large part of the fluted upland surface and the drainages between. Unit is mapped where surficial deposits appeared to be associated with stagnation of the Puget lobe. Unit Qgic includes ice-contact stratified drift and friable, but compact, melt-out till that appears to be permeable. These ice-contact drift and till deposits are commonly characterized by stagnant-ice morphology, including kettles, hummocky topography, and subglacial or subaerial outwash channels. This unit is typically distinguished from well-developed lodgment till by its roughness on lidar shaded-relief maps, its lack of any syndepositional shear fabric, and its association with other stagnant-ice features. Unit Qgic lies directly on top of older, possibly early Fraser-age alpine outwash, or above nonglacial sand and silt deposits of the Olympia nonglacial interval. It is rarely found on recognizable Fraser-age advance glacial deposits, and in this quadrangle, does not always overlie Fraser-age lodgment till, as Haugerud (2005) also observed on Bainbridge Island. The exception is on the Toandos Peninsula, where we map significant thicknesses of Vashon-age lodgment till (unit Qgt) below this unit. Though unit Qgic can be found in fluted drumlins as diamicton, which generally indicates subglacial emplacement, it lacks subhorizontal foliation, is permeable, and is less competent than a typical subglacial lodgment till. Because of these features it may be related to friable melt-out tills found by Laprade (2003) in the Seattle area (see additional discussion in Contreras and others, 2012b,c). In some locations, we map unit Qgic along valley walls where a thin veneer of this unit with hummocky topography resembles landslides; subtle benches inferred to be paleoshorelines can also be found ringing the valleys, suggesting that these hummocky deposits are not landslides. It is possible that some unrecognized landslides may exist where unit Qgic is mapped along valley walls.

Qgt   **Vashon lodgment till**—Diamicton with lenses of sand and gravel; gray, weathering to yellow-tan; well consolidated; dense; matrix-supported; unsorted, with disseminated cobbles in a silt-sand matrix; clasts rounded to subangular; unstratified; locally contains a shear fabric as a result of ice shear. Clasts are both northern- and Olympic-sourced. Unit Qgt thickness ranges from 1 to 200 ft, but is commonly less than 5 ft. Well-developed till is typically found on fluted upland surfaces where drumlins are smooth, wide, and well defined. Unit Qgt is typically covered by 1 to 6 ft of loose ablation till and is generally in sharp and unconformable contact with underlying units, most commonly older nonglacial sediments deposited during the Olympia nonglacial interval. On the Toandos Peninsula, these deposits are as much as 200 ft thick, which is unusually thick relative to Vashon Till deposits mapped elsewhere in the region (Polenz and others, 2013; Contreras and others, 2013), suggesting that the thickness could be structurally controlled.

Pre-Fraser Glacial and Nonglacial Deposits

Prior to the Vashon Stade of the Fraser Glaciation, both Cordilleran and Olympic-sourced glaciers deposited drift in the Quilcene area. During nonglacial intervals, rivers of the Olympic Mountains and central Cascades aggraded thick packages of sand, silt, and pebble gravel (locally only from the Olympic Mountains) into the Puget Lowland. Bretz (1913) believed that nine-tenths of the Pleistocene deposits exposed above sea level in the Puget Lowland are nonglacial deposits. Consistent with Bretz' belief, the majority of the deposits found along bluffs in the map area are nonglacial or from older glaciations and not the result of the Fraser Glaciation. The deposits directly below the surface sculpted by the Puget lobe during the last glaciation appear to have come primarily from the Olympic Mountains and central Cascades during the Olympia nonglacial interval (MIS 3) or older stages. New radiocarbon and luminescence age analyses from this study and recent geologic mapping confirm that these older nonglacial sediments dominate the stratigraphy along Hood Canal north of the Seattle fault zone and include deposits of the Whidbey and Olympia nonglacial intervals. Mapping of the Center 7.5-minute quadrangle to the north found Vashon advance deposits under the Vashon surficial deposits (Polenz and others, 2014), suggesting that a change in depositional age exists between the quadrangles for sand directly under the Vashon Till.

Clague (2000) proposed that the most extensive Quaternary stratigraphic units in the Canadian Cordillera were deposited during ice-sheet growth because there was an increase in sediment production in the alpine areas. This newly produced sediment was flushed from the mountains as alpine glaciers advanced and was deposited in the Puget Lowland by aggrading streams as base level rose. Ages from this study (Table M1) and nearby work (Contreras and others, 2013; Polenz and others, 2013) suggest that the Puget Lowland was filling with alpine-sourced material while the ice sheet was building during the Olympia nonglacial interval at least 12,000 years before the Puget lobe began advancing from British Columbia (Clague and others, 1980). We include exposures of alpine outwash deposits in the nonglacial units Qc_O and Qc_W because they appear to have been deposited at a time when the Puget Lowland was ice-free and because they could not be easily separated from nonglacial fluvial and lacustrine deposits at this map scale. On the Toandos Peninsula in the Seabeck quadrangle to the south and the Lofall quadrangle to the east, radiocarbon ages and stratigraphy suggest that alpine glaciers in this area also produced outwash prior to the arrival of the Puget lobe (Polenz and others, 2013).

We relied on four finite radiocarbon and four luminescence age estimates taken from the extensive nonglacial deposits of interbedded sand and silt (unit Qc_O) and two luminescence age estimates in unit Qc_W to interpret much of the Quaternary stratigraphy (see Table M1 for age control data). We also used dates from mapping in the nearby Lofall and Seabeck quadrangles to clarify the stratigraphy in the map area (Contreras and others, 2013; Polenz and others, 2013). The ages from the nonglacial deposits correlate with MIS 3 and 5, within the age range of the Olympia (60,000–15,000 14C yr BP) and Whidbey (130–70 ka) nonglacial intervals (Troost, 1999; Easterbrook, 1986). The well-bedded and well-sorted nature of the deposits and the inclusion of organic layers further indicate nonglacial deposition.

On the Bolton and Toandos Peninsulas, we found limited exposure of drift between Olympia-age sediments and silt of the Whidbey Formation. We infer that this unit is Possession Drift (unit Qgd_P) because of its stratigraphic position and because it consists of northern-sourced pebble-gravel diamicton and dropstones of various volcanic lithologies. The discontinuous exposures suggest erosion of this unit prior to deposition of the overlying Olympia nonglacial deposits. Previous work to the south in the Holly, Lofall, Poulsbo, and Seabeck quadrangles identified similar stratigraphic relationships (Contreras and others, 2012b; 2013; Polenz and others, 2013).

Exposures of the Whidbey Formation in the map area consist of laminated beds of silt, sand, and clay. These beds are generally exposed at elevations below 200 to 250 ft. However, Whidbey-age sediment is found at higher elevations in some areas on the Bolton Peninsula, including age site GD14 (near Lindsays Beach). In these areas, tectonic deformation may have elevated older deposits.

Qc_O **Olympia nonglacial deposits**—Sand, silt, pebble gravel, and minor peat; tan and gray to light orange and dark brown; loose to moderately compact; clasts subangular to subrounded; well stratified and sorted; laminated to very thickly bedded or massive; locally crossbedded and ripple marked. Sand grains are dominated by monocrystalline quartz, plagioclase feldspar, and potassium feldspar, with minor hornblende and lithic grains. On the Bolton Peninsula, the unit is interbedded with sand and pebble gravel composed of basalt and sandstone lithic grains derived from the Olympic Mountains. Unit Qc_O is as much as 200 ft thick and is distributed throughout the map area. On the west side of the Toandos Peninsula it is found above approximately 250 ft in elevation; on the east side, it is exposed down to

sea level. On the Bolton Peninsula, unit Qc_o is exposed discontinuously above approximately 250 ft in elevation. This unit was deposited in a lacustrine environment or on low-gradient flood plains, either above northern-sourced drift—thought to be Possession Drift—or directly on top of the Whidbey Formation. Along the northern boundary of the map, this unit is queried because ages obtained by Polenz and others (2014) suggest that Vashon advance deposits are found to the north in the Center quadrangle. Without age data, the Vashon advance and the older nonglacial deposits appear so similar that we cannot separate them along the northern boundary. Unit Qc_o was deposited during the Olympia nonglacial interval (MIS 3) and is dated at approximately 60,000–15,000 14C yr BP (Troost, 1999).

The source of the Olympia nonglacial deposits is most likely intrusive granitic rock of the Cascades, such as that found in the Snoqualmie, Index, and Grotto batholiths (J. D. Dragovich, Wash. Div. of Geology and Earth Resources, oral commun., 2013). The dominant sand facies of this unit is petrographically indistinguishable from nonglacial sands observed in several quadrangles on the east side of the Puget Lowland and contains more potassium feldspar and monocrystalline quartz than would be expected from source rocks in British Columbia (Dragovich and others, 2013). This suggests that sediment was transported west across the Puget Lowland and deposited against the base of the Olympic Mountains at the same time that rivers draining the Olympics were depositing alluvium as far east as Bainbridge Island (Deeter, 1979; Haugerud, 2005).

The Quadra Sand, as studied by Clague (1976, 1977) and Clague and others (2005) at the type locality in British Columbia, is similar in age and lithology to unit Qc_o as identified in the map area and is likely of similar origin. The Quadra Sand is also found at elevations above sea level, likely as a result of glacio-isostatic rebound after the expansive Cordilleran ice sheet retreated.

Qgd_p **Possession Drift**—Diamicton and sand to pebble gravel with minor silt; coarsens upward from silt and sand with dropstones to pebble gravel and diamicton; includes metamorphic and granitic clasts and locally derived basalt; light brown to gray; clasts subrounded to rounded; well to moderately sorted and unsorted; moderately stratified and medium to thickly bedded; very dense and massive. The maximum observed thickness of unit Qgd_p is about 150 ft on the Bolton and Toandos Peninsulas; in other locations it is a thin and discontinuous till or is represented by dropstones at the top of the Whidbey Formation (unit Qc_w). Wells that show a full sequence of this unit indicate that, locally, unit Qgd_p may have a maximum thickness of 250 ft. This map unit may include unrecognized older or younger drift because little age control is available; unless stratigraphy indicated an alternative unit, we assumed that the few exposures of northern-sourced drift found under deposits of the Olympia nonglacial interval were Possession in age. The age range for Possession Drift is thought to be 60 to 80 ka (Easterbrook and others, 1967).

Qc_w **Whidbey Formation**—Silt, clay, and sand, with minor sandy pebble gravel; light gray to light brown; dense and stiff; clasts subangular to subrounded; well stratified and well sorted; thinly laminated to very thickly bedded. Some portions of the unit contain preserved organic materials and tephra. Unit Qc_w appears to have an average thickness of about 150 ft, with a maximum thickness of about 200 ft. This unit is exposed along steep bluffs and in valleys on the Bolton and Toandos Peninsulas below approximately 200 ft in elevation. This nonglacial sediment was deposited in a prodelta environment that received sand, silt, and clay from deltas to the north and east.

Thin, discontinuous, and oxidized northern-sourced drift locally overlies this unit; we assume that this is Possession Drift (MIS 4). Where too thin to show at map scale, the drift is included in unit Qc_w. The base of unit Qc_w is best exposed at the north end of Dabob Bay at photo site P1 (Fig. 1; sec. 15, T27N R1W, map sheet). At this site, unit Qc_w appears to be deposited conformably on Double Bluff Drift (unit Qgd_d)(MIS 6) or older unit Qpd. On the Bolton Peninsula, unit Qc_w contains beds of basalt-clast-rich alpine outwash—sandy pebble gravel interbedded with sequences of sand and silt. Tectonic uplift or aggradation during nonglacial intervals may be responsible for depositing this sediment at elevations as much as 200 ft above modern sea level.

We rely on two luminescence age estimates from this study, 72.98 ±3.51 and 113.59 ±6.91 ka (GD2 and GD3 east of Tarboo Bay; sec. 3, T27N R1W), and two from nearby Holly and Eldon quadrangles at 82.5 ±3.89 ka and 134 ±9.74 ka (Contreras and others, 2012a,c). Together, these ages correspond with those provided by Easterbrook (1994) for the Whidbey Formation less than 20 mi

northeast of the map area. One of the age estimates from site GD2 is younger than the established age for the Whidbey Formation; however, given the stratigraphic position and the uncertainty of the dating techniques, this exposure is still most likely part of the Whidbey Formation.

A tephra previously identified by Birdseye (1976b) at age site GD14 (near Lindsays Beach; sec. 32, T27N R1W) was analyzed for this study and correlated with ashes 11 and 13 from Carp Lake in the southwestern Columbia Basin, which have reported ages between 100 to 200 ka (Franklin F. Foit, Wash. State Univ., written commun., 2013)(see Appendix E for microprobe analysis). Birdseye suggested that this ash was deposited during the Olympia nonglacial interval because he found it above drift that he correlated with Possession Drift. We instead correlate this deposit with the Whidbey Formation, based on the tephra analysis and the inferred tectonic deformation of the Dabob Bay fault zone at the south end of the Bolton Peninsula.

Unit Qc_w is often a poor aquifer; water wells are typically drilled through it and are developed in older outwash below. Laminated clay in unit Qc_w makes it a hydrologic barrier, creating springs at the top of the unit.

Qgd_d **Double Bluff Drift**—Diamicton and sandy pebble gravel; coarsens upward from silt and sand with dropstones to pebble gravel and diamicton; includes metamorphic and granitic clasts and locally derived basalt; gray to blue gray; very dense. Unit Qgd_d is found at the north end of Dabob Bay and the south end of the Bolton Peninsula. It is stratigraphically between units we map as nonglacial deposits. We infer that this unit is overlain by the Whidbey Formation (unit Qc_w) and deposited on nonglacial deposits of unknown age (unit Qc). We believe unit Qgd_d was deposited during MIS 6 but do not have additional age control. We tentatively correlate these deposits with the Double Bluff Drift on Whidbey Island (Easterbrook and others, 1967) because it is northern-sourced drift stratigraphically below nonglacial deposits of the Whidbey Interglaciation. However, this unit may be older than the Double Bluff Glaciation.

Qc **Pre-Double Bluff nonglacial deposits, undivided**—Predominantly silty clay, sand, and gravel, with minor peat and wood; brown-gray and blue-gray; very dense to hard. Unit Qc is stratigraphically below units we map as Double Bluff Drift (Easterbrook and others, 1967). This unit could be as young as the Hamm Creek interglaciation (MIS 7)(Troost and Booth, 2008) or much older; meaningful age-control data is not available for any exposures of unit Qc. At age site GD17, organic material interbedded with paleosols from this unit were radiocarbon infinite. On the south end of Bolton Peninsula and between Long Spit and Camp Discovery on the Toandos Peninsula, tectonic deformation and stratigraphic position suggest that these nonglacial deposits are older than Double Bluff deposits.

Qpd **Pre-Fraser glacial drift, undivided**—Till and minor sandy pebble to cobble gravel; gray; compact; clasts subangular to subrounded; moderately sorted and stratified to unsorted and unstratified; includes high-grade metamorphic and granitic clasts that indicate a northern source. Unit Qpd is found on the western edge of the map area, south of Quilcene, and on the west side of the Bolton Peninsula where it includes northern-sourced diamict and outwash of unknown age. This unit closely resembles unit Qgd_d mapped in nearby quadrangles (Contreras and others, 2012a,b), but exposures did not allow us to confidently differentiate it from Possession, Double Bluff, or older glacial deposits. The unit may reflect multiple glacial advances.

Tertiary Sedimentary and Volcanic Rocks

Arnold (1906) proposed the name Crescent Formation for 1,200 ft of basalt and sedimentary rocks exposed on the west side of Crescent Bay, approximately 43 mi northwest of the map area. Brown and others (1960) designated a type section for the overlying Aldwell Formation along Lake Aldwell. We relied primarily on the work of Spencer (1984) for determining sedimentary bedrock stratigraphy above the Crescent basalt in the map area. Spencer's work was particularly valuable because it helped us decipher the structural complexity of the area. Our efforts at collecting and analyzing foraminifera were largely unsuccessful and yielded few biostratigraphically significant fossils—the foraminifera present in our samples were too recrystallized to be identified to the species level (Nesbitt, written commun., 2014). Our microfossil sample locations are shown on the map; any identifiable fossils are noted in Table M1.

Em₂t **Townsend Shale (late Eocene)**—Marine mudstone, siltstone, and sandstone; dominated by quartz, with minor feldspar, lithics, mica, pyrite, and rare grains of glauconite (Spencer, 1984); gray to brown; massive to well bedded; moderately to well sorted; many of the lenticular sandstone beds are cross-stratified; calcareous concretions and nodules of siderite are locally abundant. Concretions in the vicinity of Fishermans Point on the Bolton Peninsula contain glendonite crystals, suggesting a fossilized methane seep (Nesbitt, written commun., 2014). This unit is best exposed on the southern tip of Bolton Peninsula. Biostratigraphic analysis by Spencer (1983a, 1984) correlated this unit with the Townsend Shale (Durham, 1944) and members of the Twin River Group (Snavely and others, 1978). He found that the foraminifera in this unit are upper Narizian in age; however, we are reluctant to correlate these rocks with the Twin River Group because of problems associated with stratigraphic consistency within that group (Nesbitt and others, 2010; Nesbitt, written commun., 2014).

Em₂ss **Sandstone of Snow Creek of Spencer (1984)(late? Eocene)**—Micaceous sandstone and sandy siltstone with thin beds of pebble conglomerate; clasts dominated by quartz and feldspar, with minor biotite, hornblende, chlorite, and muscovite; chert clasts comprise a significant proportion of grains classified as quartz (Spencer, 1984); gray to brown and orange-brown; clay to medium sand-sized grains; subangular to subrounded grains; well to moderately well sorted; massive to thinly bedded. Surface exposures are highly weathered and oxidized, with abundant alteration material. The sandstone of Snow Creek is best exposed along Center Road north of the town of Quilcene. Exposures within the Quilcene quadrangle generally lack sufficiently well-preserved foraminifera and other fossils to perform detailed biostratigraphic study and age correlations. We relied on the work of Spencer (1983b, 1984) to correlate exposures of sandstone in the northwest corner of the map area with the sandstone of Snow Creek, identified by Spencer as the "Snow Creek member of the Lyre Formation". Our samples at site GD8 (sec. 13, T27N R2W) did not contain any microfossils (Nesbitt, written commun., 2014). However, the type locality is abundantly fossiliferous and contains foraminifera and other fossils characteristic of the upper Narizian (Spencer, 1984).

Em₂a **Aldwell Formation (early to middle Eocene)**—Lithic sandstone and bedded siltstone; clasts include abundant feldspars, quartz, and lithics, with minor pyrite, hornblende, and biotite; lithic clasts dominantly basaltic; gray to gray-green; fine to coarse grained; subangular to subrounded; poorly to moderately sorted; massive to well-bedded; a fine matrix consisting of clays and other alteration minerals suggests weathering of basaltic clasts. Minor deformation of grains (sweeping extinctions in quartz and abundant subgrains in some clasts) from the exposures along the west side of Quilcene Bay indicate local tectonic activity. This unit is exposed between Quilcene Boat Haven (sec. 25, T27N R2W) and Frenchmans Point on the west side of Quilcene Bay, stratigraphically above the Crescent Formation (Spencer, 1984; Yount and Gower, 1991). The Aldwell Formation (Brown and others, 1960) exhibits an interfingering relationship with the underlying Crescent Formation and locally contains lenses of volcanic material (Rau, 1964; Spencer, 1984). The Aldwell Formation is poorly fossiliferous here but contains foraminifera and isolated macrofossils. Biostratigraphic analysis by Spencer (1984) assigned a late Ulatisian to Narizian age. A late Eocene to early Miocene nautilus fossil, *Aturia angustata*, was collected from date site GD13 (sec. 36, T27N R1W; Nesbitt, written commun., 2014).

Ev_c **Crescent Formation (early to middle Eocene)**—Basalt; black to greenish black, weathers to gray and medium yellow-brown; commonly occurs as fine-grained sills and flows; commonly includes amygdules of zeolite and chlorite-group minerals. Flows include rare columns, vesicles, and scoria. Unit typically contains plagioclase with intergrowths of pyroxenes and disseminated opaque minerals. Replacement of interstitial glass by chlorite and oxidation products is also common. Hirsch and Babcock (2009) obtained a $^{40}Ar/^{39}Ar$ date of 50.5 ±1.6 Ma on a basalt flow about 620 ft below the top of the exposure at Pulali Point, 1660 ft south of the southern map boundary. Squires and others (1992) thought the date might represent intrusion of a sill because biostratigraphic control yielded a greater (than 50.5 Ma) age for upsection sedimentary rocks. Their biostratigraphic age estimate differs from that of Armentrout and others (1983) and a more recent evaluation by Nesbitt (written commun., 2013) and may also conflict with age control for the Narizian type section in California (Squires and others, 1992; additional details provided by Polenz and others, 2013). Locally subdivided into:

Em$_{1c}$ **Sedimentary rocks of the Crescent Formation (early to middle Eocene)**—Basaltic conglomerate and lithic sandstone; dark gray-black; clasts sand to cobble sized; rounded; poorly sorted. Exposed in an isolated outcrop as a 15 ft-thick bed along the west side of Quilcene Bay. Basalt flows of the Crescent Formation form the upper and lower contacts. The northwestern contact between this unit and Crescent Formation basalt may be fault-controlled; sheared surfaces and approximately 5 ft of friable fault gouge were observed in outcrop.

RESULTS

Nonglacial Deposits of the Olympia and Whidbey Nonglacial Intervals

Deposits of the Olympia nonglacial interval (MIS 3) in the map area are well-sorted, homogeneous quartz- and potassium-feldspar-rich sand and silt interbedded with pebble gravel and sand from the Olympic Mountains. The abundant monocrystalline quartz, significant potassium feldspar, and minor hornblende and pyroxene grains in these beds suggest they are equivalent to ancient Snoqualmie and Skykomish River–provenance alluvium (Dragovich and others, 2013) and are not the result of an advancing Cordilleran ice sheet (Dragovich, oral commun., 2013). The sands appear to have been deposited in a lacustrine or low-energy fluvial environment without dropstones. They are often massive, locally crossbedded, and may be analogues to part of the "great lowland fill" described by Booth and Goldstein (1994, p. 207). However, these sands were deposited during the Olympia nonglacial interval and not during the Vashon Stade of the Fraser Glaciation. They are therefore too old to have been deposited in a proglacial lake impounded by the advancing Puget lobe if the ice didn't reach the Georgia depression in British Columbia until 18.3 ±0.17 ka (Clague and others, 1980).

To explain the deposition of extensive fluvial and lacustrine sediments above modern sea level, mapped here as unit Qc$_o$, Booth and Goldstein (1994) suggested that the Puget Lowland became a closed depression once the Puget lobe crossed the Strait of Juan de Fuca during the Vashon Stade of the Fraser Glaciation. This effectively dammed the Puget Lowland at its northern extent, forming a proglacial lake that was then filled with silt and sandy outwash (Booth, 1994; Booth and Goldstein, 1994). However, age-control data in the area suggest that this part of the Puget Lowland was filling with fluvial and lacustrine sediment during the Olympia nonglacial interval (~15,000–60,000 yr BP), a minimum of 12,000 years before the Puget lobe blocked the Strait of Juan de Fuca (Fig. M2 on map sheet; Troost, 1999). Luminescence and radiocarbon ages from both the Quilcene quadrangle and the adjacent Lofall quadrangle indicate that Vashon advance deposits are not extensive in the map area and that the thick sand and silt sequences are instead composed of Olympia-age sediments unconformably overlain by Vashon Drift (Contreras and others, 2013).

If no ice sheet was blocking the outlet of the Puget Lowland, we need to find a mechanism that would form an extensive lacustrine environment here at a time when sea level was much lower than now (Cutler and others, 2003). We suggest that alpine glaciers in both the Olympics and Cascades were actively shedding sediment into the Puget Lowland during MIS 3. It would have been possible for the ancestral Skagit and Snohomish Rivers to aggrade extensive deltas that blocked the outlet to the Strait during MIS 3, because the modern Skagit and Snohomish Rivers provide more than half of all annual sediment to Puget Sound (Czuba and others, 2011). This blockage could have caused the lowland to fill enough to create lacustrine and low-gradient fluvial environments. However, sediment discharge from rivers flowing into the Puget Lowland during MIS 3 is unknown; thus, our solution is speculative.

Other possible mechanisms for aggradation include development of the Port Ludlow uplift and Kingston arch, isostatic rebound after the Possession deglaciation, or pre-Vashon glacial deposits. Similar aggradation during the Olympia nonglacial interval has been reported in British Columbia and the Willamette Valley of Oregon (Clague and others, 2005; O'Connor and others, 2001). Clague (1977) suggested that aggradation in the Georgia depression occurred in a short period of time, as would be the case for tectonic uplift, but the estimates he provided relied on sparse data.

Although we cannot currently propose a definitive mechanism for raising the base level of the Puget Lowland and depositing thick sequences of sand and silt during the Olympia nonglacial interval, the luminescence and radiocarbon dates that constrain sediment ages in the region indicate that significant deposition occurred at this time.

Paleoshorelines and Mass-Wasting Deposits

Within the map area, relict shorelines were identified using lidar imagery to characterize local isostatic rebound in more detail and identify offset indicative of faulting. However, the preserved shorelines are discontinuous enough—likely the result of extensive erosion on the eastern Bolton Peninsula and western Toandos Peninsula—that characterization is difficult. The most prominent features indicate a relatively consistent relict shoreline at about 200 ft elevation, with a slight gradient rising to the north, consistent with Thorson (1989). The most prominent shorelines are depicted on the map as blue lines. Many drainages have mass-wasting deposits (unit Qmw) that appear graded to this 200 ft base level, suggesting that some of these deposits were mobilized while the Puget lobe was melting and lakes were present. The relict shorelines in the map area are not extensive or consistent enough to definitively identify local fault offset, with the possible exception of those in the southwest corner of the quadrangle near Whitney Point. These surfaces appear to be 5 to 10 ft higher than corresponding shorelines on the south Bolton and Toandos Peninsulas.

Landsat Satellite Images

We used Landsat satellite images to help define geologic contacts in areas inaccessible during field season. The images were resampled to smaller grids using aerial photos, and a supervised classification of the images was performed by G. Legorreta Paulín to determine lithology. The classification involved determining which spectrums corresponded to sites of known lithology, then assigning the defined lithologies to the remaining areas of the image.

The images provided good correlation with Vashon-age, northern-sourced lodgment till, Olympia-age sand, and Whidbey Formation fine-grained deposits (units Qgt, Qc_o, and Qc_w, respectively). A surprising correlation involved areas with thick deposits of glacial till. These deposits along Hood Canal are often thin, discontinuous sheets over older glacial and nonglacial deposits, and the contact is often found at the slope break. On the Toandos Peninsula, there were deposits as much as 150 ft thick that extended considerable distances down the slope past the slope break, making mapping based on topography difficult. Field observations combined with satellite images were a useful tool in mapping the thick till unit, well-sorted sand, and fine-grained nonglacial deposits.

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REFERENCES CITED

Armentrout, J. M.; Hull, D. A.; Beaulieu, J. D.; Rau, W. W., 1983, Correlation of Cenozoic stratigraphic units of western Oregon and Washington: Oregon Department of Geology and Mineral Industries Oil and Gas Investigation 7, 90 p., 1 plate.

Arnold, Ralph, 1906, Geological reconnaissance of the coast of the Olympic Peninsula, Washington: Geological Society of America Bulletin, v. 17, p. 451-468.

Babcock, R. S.; Burmester, R. F.; Engebretson, D. C.; Warnock, A. C.; Clark, K. P., 1992, A rifted margin origin for the Crescent basalts and related rocks in the northern Coast Range volcanic province, Washington and British Columbia: Journal of Geophysical Research, v. 97, no. B5, p. 6799-6821.

Beale, Harriet, 1990, Relative rise in sea-level during the late Holocene at six salt marshes in the Puget basin, Washington: Western Washington University Master of Science thesis, 157 p.

Birdseye, R. U., 1976a, Geologic map of east-central Jefferson County, Washington: Washington Division of Geology and Earth Resources Open File Report 76-26, 1 sheet, scale 1:24,000. [http://www.dnr.wa.gov/publications/ger_ofr76-26_geologic_ map_jefferson_co_24k.pdf]

Birdseye, R. U., 1976b, Glacial and environmental geology of east-central Jefferson County, Washington: North Carolina State University Master of Science thesis, 96 p.

Blakely, R. J.; Sherrod, B. L.; Hughes, J. F.; Anderson, M. L.; Wells, R. E.; Weaver, C. S., 2009, Saddle Mountain fault deformation zone, Olympic Peninsula, Washington—Western boundary of the Seattle uplift: Geosphere, v. 5, no. 2, p. 105-125.

Booth, D. B., 1994, Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation: Geology, v. 22, no. 8, p. 695-698.

Booth, D. B.; Goldstein, B. S., 1994, Patterns and processes of landscape development by the Puget lobe ice sheet. In Lasmanis, Raymond; Cheney, E. S., convenors, Regional geology of Washington State: Washington Division of Geology and Earth Resources Bulletin 80, p. 207-218.

Borchardt, G. A.; Aruscavage, P. J.; Millard, H. T., Jr., 1972, Correlation of the Bishop ash, a Pleistocene marker bed, using instrumental neutron activation analysis: Journal of Sedimentary Petrology, v. 42, no. 2, p. 301-306.

Bowman, J. D.; Czajkowski, J. L., 2013, Washington State seismogenic features database—GIS data: Washington Division of Geology and Earth Resources Digital Data Series DS-1, version 3.0. [http://www.dnr.wa.gov/publications/ger_portal_seismogenic_features.zip]

Bretz, J H., 1913, Glaciation of the Puget Sound region: Washington Geological Survey Bulletin 8, 244 p., 3 plates. [http://www.dnr.wa.gov/publications/ger_b8_glaciation_pugetsound.pdf]

Brocher, T. M.; Parsons, T. E.; Blakely, R. J.; Christensen, N. I.; Fisher, M. A.; Wells, R. E.; SHIPS Working Group, 2001, Upper crustal structure in Puget Lowland, Washington—Results from the 1998 Seismic Hazards Investigations in Puget Sound: Journal of Geophysical Research, v. 106, no. B7, p. 13,541-13,564.

Brown, R. D., Jr.; Gower, H. D.; Snavely, P. D., Jr., 1960, Geology of the Port Angeles–Lake Crescent area, Clallam County, Washington: U.S. Geological Survey Oil and Gas Investigations Map OM-203, 1 sheet, scale 1:62,500.

Carson, R. J., 1980, Quaternary, environmental, and economic geology of the eastern Olympic Peninsula, Washington: [unpub. report], 275 p.

Clague, J. J., 1976, Quadra Sand and its relation to the late Wisconsin glaciation of southwest British Columbia: Canadian Journal of Earth Sciences, v. 13, no. 6, p. 803-815.

Clague, J. J., 1977, Quadra Sand—A study of the late Pleistocene geology and geomorphic history of coastal southwest British Columbia: Geological Survey of Canada Paper 17-77, 24 p.

Clague, J. J., 2000, Recognizing order in chaotic sequences of Quaternary sediments in the Canadian Cordillera: Quaternary International, v. 68-71, p. 29-38.

Clague, J. J.; Armstrong, J. E.; Mathews, W. H., 1980, Advance of the late Wisconsin Cordilleran ice sheet in southern British Columbia since 22,000 yr B.P.: Quaternary Research, v. 13, no. 3, p. 322-326.

Clague, J. J.; Froese, Duane; Hutchinson, Ian; James, T. S.; Simon, K. M., 2005, Early growth of the last Cordilleran ice sheet deduced from glacio-isostatic depression in southwest British Columbia, Canada: Quaternary Research, v. 63, no. 1, p. 53-59.

Contreras, T. A.; Legorreta Paulín, Gabriel; Czajkowski, J. L.; Polenz, Michael; Logan, R. L.; Carson, R. J.; Mahan, S. A.; Walsh, T. J.; Johnson, C. N.; Skov, R. H., 2010, Geologic map of the Lilliwaup 7.5-minute quadrangle, Mason County, Washington: Washington Division of Geology and Earth Resources Open File Report 2010-4, 13 p., 1 plate, scale 1:24,000. [http://www.dnr.wa.gov/publications/ger_ofr2010-4_geol_map_lilliwaup_24k.zip]

Contreras, T. A.; Spangler, Eleanor; Fusso, L. A.; Reioux, D. A.; Legorreta Paulín, Gabriel; Pringle, P. T.; Carson, R. J.; Lindstrum, E. F.; Clark, K. P.; Tepper, J. H.; Pileggi, Domenico; Mahan, S. A., 2012a, Geologic map of the Eldon 7.5-minute quadrangle, Jefferson, Kitsap, and Mason Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2012-03, 1 sheet, scale 1:24,000, with 60 p. text. [http://www.dnr.wa.gov/publications/ger_ms2012-03_geol_map_ eldon_24k.zip]

Contreras, T. A.; Weeks, S. A.; Stanton, K. M. D.; Stanton, B. W.; Perry, B. B.; Walsh, T. J.; Carson, R. J.; Clark, K. P.; Mahan, S. A., 2012b, Geologic map of the Holly 7.5-minute quadrangle, Jefferson, Kitsap, and Mason Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2011-5, 1 sheet, scale 1:24,000, 13 p. text. [http://www.dnr.wa.gov/publications/ger_ofr2011-5_geol_map_holly_24k.zip]

Contreras, T. A.; Weeks, S. A.; Perry, B. B., 2012c, Analytical data from the Holly 7.5-minute quadrangle, Jefferson, Kitsap, and Mason Counties, Washington—Supplement to Open File Report 2011-5: Washington Division of Geology and Earth Resources Open File Report 2011-6, 16 p. [http://www.dnr.wa.gov/publications/ger_ofr2011-6_holly_supplement.pdf]

Contreras, T. A.; Stone, K. A.; Legorreta Paulín, Gabriel, 2013, Geologic map of the Lofall 7.5-minute quadrangle, Jefferson and Kitsap Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2013-03, 1 sheet, scale 1:24:000, 19 p. text. [http://www.dnr.wa.gov/publications/ger_ms2013-03_geol_map_lofall_24k.zip].

Cutler, K. B.; Edwards, R. L.; Taylor, F. W.; Cheng, H.; Adkins, J.; Gallup, C. D.; Cutler, P. M.; Burr, G. S.; Bloom, A. L., 2003, Rapid sea-level fall and deep-ocean temperature change since the last interglacial period: Earth and Planetary Science Letters, v. 206, is. 3-4, p. 253-271.

Czuba, J. A.; Magirl, C. S.; Czuba, C. R.; Grossman, E. E.; Curran, C. A.; Gendaszek, A. S.; Dinicola, R. S., 2011, Sediment load from major rivers into Puget Sound and its adjacent waters: U.S. Geological Survey Fact Sheet 2011-3083, 4 p. [http://pubs.usgs.gov/fs/2011/3083/]

Dadisman, S. V.; Johnson, S. Y.; Childs, J. R., 1997, Marine, high-resolution, multichannel, seismic-reflection data collected during Cruise G3-95-PS, northwestern Washington: U.S. Geological Survey Open-File Report 97-735, 3 CD-ROM disks.

Deeter, J. D., 1979, Quaternary geology and stratigraphy of Kitsap County, Washington: Western Washington University Master of Science thesis, 175 p., 2 pl.

Derkey, R. E.; Hehemann, N. J.; Alldritt, Katelin, 2009, Geologic map of the Lake Wooten 7.5-minute quadrangle, Mason County, Washington: Washington Division of Geology and Earth Resources Open File Report 2009-5, 1 sheet, scale 1:24,000. [http://www.dnr.wa.gov/publications/ger_ofr2009-5_geol_map_lakewooten_24k.pdf]

Dethier, D. P.; Pessl, Fred, Jr.; Keuler, R. F.; Balzarini, M. A.; Pevear, D. R., 1995, Late Wisconsinian glaciomarine deposition and isostatic rebound, northern Puget Lowland, Washington: Geological Society of America Bulletin, v. 107, no. 11, p. 1288-1303.

Dragovich, J. D.; Pringle, P. T.; Walsh, T. J., 1994, Extent and geometry of the mid-Holocene Osceola mudflow in the Puget Lowland—Implications for Holocene sedimentation and paleogeography: Washington Geology, v. 22, no. 3, p. 3-26. [http://www.dnr.wa.gov/Publications/ger_washington_geology_1994_v22_no3.pdf]

Dragovich, J. D.; Littke, H. A.; Mahan, S. A.; Anderson, M. L.; MacDonald, J. H., Jr.; Cakir, Recep; Stoker, B. A.; Koger, C. J.; DuFrane, S. A.; Bethel, J. P.; Smith, D. T.; Villeneuve, N. M., 2013, Geologic map of the Sultan 7.5-minute quadrangle, Snohomish and King Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2013-01, 1 sheet, scale 1:24,000, 49 p. text. [http://www.dnr.wa.gov/publications/ger_ms2013-01_geol_map_sultan_24k.zip]

Durham, J. W., 1944, Megafaunal zones of the Oligocene of northwestern Washington: University of California Department of Geological Sciences Bulletin, v. 27, no. 5, p. 101-212.

Easterbrook, D. J., 1986, Stratigraphy and chronology of Quaternary deposits of the Puget Lowland and Olympic Mountains of Washington and the Cascade mountains of Washington and Oregon: Quaternary Science Reviews, v. 5, p. 145-159.

Easterbrook, D. J., 1994, Chronology of pre-late Wisconsin Pleistocene sediments in the Puget Lowland, Washington. In Lasmanis, Raymond; Cheney, E. S., convenors, Regional geology of Washington State: Washington Division of Geology and Earth Resources Bulletin 80, p. 191-206. [http://www.dnr.wa.gov/publications/ger_b80_regional_geol_wa_2.pdf]

Easterbrook, D. J.; Crandell, D. R.; Leopold, E. B., 1967, Pre-Olympia Pleistocene stratigraphy and chronology in the central Puget Lowland, Washington: Geological Society of America Bulletin, v. 78, no. 1, p. 13-20.

Elmendorf, W. W., 1992, The structure of Twana culture—With comparative notes on the structure of Yurok culture: WSU Press, 576 p.

Eronen, Matti; Kankainen, Tuovi; Tsukada, Matsuo, 1987, Late Holocene sea-level record in a core from the Puget Lowland, Washington: Quaternary Research, v. 27, no. 2, p. 147-159.

Grimstad, Peder; Carson, R. J., 1981, Geology and ground-water resources of eastern Jefferson County, Washington: Washington Department of Ecology Water-Supply Bulletin 54, 125 p., 3 plates. [http://www.ecy.wa.gov/programs/eap/wsb/wsb_All.html]

Haeussler, P. J.; Yount, J. C.; Wells, R. E., 1999, Preliminary geologic map of the Uncas 7.5′ quadrangle, Clallam and Jefferson Counties, Washington: U.S. Geological Survey Open-File Report 99-421, 1 sheet, scale 1:24,000. [http://pubs.er.usgs.gov/usgspubs/ofr/ofr99421]

Hamlin, W. H., 1962, Geology and foraminifera of the Mount Walker–Quilcene–Leland Lake area, Jefferson County, Washington: University of Washington Master of Science thesis, 127 p.

Hanson, K. L., 1976, Geologic map of the Uncas–Port Ludlow area, Jefferson County, Washington: Washington Division of Geology and Earth Resources Open File Report 76-20, 1 sheet, scale 1:24,000. [http://www.dnr.wa.gov/publications/ger_ofr76-20_geol_map_uncas_port_ludlow_24k.pdf]

Hanson, K. L., 1977, The Quaternary and environmental geology of the Uncas–Port Ludlow area, Jefferson County, Washington: University of Oregon Master of Science thesis, 82 p., 5 plates.

Haugerud, R. A., 2005, Preliminary geologic map of Bainbridge Island, Washington: U.S. Geological Survey Open-File Report 2005-1387, version 1.0, 1 sheet, scale 1:24,000. [http://pubs.usgs.gov/of/2005/1387]

Haugerud, R. A., 2009a, Preliminary geomorphic map of the Kitsap Peninsula, Washington; version 1.0: U.S. Geological Survey Open-File Report 2009-1033, 2 sheets, scale 1:36,000. [http://pubs.usgs.gov/of/2009/1033/]

Haugerud, R. A., 2009b, Deglaciation of the southern Salish lowland [abstract]. In Northwest Scientific Association, The Pacific Northwest in a changing environment—Northwest Scientific Association 81st annual meeting; Program with abstracts: Northwest Scientific Association, p. 27-28.

Haugerud, Ralph; Haeussler, Peter, 2000, The bedrock geology of Seattle, May 20–21 2000: Northwest Geological Society, Society Field Trips in Pacific Northwest Geology, 11 p. [http://www.nwgs.org/field_trip_guides/11.bedrockgeologyof seattle.pdf]

Hirsch, D. M.; Babcock, R. S., 2009, Spatially heterogeneous burial and high-P/T metamorphism in the Crescent Formation, Olympic Peninsula, Washington: American Mineralogist, v. 94, no. 8-9, p. 1103-1110.

Kramer, S. L., 1996, Geotechnical earthquake engineering: Prentice Hall, 653 p.

Lamb, A. P.; Liberty, L. M.; Blakely, R. J.; Pratt, T. L.; Sherrod, B. L.; van Wijk, K., 2012, Western limits of the Seattle fault zone and its interaction with the Olympic Peninsula, Washington: Geosphere, v. 8, no. 3, doi: 10.1130/GES00780.1.

Laprade, W. T., 2003, Subglacially reworked till in the Puget Lowland [abstract]: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 216.

Mann, G. M.; Meyer, C. E., 1993, Late Cenozoic structure and correlations to seismicity along the Olympic–Wallowa lineament, northwest United States: Geological Society of America Bulletin, v. 105, no. 7, p. 853-871.

Mann, G. M., 1994, Late Cenozoic structure and correlation to seismicity along the Olympic–Wallowa lineament, northwestern United States—Discussion and reply; Reply: Geological Society of America Bulletin, v. 106, no. 12, p. 1639-1641.

Mann, Paul; Hempton, M. R.; Bradley, D. C.; Burke, Kevin, 1983, Development of pull-apart basins: Journal of Geology, v. 91, no. 5, p. 529-554.

McCaffrey, R.; Qamar, A. I.; King, R. W.; Wells, R.; Khazaradze, G.; Williams, C. A.; Stevens, C. W.; Vollick, J. J.; Zwick, P. C., 2007, Fault locking, block rotation and crustal deformation in the Pacific Northwest: Geophysical Journal International, v. 169, no. 3, p. 1315-1340.

Minard, J. P., 1983, Geologic map of the Edmonds East and part of the Edmonds West quadrangles, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1541, 1 sheet, scale 1:24,000. [http://ngmdb.usgs.gov/prodesc/proddesc_7448.htm]

Newcomb, R. C., 1952, Ground-water resources of Snohomish County, Washington: U.S. Geological Survey Water-Supply Paper 1135, 133 p., 2 plates. [http://pubs.er.usgs.gov/usgspubs/wsp/wsp1135]

Nesbitt, E. A.; Martin, R. A.; Carroll, N. P., Grieff, J., 2010, Reassessment of the Zemorrian foraminiferal Stage and Juanian molluscan Stage north of the Olympic Mountains, Washington State and Vancouver Island: Newsletter on Stratigraphy, v. 43, no. 3, p. 275-291.

Nesbitt, E. A.; Martin, R. A.; Campbell, K. A., 2013, New records of Oligocene diffuse hydrocarbon seeps, northern Cascadia margin: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 390, p. 116-129.

O'Connor, J. E.; Sarna-Wojcicki, A. M.; Wozniak, K. C.; Polette, D. J.; Fleck, R. J., 2001, Origin, extent, and thickness of Quaternary geologic units in the Willamette Valley, Oregon: U.S. Geological Survey Professional Paper 1620, 54 p., 1 pl. [http://pubs.usgs.gov/pp/1620/]

Pettijohn, F. J., 1957, Sedimentary rocks; 2nd ed.: Harper & Brothers, 718 p.

Polenz, Michael; Alldritt, Katelin; Hehemann, N. J.; Logan, R. L., 2009a, Geologic map of the Burley 7.5-minute quadrangle, Kitsap and Pierce Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2009-8, 1 sheet, scale 1:24,000. [http://www.dnr.wa.gov/publications/ger_ofr2009-8_geol_map_burley_24k.pdf]

Polenz, Michael; Alldritt, Katelin; Hehemann, N. J.; Sarikhan, I. Y.; Logan, R. L., 2009b, Geologic map of the Belfair 7.5-minute quadrangle, Mason, Kitsap, and Pierce Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2009-7, 1 sheet, scale 1:24,000. [http://www.dnr.wa.gov/publications/ger_ofr2009-7_geol_map_belfair_24k.pdf]

Polenz, Michael; Miller, B. A.; Davies, Nigel; Perry, B. B.; Clark, K. P.; Walsh, T. J.; Carson, R. J.; Hughes, J. F., 2012a, Geologic map of the Hoodsport 7.5-minute quadrangle, Mason County, Washington: Washington Division of Geology and Earth Resources Open File Report 2011-3, 1 sheet, scale 1:24,000, with 16 p. text. [http://www.dnr.wa.gov/publications/ger_ofr2011-3_geol_map_hoodsport_24k.zip]

Polenz, Michael; Spangler, Eleanor; Fusso, L. A.; Reioux, D. A.; Cole, R. A.; Walsh, T. J.; Cakir, Recep; Clark, K. P.; Tepper, J. H.; Carson, R. J.; Pileggi, Domenico; Mahan, S. A., 2012b, Geologic map of the Brinnon 7.5-minute quadrangle, Jefferson and Kitsap Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2012-02, 1 sheet, scale 1:24,000, with 47 p. text. [http://www.dnr.wa.gov/publications/ger_ms2012-02_geol_map_brinnon_24k.zip]

Polenz, Michael; Petro, G. T.; Contreras, T. A.; Stone, K. A.; Legorreta Paulín, Gabriel; Cakir, Recep, 2013, Geologic map of the Seabeck and Poulsbo 7.5-minute quadrangles, Kitsap and Jefferson Counties, Washington: Washington Division of Geology and Earth Resources Map Series 2013-02, 1 sheet, scale 1:24,000, with 20 p. text. [http://www.dnr.wa.gov/publications/ ger_ms2012-02_geol_map_seabeck-poulsbo_24k.zip]

Polenz, Michael; Gordon, H. O.; Contreras, T. A.; Patton, A. I., 2014, Geologic map of the Center 7.5-minute quadrangle, Jefferson County, Washington: Washington Division of Geology and Earth Resources Map Series 2014-02, 1 sheet, scale 1:24,000, with 33 p. text. [http://www.dnr.wa.gov/publications/ger_ms2014-02_geol_map_center_24k.pdf]

Porter, S. C.; Carson, R. J., 1971, Problems of interpreting radiocarbon dates from dead-ice terrain, with an example from the Puget Lowland of Washington: Quaternary Research, v. 1, no. 3, p. 410-414.

Porter, S. C.; Swanson, T. W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, no. 3, p. 205-213.

Pratt, T. L.; Johnson, S. Y.; Potter, C. J.; Stephenson, W. J.; Finn, C. A., 1997, Seismic reflection images beneath Puget Sound, western Washington State—The Puget Lowland thrust sheet hypothesis: Journal of Geophysical Research, v. 102, no. B12, p. 27,469-27,489.

Prescott, J. R.; Hutton, J. T., 1994, Cosmic ray contributions to dose rates for luminescence and ESR dating—Large depths and long-term time variations: Radiation Measurements, v. 23, p. 497-500.

Raisz, E. J., 1945, The Olympic–Wallowa lineament: American Journal of Science, v. 243A [Daly volume], p. 479-485. [http://earth.geology.yale.edu/~ajs/1945A/479.pdf]

Rau, W. W., 1964, Foraminifera from the northern Olympic Peninsula, Washington: U.S. Geological Survey Professional Paper 374-G, 33 p., 7 plates. [http://pubs.er.usgs.gov/usgspubs/pp/pp374G]

Reidel, S. P.; Tolan, T. L., 1994, Late Cenozoic structure and correlation to seismicity along the Olympic–Wallowa lineament, northwestern United States—Discussion and reply; Discussion: Geological Society of America Bulletin, v. 106, no. 12, p. 1634-1638.

Sarikhan, I. Y.; Stanton, K. D.; Contreras, T. A.; Polenz, Michael; Powell, Jack; Walsh, T. J.; Logan, R. L., 2008, Landslide reconnaissance following the storm event of December 1–3, 2007, in western Washington: Washington Division of Geology and Earth Resources Open File Report 2008-5, 16 p. [http://www.dnr.wa.gov/ResearchScience/Topics/GeologicHazards Mapping/Pages/landslides_dec07storm.aspx]

Simonds, F. W.; Longpre, C. I.; Justin, G. B., 2004, Ground-water system in the Chimacum Creek basin and surface water/ground water interaction in Chimacum and Tarboo Creeks and the Big and Little Quilcene Rivers, eastern Jefferson County, Washington: U.S. Geological Survey Scientific Investigations Report 2004-5058, 1 sheet, scale 1:31,680, 49 p. text. [http://pubs.water.usgs.gov/sir2004-5058]

Snavely, P. D., Jr.; Niem, A. R.; Pearl, J. E., 1978, Twin River Group (upper Eocene to lower Miocene); Defined to include the Hoko River, Makah, and Pysht Formations, Clallam County, Washington. IN Sohl, N. F.; Wright, W. B., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1977: U.S. Geological Survey Bulletin 1457-A, p. 111-120.

Spencer, P. K., 1983a, Age and paleoecology of marine siltstones exposed on the Bolton Peninsula near Quilcene, Jefferson County, Washington. In Larue, D. K.; Steel, R. J., editors, Cenozoic marine sedimentation, Pacific margin, U.S.A.: Society of Economic Paleontologists and Mineralogists Pacific Section, p. 197-203.

Spencer, P. K., 1983b, Depositional environment of some Eocene strata near Quilcene, Washington, based on trace-, macro-, and micro-fossils and lithologic associations. In Larue, D. K.; Steel, R. J., editors, Cenozoic marine sedimentation; Pacific margin, U.S.A.: Society of Economic Paleontologists and Mineralogists Pacific Section, p. 233-239.

Spencer, P. K., 1984, Lower Tertiary biostratigraphy and paleoecology of the Quilcene–Discovery Bay area, northeast Olympic Peninsula, Washington: University of Washington Doctor of Philosophy thesis, 173 p., 2 plates.

Squires, R. L.; Goedert, J. L.; Kaler, K. L., 1992, Paleontology and stratigraphy of Eocene rocks at Pulali Point, Jefferson County, eastern Olympic Peninsula, Washington: Washington Division of Geology and Earth Resources Report of Investigations 31, 27 p. [http://www.dnr.wa.gov/publications/ger_ri31_eocene_rock_jefferson_county.pdf]

Tabor, R. W.; Cady, W. M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000. [http://ngmdb.usgs.gov/prodesc/proddesc_9852.htm]

Tabor, R. W.; Haeussler, P. J.; Haugerud, R. A.; Wells, R. E., 2011, Lidar-revised geologic map of the Uncas 7.5′ quadrangle, Clallam and Jefferson Counties, Washington: U.S. Geological Survey Scientific Investigations Map 3160, 2 sheets, scale 1:24,000, with 9 p. text. [http://pubs.usgs.gov/sim/3160]

Thorson, R. M., 1981, Isostatic effects of the last glaciation in the Puget Lowland, Washington: U.S. Geological Survey Open-File Report 81-370, 100 p., 1 plate. [http://pubs.er.usgs.gov/publication/ofr81370]

Thorson, R. M., 1989, Glacio-isostatic response of the Puget Sound area, Washington: Geological Society of America Bulletin, v. 101, no. 9, p. 1163-1174.

Troost, K. G., 1999, The Olympia nonglacial interval in the southcentral Puget Lowland, Washington: University of Washington Master of Science thesis, 123 p.

Troost, K. G.; Booth, D. B., 2008, Geology of Seattle and the Seattle area, Washington. In Baum, R. L.; Godt, J. W.; Highland, L. M., editors, Landslides and engineering geology of the Seattle, Washington, area: Geological Society of America Reviews in Engineering Geology XX, p. 1-35. [http://www.wou.edu/las/physci/taylor/g473/seismic_hazards/troost_booth_2008_geo_ seattle.pdf]

U.S. Geological Survey Geologic Names Committee, 2010, Divisions of geologic time—Major chronostratigraphic and geochronologic units: U.S. Geological Survey Fact Sheet 2010-3059, 2 p. [http://pubs.usgs.gov/fs/2010/3059/]

Waitt, R. B., Jr.; Thorson, R. M., 1983, The Cordilleran ice sheet in Washington, Idaho, and Montana. In Porter, S. C., editor, The late Pleistocene; Volume 1 of Wright, H. E., Jr., editor, Late-Quaternary environments of the United States: University of Minnesota Press, p. 53-70.

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 11, Jefferson County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.

Whitlock, C.; Sarna-Wojcicki, A. M.; Bartlein, P. J.; Nickmann, R. J., 2000, Environmental history and tephrostratigraphy at Carp Lake, southwestern Columbia Basin, Washington, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 155, no. 1-2, p. 7-29.

Yount, J. C.; Gower, H. D., 1991, Bedrock geologic map of the Seattle 30′ by 60′ quadrangle, Washington: U.S. Geological Survey Open-File Report 91-147, 37 p., 4 plates. [http://pubs.er.usgs.gov/publication/ofr91147]

Yount, J. C.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30′ x 60′ quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000. [http://ngmdb.usgs.gov/ prodesc/ proddesc_12654.htm]

Appendix A. Luminescence Age Data for Pleistocene Nonglacial Deposits

Table A1. Optically stimulated luminescence (OSL) and infrared stimulated luminescence (IRSL) data and ages from the Quilcene 7.5-minute quadrangle, processed and analyzed by Shannon Mahan, USGS Luminescence Dating Laboratory. Table provides elemental concentrations, cosmic and total dose rates, equivalent doses, and ages from IRSL (feldspar) and quartz OSL. Samples are located on map sheet. K, % potassium; Gy, Gray (unit of absorbed radiation); ka, 1,000 years.

Date site	Sample ID	Lat./Long. (decimal degrees)	Map unit	Water content[a] (%)	K (%)[b]	U (ppm)[b]	Th (ppm)[b]	Cosmic dose[c] (Gy/ka)	Total dose rate (Gy/ka)	Equivalent dose	n[d]	Analytic method	Age estimate[e]	Notes
GD2	Quilcene-2	47.856 / −122.793	Qc$_w$	13 (35)	1.25 ±0.03	1.09 ±0.06	2.22 ±0.23	0.03 ±0.01	1.38 ±0.06	101 ±2.53	15 (24)	OSL	72.980 ±3.510 ka	Planar to crossbedded, tan, compact, silty sand and sandy silt of northern or Cascade provenance, dominated by quartz with minor potassium-feldspar and lithic grains. Rippled bedding surfaces indicate a flow direction of 215°. The discrepancy between IRSL and OSL age dates indicates that the OSL date on this sample is an underestimate.
GD3									1.84 ±0.08f	209 ±9.41f	− −	IRSL	113.590 ±6.910 ka	
GD6	Quilcene-3	47.834 / −122.832	Qc$_o$	7 (28)	1.13 ±0.05	1.14 ±0.12	4.53 ±0.41	0.17 ±0.01	1.64 ±0.09	45.9 ±1.34	18 (24)	OSL	27.960 ±1.740 ka	Planar to crossbedded, tan, compact, fine sand of northern or Cascade provenance, dominated by quartz and polycrystalline quartz with minor potassium feldspar and plagioclase. The outcrop contains thin pebble beds with rounded and subrounded granitic and metamorphic clasts as much as 2 in. in diameter. The sandy beds are overlain by light brown, dense, sandy pebble-cobble gravel with till clasts. This contact is erosional and can be observed approximately 6 ft above the sampled bed.
GD7									2.26 ±0.12f	82.8 ±4.97f	− −	IRSL	36.640 ±2.980 ka	
GD18	Quilcene-1	47.778 / −122.785	Qc$_o$	7 (29)	1.17 ±0.04	0.84 ±0.08	2.72 ±0.36	0.17 ±0.01	1.49 ±0.09	32.8 ±2.79	16 (24)	OSL	22.000 ±2.300 ka	Planar to crossbedded, white to tan, compact, fine sand of northern or Cascade provenance, dominated by quartz and polycrystalline quartz with minor potassium-feldspar, plagioclase, and other lithic grains. The outcrop contains thin pebble beds with rounded granitic and metamorphic clasts as much as 3 in. in diameter. Crossbedding indicates a variable flow pattern to the northeast and northwest.
GD19									1.93 ±0.12f	51.0 ±2.55f	− −	IRSL	26.420 ±2.130 ka	

a Field moisture, with values in parentheses indicating the complete sample saturation %. Ages calculated using approximately 60% of saturation values.

b Analyses obtained using high-resolution gamma spectrometry (HPGe detector).

c Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994). Gy = Gray (unit of absorbed radiation).

d Number of replicated equivalent dose (De) estimates used to calculate the equivalent dose. Values in parentheses indicate total number of measurements included in calculating the represented equivalent dose and age using the minimum age model (MAM). All aliquots passed methodology tests.

e Dose rate and age for fine-grained 250-180 micron-sized quartz. Exponential + linear fit used on single aliquot regeneration equivalent doses; errors to one sigma; ages and errors rounded.

f Feldspar from fine-grained 4-11 micron polymineral silt. Exponential fit used for multiple aliquot additive dose. Errors to one sigma. Fade tests indicate ~1 g/decade correction.

Appendix B. Active Seismicity in and near the Map Area

Table B1. Focal mechanisms of the 2013–2014 earthquake swarm in and near the Quilcene 7.5-minute quadrangle. Data and plane calculations provided by the PNSN website on March 28, 2014. Strike is measured from north and dip direction is 90° clockwise from the strike azimuth.

Focal mechanism no.	Lat./Long. (decimal degrees)	Event ID	Magnitude	Depth (mi)	Date and time	Plane A: strike, dip (degrees)	Plane B: strike, dip (degrees)
1	47.7758 -122.8945	60740541	1.9	11.8	2012/04/12 23:01:32 PDT	130, 80	224, 70
2	47.7852 -122.8110	60732952	2.0	12.5	2014/04/05 09:55:46 PDT	115, 75	210, 71
3	47.7387 -122.8395	60723171	0.4	10.7	2014/03/19 05:03:08 PDT	000, 30	099, 85
4	47.7367 -122.8308	60723166	0.8	10.1	2014/03/19 04:59:53 PDT	355, 25	094, 86
5	47.7395 -122.8283	60723111	0.7	10.1	2014/03/19 01:11:11 PDT	000, 25	270, 90
6	47.7435 -122.8815	60723101	1.7	11.1	2014/03/19 01:04:27 PDT	110, 85	209, 30
7	47.7398 -122.8542	60680037	0.7	10.8	2014/01/30 02:20:53 PST	005, 35	095, 90
8	47.7385 -122.8327	60664267	0.9	10.0	2014/01/05 18:34:02 PST	320, 90	095, 00
9	47.7430 -122.8740	60650647	2.2	11.1	2013/12/13 14:54:07 PST	125, 70	222, 71
10	47.7442 -122.8592	60645032	2.2	11.3	2013/12/06 18:08:14 PST	325, 75	200, 25
11	47.7427 -122.8922	60646106	2.9	11.9	2013/12/06 04:57:07 PST	195, 30	312, 76
12	47.7412 -122.8915	60645891	3.5	12.2	2013/12/05 23:55:51 PST	100, 80	216, 22
13	47.7775 -122.7792	60640066	2.2	12.9	2013/11/28 10:48:33 PST	115, 65	225, 54

Appendix C. Significant Sites

Table C1. Descriptions of significant sites.

Site no.	Location	Description
S1	sec. 12, T27N R2W	Rice Lake. This lake is likely the "little sinkhole" mentioned by Raisz (1945) in his original description of structural features along the Olympic–Wallowa lineament.
S2	sec. 17, T27N R1W	Sedimentary bedrock exposure ends abruptly and Whidbey-age bedded sand—exposed at this site and to the south—appears deformed. A right-lateral fault is inferred at this location.
S3	sec. 17, T27N R1W	Geomorphic lineament in fine pebbly sand. The feature is approximately 15 ft wide and 12 ft deep with a trend of 210º.
S4	sec. 18, T27N R1W	Marsh developed where Donovan Creek drains into Quilcene Bay. Stratigraphy and radiocarbon dating of peat indicate the existence of a marsh in this location beginning 3,170 ±90 radiocarbon yr BP (Beale, 1990).
S5	sec. 36, T27N R2W	Shallow, arcuate scarp along the western map boundary. This scarp may be indicative of a historic mass-wasting event.
S6	sec. 31, T27N R1W	Sedimentary bedrock exposure ends abruptly and the overlying Quaternary sediments, exposed at this site and to the north, are deformed. Unit Qc_w north of this site contains beds of basalt-clast-rich alpine outwash.
S7	sec. 36, T27N R2W	Shallow, arcuate scarp along the western map boundary. This scarp may be indicative of an historic mass-wasting event.
S8	sec. 32, T27N R1W	Location of a large translational slide that occurred in 2009 and compromised a home built above the steep bluff. It appears that the unconsolidated nonglacial deposits underlying pre-Vashon till provided a slip plane that allowed for failure.
S9	sec. 31, T27N R1W	A marsh developed behind the sandy spit at Fishermans Point. Stratigraphy and radiocarbon-dating of peat in this marsh indicate less than 3 m of vertical displacement in the last 2,950 ±70 radiocarbon yr BP (Beale, 1990).

Appendix D. Depth-to-Bedrock Estimates from Passive Seismic Survey Data

Passive seismic measurements for determining depth to bedrock were recorded for this study using a Tromino device (spectral range of 0.1–128 Hz) at six sites. This technique, known as the 'Nakamura's technique' or horizontal to vertical spectral ratio (HVSR), records ambient seismic waves using a three-component seismograph. When processed, the data provide approximate depth to bedrock or other density contrasts below the site. We used a formula from Kramer (1996) to infer depth to bedrock marked by a seismic velocity contrast—an increase in velocity at depth:

$$Depth = Vs/(4*(fr))$$

where Vs is the mean shear-wave velocity in the deposits above the estimated depth, and fr is the resonant frequency corresponding to peak HVSR. We assumed reasonable Vs values for unconsolidated deposits of between 54 and 154 m/s, based on site conditions, and modeled the HVSR data. We typically used approximately 150 m/s at all sites, except site HVSR3 where we used 54 m/s because shear waves propagate at a lower velocity in the loose sediment of that area.

Table D1. Depth to bedrock estimates. Seismic sites are shown on the map by red rectangles and labeled with the site number. Location is from the public land survey as section, township and range (TRS). Latitude and longitude coordinates were recorded using a handheld GPS. Elevations are in feet, estimated using lidar elevations from the Puget Sound Lidar Consortium. Shear wave velocity for the upper 30 m (Vs30) is approximately modeled from the data collected for this study, when the data and technique allowed for this calculation. Note that where velocity contrast was not observed, Vs30 was not calculated. The range of shear wave velocities for sediments was determined by modeling the H/V spectral data for depths. Asterisks represent sites where bedrock was not detected. – –, no data.

Seismic site no.	Location TRS	Latitude and longitude (decimal degrees)	Elevation (ft)	Estimated Vs 30 (m/s)	Depth to bedrock estimate (ft)	Bedrock elevation estimate (ft)	Notes
HVSR1	sec. 13, T27N R2W	47.82477 -122.87470	37	264	>72*	<-35*	This site has unconsolidated alluvium at the surface and in well reports. The higher velocity of 465 m/s at 72 ft depth likely indicates consolidated glacial deposits or faulted bedrock.
HVSR2	sec. 8, T27N R1W	47.85150 -122.84268	632	– –	0	632	No contrast in velocity. Based on field exposures, this site likely has bedrock at or near the surface.
HVSR3	sec. 20, T27N R1W	47.81323 -122.83521	545	94	>118*	<427*	Bedrock is deep here. A small velocity contrast occurs at 118 ft, but it likely represents consolidated glacial deposits.
HVSR4	sec. 32, T27N R1W	47.79220 -122.82882	286	397	>39*	<247*	Low-quality data due to nearby cliff. However, there is a contrast in velocity at 39 ft that doesn't appear to be bedrock because the velocity is too low. This velocity contrast likely indicates glacial drift of unit Qgd$_d$. Although Birdseye (1976a) mapped sedimentary bedrock nearby, we did not find these exposures, nor does our subsurface data suggest the presence of shallow bedrock.
HVSR5	sec. 31, T27N R1W	47.78694 -122.84817	231	– –	0	231	No contrast in velocity; based on field exposures, this site has bedrock at or near the surface.
HVSR6	sec. 18, T27N R1W	47.83185 -122.86178	12	388	42	-30	Good-quality data shows bedrock at 42 ft below site. Bedrock is also visible at this elevation in nearby exposures. Data indicates that this sedimentary bedrock has a velocity of 614 m/s.

Appendix E. Tephra Electron Microprobe Geochemical Data

Table E1. New electron microprobe geochemical data on tephra at age site GD14 (unit Qc_W). The tephra was sampled from an exposure that Birdseye (1976b) documented as the Lindsays Beach tephra (sec. 32, T27N R1W). We sampled the tephra and submitted it to Washington State University's Geoanalytical Lab for microprobe analysis and tephra correlation by Franklin Foit. The analysis of 16 shards of the volcanic ash suggests a good compositional match (similarity coefficient = 0.96, Borchardt and others, 1972) to ashes 11 and 13 from Carp Lake in southwestern Columbia Basin, both of which are reported to have an age between 100 and 200 ka (Whitlock and others, 2000). Foit expressed reservation with this identification because the glass oxide standard deviations for the sample were unusually low (that is, there was very little compositional variation among the glass shards) whereas the standard deviations for Carp Lake ashes 11 and 13 are significantly larger (Foit, written commun., 2013).

Sample	Comment	No. of shards	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	Cl	Total*	Probable source	Age	Similarity coefficient**
9-660-C	tephra	16	74.24	0.45	13.11	1.96	0.37	1.32	3.66	3.80	0.09	100	Carp Lake ashes 11 and 13	100–200 ka	0.96
	standard deviation		0.17	0.04	0.13	0.05	0.03	0.09	0.07	0.10	0.01				

*Analyses normalized to 100 weight percent

**Borchardt and others (1972)