# GEOLOGIC MAP OF THE LOFALL 7.5-MINUTE QUADRANGLE, JEFFERSON AND KITSAP COUNTIES, WASHINGTON

by Trevor A. Contreras,
Kimberly A. Stone, and
Gabriel Legorreta Paulin

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## WASHINGTON STATE DEPARTMENT OF NATURAL RESOURCES

Peter Goldmark—*Commissioner of Public Lands*

## DIVISION OF GEOLOGY AND EARTH RESOURCES

David K. Norman—*State Geologist*
John P. Bromley—*Assistant State Geologist*

**Washington State Department of Natural Resources**
**Division of Geology and Earth Resources**

*Mailing Address:*
MS 47007
Olympia, WA 98504-7007

*Street Address:*
Natural Resources Bldg, Rm 148
1111 Washington St SE
Olympia, WA 98501

*Phone:* 360-902-1450
*Fax:* 360-902-1785
*E-mail:* geology@dnr.wa.gov
*Website:* http://www.dnr.wa.gov/geology

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**MAP SHEET**

Geologic map of the Lofall 7.5-minute quadrangle, Jefferson and Kitsap Counties, Washington

# Geologic Map of the Lofall 7.5-minute Quadrangle, Jefferson and Kitsap Counties, Washington

by Trevor A. Contreras[1], Kimberly A. Stone[1], and Gabriel Legorreta Paulin[2]

[1] Washington Division of
Geology and Earth Resources
MS 47007
Olympia, WA 98504-7007

[2] Universidad Nacional Autónoma de México
Instituto de Geografía
Ciudad Universitaria, Del Coyoacán
cp 04510, México, D.F.

## INTRODUCTION

The map area in the western Puget Lowland straddles Hood Canal between Naval Base Kitsap–Bangor and the Hood Canal Bridge. It includes the northern portion of the city of Poulsbo. Most of the map area is covered by nonglacial sediment and sediment left by alpine glaciers of the Olympic Mountains and the Puget lobe of the Cordilleran ice sheet, which advanced from Canada several times during the Pleistocene Epoch. This mapping was undertaken to identify the area's geologic hazards, including active faults and landslides, and to delineate the glacial stratigraphy and hydrologic characteristics of the area to assist local government and scientists working on the problem of low concentrations of dissolved oxygen in Hood Canal.

Segments of the Seattle and Hood Canal faults have been identified nearby (Blakely and others, 2009; Lamb and others, 2012) and the seismically active Kingston arch projects into the quadrangle. How these faults and structures interact is not well understood. To the south of the quadrangle, the Seattle fault zone has been mapped as far west as Hood Canal (Lamb and others, 2012; Contreras and others, 2012c). Geophysical models by Lamb and others (2012) and Blakely and others (2009) suggest that the Seattle fault zone crosses Hood Canal to the southwest of the map area to connect with the Saddle Mountain fault zone, a complex network of faults southwest of Brinnon. Pratt and others (1997) and Brocher and others (2001) map the Seattle basin to the south of the map area and the Port Ludlow uplift beginning near the north end the map area and continuing to the north (Fig. 1 on map sheet).

Persistent landslides continue to damage property and infrastructure in the area, particularly near the Hood Canal Bridge. Many of these slides initiate on silts and clays of the Olympia nonglacial interval.

Previous workers have mapped the geological units (Birdseye, 1976a,b; Hanson, 1976; Deeter, 1979; Yount and Gower, 1991; Yount and others, 1993), the hydrogeology (Sceva, 1957; Garling and others, 1965; Grimstad and Carson, 1981; Kahle, 1998); sea level during the Holocene (Eronen and others, 1987), and documented the glacial recessional lake history (Bretz, 1913; Thorson, 1989; Haugerud, 2009b).

Throughout the text, we refer to significant sites numbered S1 to S3 and indicated by orange diamonds on the map. Water wells or borings whose logs were used for this mapping are depicted as gray circles and labeled W or B with a number. These wells or borings can be cross referenced with the Washington State Department of Ecology (WADOE) well tag, if applicable, in Table 1 on the map sheet. These sites are often connected with additional data found on the map sheet or in the appendix, including radiocarbon ($^{14}C$) and infrared stimulated luminescence (IRSL) dates (Table 2 on map sheet) and pollen data (Appendix A).

## GEOLOGIC OVERVIEW

Determining the type of bedrock and thickness of glacial sediments beneath the map area is hampered by limited subsurface data and the structural complexity caused by the intersection of the Kingston arch, Seattle basin, and Seattle fault. The only bedrock exposure in the map area is along Squamish Harbor near Shine (sec. 3, T27N R1E). It was mapped by Hanson (1976) and Yount and Gower (1991) as basalt of the Eocene Crescent Formation. Only a few wells and borings in the Shine area encountered this basalt. However, the Union Oil Co. Pope and Talbot No.

18-1 well, drilled in 1972 less than 2 mi east of the quadrangle (Fig. 1 on map sheet), intersected the Blakeley Formation (Fulmer, 1975). Geophysical models (Pratt and others, 1997; Brocher and others, 2001; Lamb and others, 2012; Blakely and others, 2009; Haug, 1998) and geophysical data help constrain depth to bedrock and provide insight into faulting in the area.

Previous work (Birdseye, 1976a,b,c; Deeter, 1979; Garling and others, 1965; Grimstad and Carson, 1981; Hanson, 1976; Kahle, 1998; WADOE, 1978, 1979; Yount and others, 1993) described the Pleistocene stratigraphy in the map area and provided subsurface information relating to groundwater. These authors documented repeated Pleistocene glacial incursions that deposited most of the quadrangle's unconsolidated sediment, and they attempted to classify and correlate these deposits within the Puget Lowland. Additionally, many workers mapped significant nonglacial deposits in the area.

The eastern Olympic Mountains consist of basalt of the Eocene Crescent Formation overlain by sandstone and siltstone of the Eocene–Oligocene Lincoln Creek Formation, while to the north, the North Cascades and British Columbia consist of a variety of volcanic, granitic, and metamorphic rocks. We broadly classify the various drifts as 'Olympic-sourced' or 'northern-sourced'. Olympic-sourced drift contains basalt, sandstone, and rare phyllite (in addition to rare reworked granitic and metamorphic clasts), indicating deposition by alpine glaciers of the Olympic Mountains. Northern-sourced drift generally contains granitic and metamorphic rock clasts, suggesting deposition by the Cordilleran ice sheet, but it also typically contains abundant locally derived basalt clasts. The Cordilleran ice sheet overrode the map area, incorporated sediment shed from the Olympic Mountains, and deposited northern-sourced sediment in the Olympic foothills, resulting in occurrences of northern-sourced granitic and metamorphic rocks mingled with the dominantly basalt- and sandstone-rich Olympic-sourced drift.

Figure 2 (on map sheet) depicts the glacial history of the Puget Lowland and related Marine Isotope Stages (MIS) using variations in the ratio of $^{18}O/^{16}O$, which delineate warm and cool climatic intervals and show 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.

Nonglacial deposits were distinguished primarily by the presence of organic matter and ages coincident with inferred nonglacial intervals (Fig. 2). While some nonglacial units contain alluvium that was likely eroded in part by alpine glaciers, the Puget Lowland was ice-free at the time of their deposition. A modern example of this process is the sediment deposited into Hood Canal by the Dosewallips River, which includes a minor amount of sediment derived from the melting Eel Glacier. While this sediment came from an alpine glacial setting, it is being deposited in the Puget Lowland during a nonglacial interval.

## POSTGLACIAL LANDFORMS

### Landslides

Historic bluff failures have occurred at Termination Point, and mass wasting was again active there during the winters of 1996 through 1999 (W. Gerstel, Qwg Applied Geology, oral commun., 2012; W. J. Perkens, Shannon and Wilson, unpub. report, 2000). At least one home was moved back from the bluff after the 1996–1997 storms reactivated landslides west of the Hood Canal Bridge. More recent damage to Thorndyke Road occurred between Thorndyke Bay and South Point on what appears to be a large deep-seated slope failure. Bluff failure at Termination Point is likely related to tectonic deformation along potentially tectonically active structures associated with the Kingston arch (see *Structure*, p. 3). This deformation has tilted the nonglacial deposits (unit Qco) south toward the canal by up to 12 degrees, promoting bluff failure.

Birdseye (1976b), Deeter (1979), and WADOE (1979) identified numerous landforms as landslides along the bluffs of Hood Canal. We have mapped five main areas as landslides along the shoreline, based on morphology and signs of instability. Two of these locations don't seem to be deep-seated landslides, because the midbluff slope break corresponds with recessional lake shorelines at similar elevations and the deposits on these benches aren't landslide material. Instead they appear to be ice-contact stratified drift, suggesting deposition in an ice-marginal drainage environment. These stratified deposits can be unstable where deposited on less permeable silts. Additionally, the bluff and the deposits on the bench can be periodically unstable. At one location north of Thorndyke Bay, we observed instability of recessional outwash sands and gravels deposited on this mid-slope bench, but the Olympia-age sands, silts, and pebble gravels below are not deformed. Instead, landslides occur above the beach bluff, likely failing on fine-grained deposits of the Olympia nonglacial interval. These benches may be the result of erosion along an ice-marginal drainage or stagnant-ice features such as those found in the southern Hood Canal area (Contreras

and others, 2012a,c). These midslope benches parallel Hood Canal on the west side and ring each moderately sized drainage on both sides of the canal between Lilliwaup and Holly (Contreras and others, 2012c).

Additional modification of the topography likely occurred during earthquakes, given proximity to active faults and stratigraphy conducive to liquefaction. Determining the true nature of these landforms is beyond the scope of this mapping. Site-specific analysis is required to adequately assess slope stability.

### Nonglacial Sand Deposits

Extensive sand deposited during the Olympia nonglacial interval (unit $Qc_o$), reworked by glacial recessional meltwater and modern stream and beach transport, provide abundant sand to this part of Hood Canal. This sand is easily eroded and transported to beaches and is in stark contrast to material available to the south. Mapping in the Lofall quadrangle, we found extensive shallow sandy beaches not encountered in our previous geologic mapping in the southern Hood Canal area. In many places along the bluffs, this sand with interbedded silt extends from sea level to 300 ft above sea level and was generally mapped as advance deposits of the Vashon glaciation by previous investigators (Deeter, 1979; Kahle, 1998; Yount and others, 1993). (See additional discussion under $Qc_o$, p. 8.)

## STRUCTURE

It is difficult to model the interaction of the Seattle, southern Whidbey Island, and Hood Canal fault zones in the quadrangle due to the structural complexity, relatively minor changes in geophysical anomalies, and absence of bedrock exposure. Our map provides additional field evidence for the Lofall fault and Port Ludlow uplift (Brocher and others, 2001) and other structures that appear to deform Pleistocene deposits. We suggest that there is a connection between the Kingston arch (Johnson and others, 1994) and the Lofall fault, based on magnetic anomalies and their proximity to one another.

### Lofall Fault Zone

The Lofall fault as named by Brocher and others (2001) bounds the southern edge of the Port Ludlow uplift—an uplift of unknown origin adjacent to and west of the Kingston arch (Pratt and others, 1997). The Port Ludlow uplift is cored by basalt of the Crescent Formation (Arnold, 1906) and shows up in Brocher's tomographic model and in gravity and magnetic anomalies. Its southern edge approximately parallels the north shore of Squamish Harbor where we map a fault through Squamish Harbor to the north edge of the map that is likely associated with Brocher and others' Lofall fault. We mapped this fault based on magnetic anomalies, deformation of Pleistocene deposits, and the apparent offset of basalt, which is exposed at the surface to the north of the fault and drops more than 3,000 to the south in the Seattle basin.

Magnetic anomalies suggest that a northwest-trending structure connects the Kingston arch and Lofall fault. We mapped the Lofall fault along this anomaly where basalt is exposed at the surface and observed in subsurface logs. This fault appears to have deformed silts of the Olympia nonglacial interval (unit $Qc_o$) at the base of the bluff near Termination Point. These deposits dip south by up to 12 degrees and are raised a minimum of 16 ft above modern sea-level in places (significant site S1, sec. 2, T27N R1E). The silts contain articulated marine shells in growth position from a time when sea level could have been much lower than present (Cutler and others, 2003). (See additional discussion under $Qc_o$, p. 10.) We believe the dip of these beds is caused by tectonic deformation and contributes to bluff failure.

We map a northwest-trending topographic lineament south of the Kingston arch (sec. 14, T27N R1E) that is parallel with the magnetic anomalies. This topographic lineament coincides with a 1,500-ft portion of the shoreline that protrudes 300 ft into Hood Canal. We do not know what this lineament represents.

Brocher and others (2001) observed a N–S-trending structure that bounds the Port Ludlow uplift on the east edge, in both their tomographic model and their magnetic and gravity data. We mapped this structure as an unnamed fault along magnetic anomalies because it appears to offset basalt found at the surface on the west side of the canal and basalt found 3,200 ft below sea level in the Union Oil Co. Pope and Talbot no. 18-1 well.

### Kingston Arch

Two exploration wells were drilled to the east of the map area in 1972 along an east-plunging anticline termed the 'Kingston arch'. Shallow upper-plate seismicity in the area suggests the structure could be active (Pacific Northwest

Seismic Network, http://www.pnsn.org/), and Mace and Keranen (2012) found faults cutting postglacial sediment on the northern flank of the Kingston arch to the east of the map area. We mapped the Kingston arch where an apparent anticline crosses seismic line 75 of Dadisman and others (1997). We also extrapolated this structure toward the Pope and Talbot no. 18-1 well to the southeast (see Fig. 1 on map sheet), but we are not confident about the orientation or extension of the arch to the west side of Hood Canal and thus did not map it along the western part of the map area. The seismic and magnetic data north of the Kingston arch suggest structural complexity. We speculate that the arch, the Lofall fault zone, and the unnamed N–S-trending structure of Brocher and others (2001) are connected.

### Vinland Syncline

Along the east shore between Vinland and Lofall, we map a northwest-trending syncline in silts, with limbs dipping up to 8 degrees. The deformed silts likely represent the Whidbey Formation or Possession Drift and could be of glaciotectonic origin. We extend the fold to a syncline we noted in seismic line 75 of Dadisman and others (1997) and depict it in the cross section, but have little additional data about this fold.

## DESCRIPTION OF MAP UNITS

Our map shows deposits generally having a thickness of at least 5 ft, although where stiff, impermeable, or geotechnically significant (for example, till or peat), we locally mapped thinner deposits. In most areas, we relied considerably on geomorphology, field relations, subsurface records, and Landsat satellite images to infer lithology. We used the Udden-Wentworth scale (Pettijohn, 1957) to classify unconsolidated sediments. Our mapping on Naval Base Kitsap–Bangor relied heavily on previous geological mapping included in Kahle (1998) and is poorly constrained because we could not access the area. We changed units based on our nearby mapping and new radiocarbon and IRSL dates, and we refined locations using lidar topographic hillshades.

We used the time scale of the U.S. Geological Survey Geologic Names Committee (2010). Most radiocarbon age estimates are stated as conventional carbon-14 ages and include “yr BP” after the date. In places, calibrated dates from other reports are included and “cal yr BP” is noted after the date. A USGS 7.5-minute topographic map of the Lofall quadrangle was used as a base map, but contact locations were generally refined by reference to a LiDAR (light detection and ranging, hereafter lidar) image, aerial photos, and field observations.

### 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, such as the Hood Canal Bridge).

Qa **Alluvium**—Sand to cobble gravel, locally includes silt, clay, and peat; typically gray and generally unweathered; loose; clasts subrounded; moderately to well sorted; stratified to massive; includes some lacustrine and beach deposits and may include unrecognized older glacial outwash; consists of reworked glacial and nonglacial deposits.

Qb **Beach deposits**—Sand to boulder gravel with shells and driftwood; gray to brown-gray; clasts moderately to well rounded; may be well sorted; loose; derived from shore bluffs, streams, and underlying deposits. This 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 a result of easily eroded sand from extensive nonglacial deposits derived from the central Cascades (see additional information under $Qc_o$, p. 10). 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.

$Qa_m$ **Relict alluvium and salt-marsh deposits**—Silty sand, silt, and pebble to cobble gravel, locally includes silt, clay, peat, and detrital wood; typically tan and generally unweathered; loose; clasts subrounded;

moderately to well sorted; stratified to massively bedded; may include older tide-flat deposits above current salt marsh. This unit is less than 6,000 years old and has been used to study relative sea level (Eronen and others, 1987; GS1, sec. 32, T28N R1W) and tsunami deposits (Bourgeois, 2008) because of its unique location at Shine and extensive peat deposits that have recorded sea level fluctuations, tephra, and pollen during the Holocene.

## 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 includes upland wetlands and flat surfaces in closed basins, except where standing water was identified. We mapped some peat on the basis of topography and aerial photos. Unit Qp overlies Vashon Drift and older glacial deposits and typically is Holocene but may include some late Pleistocene deposits.

Qls **Landslide deposits**—Diamicton; loose or soft; clasts subangular to rounded; unsorted to poorly sorted; 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. Absence of a mapped slide does not imply absence of landslide hazard; some slides are too small to show at map scale. Where mapped, we had additional evidence to infer landslide movement, other than geomorphology. This often includes historical accounts of movement and damaged infrastructure. An example of this is near Termination Point during 1996–1997 storms, where bluff failure threatened some homes. Many deep-seated landslides appear to initiate on fine-grained sand and silts of the Olympia nonglacial interval. We map some landforms that could be ice-marginal drainage channels or shorelines of recessional lakes as landslide deposits, such as the bench north of South Point (secs. 9 and 16, T27N R1E). We are uncertain if they are deep-seated landslides, but other signs of instability encouraged us to map them as such. A similar example is just north of Thorndyke Bay (sec. 19, T27N R1E), where the mid-slope bench is covered with sand and gravel and is unstable. However, the Olympia-age deposits at the base of bluff do not appear disturbed, as would be expected if the landform were a deep-seated landslide. This unit is mostly Holocene but may include some late Pleistocene deposits.

Qmw **Mass-wasting deposits**—Pebble to boulder gravel, sand, 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 lidar shaded-relief maps suggested mass-wasting deposits large enough to show at map scale, but where the landform is not clearly a landslide. Absence of a mapped mass-wasting deposit does not imply absence of slope instability or hazard. This unit is mostly Holocene but may include some late Pleistocene deposits.

Qaf **Alluvial fan deposits**—Sand and gravel and debris-flow diamicton; gray, weathering to brownish-orange; loose; clasts subrounded to rounded; typically poorly to moderately sorted; massive to weakly stratified. This 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 during the December 2007 storms. This aggradation added 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 locally includes some latest Pleistocene recessional deposits of the Fraser glaciation.

## PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

### Vashon Stade of the Fraser Glaciation (MIS 2)

The Puget lobe of the Cordilleran ice sheet covered the map area between about 17,000 and 15,700 cal yr ago, based on work to the southwest in the Hoodsport quadrangle (Polenz and others, 2012a). The ice filled the Puget Lowland to an elevation of 3,100 ft in the adjacent Brinnon quadrangle (Polenz and others, 2012b) and approximately 2,200 ft in the Eldon quadrangle to the south (Contreras and others, 2012a). Vashon drift in the map area is mostly an

unweathered, discontinuous, thin layer of subglacial melt-out till or ice-contact stratified drift (stagnant-ice) deposits with little lodgment till.

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). In the map area, the Puget lobe may have stagnated, causing the ice sheet to abruptly collapse into marine water at the Strait of Juan de Fuca (Ralph Haugerud, USGS, oral commun., 2012). This event was inferred from the lack of recessional moraines in the central Puget Lowland and the prevalence of stagnant-ice features such as eskers and kame and kettle topography.

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 from south to north. These lakes were graded to spillways to the south and eventually to the north. By the time parts of the map area were ice free, Lake Russell (named by Bretz) had formed. It was graded to the Black Lake spillway near Olympia. As ice continued to melt and provide additional spillways, Lake Bretz (Waitt and Thorson, 1983) drained to the north at Port Discovery and had progressively lower spillways (Haugerud, 2009b). Bretz noted deposits in Big Valley graded to lowering lake levels and termed this the Poulsbo channel, extending from Poulsbo to Hood Canal. Thorson (1981, 1989) studied the isostatic uplift of the area using recessional lake levels, which are represented by the modern elevations of delta deposits formed in these recessional lakes. 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 rising to the north at approximately 0.85 m/km (4.5 ft/mi). Within the map area, isostatic rebound is approximately 80 m (260 ft)(Thorson, 1989) of total uplift since deglaciation and less than 30 m (100 ft) since the marine limit (highest relict marine shoreline) was reached, when marine waters entered the Puget Lowland as the ice melted (Dethier and others, 1995).

Haugerud (2009b) mapped extensive outwash surfaces graded to various recessional lake levels on the Kitsap Peninsula. In the map area, he mapped outwash flats east and southeast of Breidablick that graded to Lake Russell at about 380 ft elevation. He also mapped recessional delta deposits near Breidablick, locally mined for sand and gravel, as graded to Lake Bretz. Haugerud inferred that (1) outwash channels in Big Valley and around Breidablick were graded to declining levels of Lake Bretz, and (2) the area just to the east of Big Valley was covered in ice at this time, based on the lack of channels to the east, and this ice forced down-cutting and erosion of the channel at Big Valley.

Mapping to the southeast on Bainbridge Island (Haugerud, 2005) and in the Suquamish quadrangle (Haugerud and Troost, 2011) depicted recessional sediments that were deposited in marine water at a sea level lower than modern and have since been isostatically uplifted. Haugerud (2009b) also suggested that the recessional delta at Lofall was graded to the marine limit at this time and is now isostatically uplifted. We mapped the Lofall delta near Kitsap Memorial State Park as outwash deposits (unit Qgo), but did not map it specifically as marine deposits because we didn't find evidence of marine deposition or find it necessary to map this deposit as a separate unit based on the possibility that it was deposited into and graded to marine water. We also acknowledge that the southern boundary of map area intersects the marine limit and that marine emergence gravels are found, but they are not thick or extensive enough to depict at map scale. These emergence gravels are the result of sediment deposited into marine water and later uplifted by isostatic rebound. Polenz and others (2013) found evidence for emergence gravels along Liberty Bay in the Poulsbo quadrangle but were unable to find convincing and extensive deposits to depict at map scale. They suggest that shorelines in the vicinity may represent this marine emergence. Haugerud and Troost (2011) map emergence gravels to the southeast of the map area.

We suspect that benches formed within modern drainages are graded to recessional lake levels. Many of these benches have what look like deep-seated landslide morphology. However, we think these landforms are the result of erosion and deposition during ice recession instead of mass wasting. These assertions are based on the following: (1) much of the landscape development occurred as the ice melted at the end of the glaciation, prior to vegetation, and we know that little modification has occurred since, because many surficial glacial landforms are preserved in this portion of the Puget Lowland, and (2) after the meltwaters cut down through existing deposits and recessional lakes covered the area, deposits along their shorelines formed benches at the various elevations. Examples of these deposits are in the unnamed stream drainage west of Breidablick. In the bottom of the drainage, the silts (unit Qcw) appear undisturbed and the bench appears to be graded to an elevation of about 125 ft—an elevation similar to other benches nearby. The materials making up the bench are sands and pebble gravels that do not appear to be colluvium derived from the surrounding drainage walls. If they were, they would be primarily sand and silt fragments. We suggest these benches are not landslides, but actually material that serves to buttress or support the walls of the drainage.

***Recessional Deposits***

Mapped recessional deposits of the Fraser Glaciation are units Qgoaf, Qgo, Qgog, Qgos, Qgic, and Qge. Porter and Carson (1971), Porter and Swanson (1998), and Haugerud (2009a) noted that deglaciation following the Vashon stade in the southern Puget Lowland probably began with stagnation of the ice sheet: 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 Lofall quadrangle; Polenz and others (2009a,b), Derkey and others (2009), and Contreras and others (2010, 2012a,b) depict stagnant-ice features throughout the area. Previous mapping assumed that the area is covered with Vashon-age lodgment till; however, shaded relief on lidar images and field work show that stagnant-ice deposits are more extensive at the surface than previous mapping suggests. The apparent roughness in topography on and near drumlins coincides with locations of stagnant-ice deposits and lack of lodgment till. We did find areas with mappable thickness of well-developed lodgment till that we mapped as unit Qgt. These deposits are likely younger than 16,420 cal yr BP, based on work by Porter and Swanson (1998) for the ice retreat from the Puget Lowland.

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 glacial meltwater outwash channels in isolated basins on the fluted upland surface. It is difficult to separate from units Qgic, Qgog, and Qgos, resulting in approximate boundaries between units. Locally divided into:

Qgoaf **Vashon alluvial fan deposits**—Sand and pebble gravel, silt, and cobbles; loose; subrounded; moderately to poorly sorted; stratified; form concentric lobes where outwash streams emerge from confining valleys. The relict fans do not appear to receive sediment and are often incised by modern streams. The unit is mostly mapped along the eastern edge of the map in or near Big Valley. The unit is recognized where lidar reveals dissected relict-fan morphology, often smoothed by recessional lakes. The fans were formed as the glacial ice melted or shortly thereafter, often eroding pre-Vashon nonglacial deposits, specifically sand from unit $Qc_o$.

Qgog **Vashon recessional outwash gravel**—Pebble and cobble gravel, sand, and local silt; gray to tan, locally iron-stained to red-brown and yellow, but clasts typically unweathered; clasts moderately to well rounded; moderately to well sorted; loose; typically 10 to 100 ft thick. The unit is mapped in outwash channels graded to recessional Lake Bretz as water drained to the north to Discovery Bay at approximately 200 to 300 ft in elevation. Unit Qgog rests on older nonglacial deposits and includes rip-up clasts of silt and peat eroded from these deposits. It can be differentiated from unit Qgo where recent gravel mining suggests viable deposits, as in the northwest corner of the map area, and extended on the basis of channel morphology.

Qgos **Vashon recessional outwash sand**—Sand, with minor pebble gravel and local silt; gray to tan; loose; clasts moderately to well rounded; moderately to well sorted; typically 5 to 50 ft thick. Mapped in outwash channels graded to recessional Lake Bretz or earlier lakes as water drained to the north into Discovery Bay. It can be differentiated from units Qgo and Qgog where recessional deposits are mostly sand. Haugerud (2009b) mapped this unit as delta fronts near Lofall where it appears to be the sand facies of these deltas. Unit Qgos was deposited by meltwater into recessional lakes or marine waters, then uplifted due to isostatic rebound. We mapped it in the vicinity of Lofall and Shine and in one location on the eastern margin of the map area where extensive fluvial sand deposits were observed but sufficiently higher in elevation than expected from Lake Bretz.

Qgic **Vashon ice-contact deposits**—Diamicton, cobbly pebble gravel, silty sandy till, silty pebble gravel, and pebbly sand, with minor sand and silt; yellow-tan to gray; loose to very dense; clasts subangular to subrounded; variously sorted; massive to well stratified; accompanied by stagnant-ice features, such as kettles, hummocky topography, eskers (separately mapped as unit Qge where distinct), and subglacial or subaerial outwash channels. Unit Qgic ranges in thickness from a few to tens of feet and is mapped over a

large part of the fluted upland surface on both sides of Hood Canal. Where lacking more recognizable stagnant-ice features, unit Qgic is commonly a friable, but compact subglacial melt-out till that appears permeable. It is typically distinguished from lodgment till by its apparent roughness in lidar shaded-relief and its association with other stagnant-ice features. It crudely corresponds with areas mapped by Haugerud (2009b) as pockmarked glaciated surface (his unit gp) on the Kitsap Peninsula. Unit Qgic lies directly on top of older, possibly early Fraser, alpine drift or nonglacial sand and silt deposits of the Olympia nonglacial interval. It rarely is found on recognizable Fraser-age advance glacial deposits, and in this quadrangle does not appear to have a lodgment till beneath as Haugerud (2005) also observed on Bainbridge Island. Though it can be found in fluted drumlins (indicating subglacial emplacement) as a diamicton, it lacks subhorizontal foliation, is permeable, and is less competent than a 'typical' subglacial lodgment till. It may be related to tills found by Laprade (2003) in the Seattle area. See additional discussion in Contreras and others (2012b,c). Locally divided into:

Qge **Vashon esker deposits**—Pebble to cobble gravel and sand; tan to brown; loose; clasts moderately to well rounded; typically well sorted; commonly with a thin film of oxidized cement between grains; forms low, elongate, sinuous hills; mapped in areas that were occupied by stagnant ice in the northwest portion of the map. Eskers near Thorndyke Lake appear to be truncated below 260 ft in elevation, likely because they were modified by recessional lakes.

***Subglacial Deposits of the Fraser Glaciation***

Qgt **Vashon lodgment till**—Mixture of clay, sand, and gravel (diamicton) with rare lenses of sand and gravel; gray, weathering to yellow-tan; dense; matrix-supported; unsorted with disseminated cobbles in a silt-sand matrix; unstratified; locally contains a friable shear fabric as a result of ice shear. Clast types include both northern- and Olympic-sourced rounded to subangular clasts. Unit Qgt thickness ranges from 1 to 20 ft, but is commonly less than 5 ft. 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 a sharp, unconformable contact with underlying units, which are most commonly older nonglacial deposits or early Fraser alpine outwash.

**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 Lofall area. During nonglacial intervals, rivers of the Olympic Mountains and the central Cascades aggraded and deposited thick packages of sand, silt, and pebble gravel (locally from the Olympic Mountains). Bretz (1913) believed that nine-tenths of the Pleistocene deposits exposed above sea level in the Puget Lowland are nonglacial deposits. The majority of the deposits found along bluffs in our current mapping area are nonglacial or from older glaciations and are not the result of the Vashon glaciation. The deposits directly below the surface sculpted by the Puget lobe do not appear to be from this ice mass, but from the Olympics and central Cascades during the Olympia nonglacial interval (MIS 3) or older stages. New ages suggest that these older nonglacial sediments dominate the stratigraphy north of the Seattle fault zone along Hood Canal and include deposits of the Whidbey Formation and Olympia nonglacial intervals.

Clague (2000) suggested 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 sediment was flushed from the mountains as alpine glaciers advanced and was deposited by aggrading streams as base level rose. Our dates suggest that the Puget Lowland was filling with sediment during the Olympia nonglacial interval (MIS 3)(Fig. 2), at least 12,000 years before the Puget lobe began advancing from British Columbia (Clague and others, 1980), but while alpine glaciers were active in the mountains surrounding the Puget Lowland. This is based on our youngest radiocarbon date from a well preserved piece of wood in unit $Qc_o$ at Thorndyke Bay (GD3; sec. 25, T27N R1W).

On the Toandos Peninsula in the Seabeck quadrangle to the southwest, radiocarbon dates and stratigraphy suggest that alpine glaciers produced outwash and drift prior to the Puget lobe arriving in the area (Polenz and others, 2013). Additionally Polenz and others mapped multiple glacial drifts, suggesting multiple glaciations recorded in the deposits of the area.

We relied on four finite radiocarbon age estimates taken from the extensive nonglacial deposits of interbedded sand and silt (unit $Qc_o$) to interpret much of the Lofall stratigraphy. These ages correlate with MIS 3, falling within the age range of the Olympia nonglacial interval, spanning 60,000 to 15,000 $^{14}C$ yr BP (Troost, 1999). We also collected three luminescence samples, but the results were not available until after most of the mapping was complete, and there is some disagreement between the radiocarbon and luminescence dates. In the end we relied on carbon analyses within the Lofall map area and the Seabeck quadrangle (Polenz and others, 2013) that suggest Olympia ages. The disagreement between dating methods occurred at two locations where four ages were obtained. The samples were thought to be taken from the same material but provided vastly different results, the two carbon samples (GD3, sec. 25, T27N R1W; GD5, sec. 26, T27N R1E) were found to be substantially younger than the luminescence samples (GD4, sec. 26, T27N R1E; GD8, sec. 25, T27N R1W) at both sites. Explanations for the discrepancy include: (1) the samples were taken from different strata at GD4 and GD5 and an unrecognized unconformity exists there; however, we are confident that GD3 and GD8 were taken from the same strata; (2) the carbon samples are contaminated with younger carbon, giving erroneously younger results; and (3) the luminescence samples were not completely reset prior to being deposited. Given the uncertainties, we relied on the stratigraphy, abundant organic material, and radiocarbon results, which suggest these deposits were formed during the Olympia nonglacial interval, although they may be older and belong to the Possession Drift. It is possible the two luminescence dates are correct and the sand deposits we've mapped as deposits of the Olympia nonglacial interval (unit $Qc_o$) on the east side of Hood Canal are actually the result of the Possession glacial retreat, as they are stratigraphically above Possession Drift.

As mapped in this report, deposits of the Olympia nonglacial interval are represented by beds of well-sorted, homogeneous quartz- and potassium-feldspar-rich sand and silts interbedded with pebble gravel and sand from the Olympic Mountains when the Puget Lowland was ice free. 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, 2007, 2010, 2013) and are not the result of an advancing Cordilleran ice sheet (Joe D. Dragovich, DGER, oral commun., 2013). The sands appear to have been deposited in a lacustrine or marine environment without dropstones. They are often massive, locally crossbedded, and may be analogues to part of Booth's "great lowland fill" (1994) but are too old to have been deposited in a proglacial lake impounded by the advancing Puget lobe. Had they been deposited into a proglacial lake, they would be younger than the 18.3 ±0.17 ka date that constrains the advance of the Puget lobe into the Georgia depression (Clague and others, 1980). These sands were deposited during the Olympia nonglacial interval and not during the Vashon stade of the Fraser glaciation.

Deeter (1979) showed that the now abandoned Kitsap Formation (Garling and others, 1965) was deposited over multiple nonglacial and glacial intervals and included deposits of Whidbey, Possession, and Olympia ages. We suggest there is some evidence for Possession Drift (unit $Qgd_p$) deposited on silt of the Whidbey Formation between elevations of 200 to 275 ft on the Kitsap Peninsula. This drift consists of northern-sourced pebble-gravel diamicton and dropstones on top of silt and appears discontinuous—suggesting erosion prior to deposition of Olympia nonglacial deposits above. A good exposure of this drift near its contact with the Whidbey Formation (unit $Qc_w$) is at significant site S3 (sec. 25, T27N R1E)(elevation 255 ft). The drift included dropstones of various volcanic lithologies and a northern-sourced diamicton we infer to be Possession Drift because it is stratigraphically on top of the Whidbey Formation or advance outwash. The exposure appears to be stratigraphically below deposits we've mapped as deposits of the Olympia nonglacial interval to the northeast at age sites GD4 (sec. 26, T27N R1E) and GD5 (sec. 26, T27N R1E), but, as discussed above, could be a part of the Possession Drift. Previous work to the south in the Holly quadrangle (Contreras and others, 2012c) and in the Poulsbo quadrangle (Polenz and others, 2013) found similar stratigraphy at similar elevations.

Mapping of Possession Drift in the quadrangle (Easterbrook and others, 1967) is based on one radiocarbon age estimate on marine shells from nonglacial deposits of the Olympia nonglacial interval. The date from the shells could be erroneous, but we believe that the deposits they were found in correlate with other deposits of the Olympia nonglacial interval throughout the map area. The shells found along Squamish Harbor (age site GD2; sec. 2, T27N R1E) were deposited on the drift that we interpret as Possession Drift. We also find this drift on top of silts inferred to be Whidbey Formation on the east side of Hood Canal.

Laminated beds of silt, sand, and clay of the Whidbey Formation in the map area below approximately 200 ft in elevation. We based our correlation primarily on OSL and IRSL age estimates to the south in the Holly and Eldon quadrangles (Contreras and others, 2012a,b). No convincing evidence for deposits of the Whidbey Formation exists

on the west side of Hood Canal in the map area; organic matter and shells dated for this study provided ages too young to be considered part of the Whidbey Formation.

***Pre-Vashon Glacial and Nonglacial Deposits***

Qpf **Pre-Vashon silt**—Silt, clay, and some sand and pebble gravel; brown or gray; compact; unstratified to well stratified; generally thought to be glaciolacustrine but may include nonglacial deposits; mapped along the southern map boundary, where Polenz and others (2013) map silt below Vashon till in the Poulsbo quadrangle, but were unable to confidently assign it to Vashon advance deposits or older nonglacial deposits. The unit is likely equivalent to unit $Qc_o$ or $Qc_w$ as mapped in this quadrangle, but without age control.

Qpos **Pre-Vashon northern-sourced glacial outwash sand**—Sand, silt, clay, and pebble gravel; brown or gray; compact; unstratified to well stratified; mapped along the southern map boundary, where Polenz and others (2013) map glacial outwash sand below Vashon till in the Poulsbo quadrangle, but were unable to assign it to Vashon advance deposits or older nonglacial deposits. The unit is likely equivalent in age to unit $Qc_o$ as mapped in this quadrangle, but without age control.

Qpu **Undivided Quaternary sediment older than Vashon till**—Sandy pebble gravel and sand with mud interbeds; compact; gray, with surficial iron staining and some light-brown mud beds; mapped along the southern quadrangle boundary within Naval Base Kitsap–Bangor ('Bangor Naval Base' on map sheet), where Polenz and others (2013) map undifferentiated deposits in the Poulsbo quadrangle. The unit is likely equivalent to unit $Qc_w$ or $Qgd_p$ as mapped in this quadrangle, but without age control or access to exposures on the base.

***Deposits of the Olympia Nonglacial Interval (MIS 3)***

$Qc_o$ **Olympia nonglacial deposits**—Sand, silt, pebble gravel, minor organic matter-rich silt and peat, and rare marine shells; tan and gray to light orange and dark brown; medium dense to loose; 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, potassium feldspar, minor hornblende, and lithic grains. On the west side of Hood Canal, 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 280 ft thick and is distributed throughout the map area. On the east side of Hood Canal it is found above approximately 250 ft in elevation; on the west side, down to sea level. The unit was deposited into a lacustrine environment or meandering flood plain that included marine water at least in one location (marine shells at age site GD2; sec. 2, T27N R1E). Rare oxidized ripple marks near the top of the unit (age site GD7; sec. 9, T26N R1E) suggest shallow water deposition. We did not observe gravel facies on the east side of Hood Canal, but suspect they must extend as far east as Bainbridge Island where Deeter (1979) found Olympic-sourced gravels and Haugerud (2005) termed them the University Point beds and assigned them to the Olympia nonglacial interval. Deeter believed that alpine outwash from the Olympics required a glacial setting, but Haugerud thought the radiocarbon dates, good organization of the deposits, and peat suggested slowly aggrading streams. Polenz and others (2013) also found extensive alpine outwash to the south in the Seabeck and Poulsbo quadrangles.

The dominant sand facies of this unit contains more potassium feldspar and monocrystalline quartz than would be expected from British Columbia and is petrographically indistinguishable from nonglacial sands observed across several quadrangles on the east side of the Puget Lowland (Dragovich and others, 2007, 2009a,b, 2010, 2011, 2012). The source of these deposits is apparently north Cascades intrusive granitic rock, such as found in the Snoqualmie, Index, and Grotto batholiths (Dragovich, oral commun., 2013). This implies that sediment was transported west across the Puget Lowland and deposited against the base of the Olympic Mountains at the same time as rivers draining the Olympics were depositing alluvium as far east as Bainbridge Island (Deeter, 1979; Haugerud, 2005).

To explain the deposition of fluvial and lacustrine deposits above modern sea level, previous workers have 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, forming a proglacial lake and filling it with silt and sand outwash (Booth, 1994; Booth and Goldstein, 1994). In the map area, our age data suggest that this part of the Puget Lowland was filling with fluvial and lacustrine sediment a minimum of 12,000 years before the Puget lobe blocked the Strait. Without an ice sheet blocking the outlet of the Puget Lowland, we struggle to find the mechanism to form a lacustrine environment when sea level would have been much lower than present. (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, causing the lowland to aggrade in a lacustrine and low-gradient fluvial environment suggested by the deposits. Alpine outwash could have aggraded to the point that the lowland could vacillate between lacustrine and fluvial systems. We believe it was possible for the ancestral Skagit and Snohomish Rivers to aggrade extensive deltas because the modern basins provide more than half of all annual sediment to the Puget Sound (Czuba and others, 2011), so these rivers could have impounded the outlet to the Strait during MIS 3. Similar aggradation during this nonglacial interval has been reported in British Columbia and the Willamette Valley (Clague and others, 2005; O'Connor and others, 2001).

However, sediment discharge from these rivers during MIS 3 is unknown, so suggesting aggradation of these rivers is speculative. Other mechanisms could include the Port Ludlow uplift and Kingston arch blocking access to the Pacific Ocean. Clague (1977) suggested aggradation in the Georgia depression occurred in a short period of time and gave estimates, but they relied on little data. We cannot currently postulate a better mechanism for raising the base level of the Puget Lowland and depositing these sands and silts during this nonglacial interval, but our dates suggest this is what occurred within the map area.

Unit $Qc_o$ was deposited on northern-sourced drift, thought to be Possession Drift, in the vicinity of Squamish Harbor and is covered by Vashon Drift on an erosional unconformity. We did not find extensive Vashon advance deposits, for example, the Esperance Sand Member of Vashon Drift (Newcomb, 1952), on top of this unit. Silt beds at significant site S1 (sec. 2, T27N R1E) dip 12 degrees to the south, which may be the result of deformation along a fault associated with the Kingston arch. The tilting contributes to failure of the bluff at this location. Tectonic uplift may also be partially responsible for the discrepancy in base level between modern sea level and a much lower global sea level during MIS 3 (Dragovich, oral commun., 2013). Clague and others (2005) found Quadra Sand (type locality British Columbia; Clague, 1976, 1977) at elevations above sea level but suggested that glacio-isostatic depression of the crust by the expanding Cordilleran ice sheet was responsible for this apparent high base level. We do not expect depression of the crust this far south during the Olympia nonglacial interval, but the base level could have been higher due to aggradation of rivers in the Puget Lowland. Deposition into a basin with a high base level is supported by other nonglacial deposits found above sea level in nearby quadrangles (Contreras and others, 2012a; Polenz and others, 2012b). Polenz found sediments at the 'Brinnon delta' that were deposited in a lacustrine environment and had OSL age estimates indicating Olympia age. Local reports of mastodon remains are from this unit (Carson, 1980). Two pollen samples taken for this study are characteristic of an environment colder and drier than today (Estella B. Leopold, Univ. of Wash., written commun., 2013)(significant sites S1, sec. 2, T27N R1E, and S2, sec. 25, T27N R1W, in Appendix A). This pollen is similar to pollen found at Strawberry Point (Hansen and Easterbrook, 1974) and is consistent with the stratigraphic position, having Possession Drift below. Reports of poor water quality—methane gas and oil—near Four Corners (sec. 26, T27N, R1E) likely stem from organic matter in this unit. Silt at the base of the unit contains articulated marine shells (*Clinocardium nuttellii, Nuculana pernula, Macoma moeta*) in growth position that are characteristic of shallow, circum-Arctic waters (Elizabeth A. Nesbitt, Burke Museum, written commun., 2012). The shells were dated at 37,840 ±380 yr BP (age site GD2, sec. 2, T27N R1E), which places them in the Olympia nonglacial interval, but the shell date is somewhat questionable due to the possibility of erroneous dates from marine shells (see Table 2 on map sheet). The Olympia nonglacial interval occurred between 15,000 and 60,000 yr BP (Fig. 2).

### *Deposits of the Possession Glaciation (MIS 4)*

$Qgd_p$ **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; light brown to gray; clasts subrounded to rounded; moderately to well sorted and unsorted; moderately

stratified and medium to thickly bedded; very dense and massive. The maximum observed thickness of unit $Qgd_p$ is about 250 ft along the eastern border of the map area; otherwise, it is a thin, discontinuous diamicton. The unit is exposed stratigraphically above the nonglacial unit $Qc_w$ in a few drainages on the east side of Hood Canal. On the west side of Hood Canal in the vicinity of Squamish Harbor (secs. 2–4, T27N R1E), exceptional exposures at the base of the bluffs are northern-source diamicton, commonly up to 15 ft thick, with laminated marine silts of the Olympia nonglacial interval (unit $Qc_o$) or recessional outwash deposited on top. While lacking obvious shells, the unit's texture and hackly fracture pattern may indicate marine water deposition similar to Possession glaciomarine drift to the east in the Port Gamble quadrangle (Brett Cox, USGS, oral commun., 2013). As mapped, unit $Qgd_p$ may include unrecognized older or younger drift east of Big Valley (secs. 2 and 11, T26N R1E) because no age control is available. We assumed the few exposures of northern-sourced drift along the west shore of Hood Canal, found under deposits of the Olympia nonglacial interval, were Possession Drift. We infer the age for this unit from multiple radiocarbon dates that are less than 37,840 yr BP found above it (date sites GD2, sec. 2, T27N R1E; GD3, sec. 25, T27N R1W; GD5, sec. 26, T27N R1E). However, there could be an unrecognized erosional unconformity between the dated material and the diamict, making the diamict much older than Possession age. From Breidablick southwest to the southern map boundary, poor exposure and access make the unit as mapped, largely inferred. The age range for Possession Drift is thought to be 60 to 80 ka (Easterbrook and others, 1967).

### *Deposits of the Whidbey Interglaciation (MIS 5)*

$Qc_w$ **Whidbey Formation**—Silt, clay, and sand; light gray to light brown; dense and stiff; clasts typically subangular to subrounded; well stratified and well sorted; thinly laminated to very thickly bedded. Some portions of the unit contain preserved organic materials recorded in well reports. Unit $Qc_w$ appears to have an average thickness of about 250 ft, with a maximum of about 325 ft, and extend to approximately 100 ft below sea level. This unit is found along the eastern shores of Hood Canal between Lofall and the southern map boundary. It appears to represent nonglacial prodelta deposits that received sand, silt, and clay from deltas to the north and east. Contact relations are unclear, but well reports and rare exposures suggest that thin, discontinuous, oxidized northern-sourced glacial drift is present above this unit; we assume this is Possession Drift (MIS 4). The base of this unit is not well exposed in the map area. However, exposures along the bluffs north of Vinland (sec. 28, T27N R1E) suggest deposition directly on northern-sourced drift inferred to be Double Bluff Drift (MIS 6) or older (unit Qpd). We cannot explain the apparent high base level needed to deposit these nonglacial sediments at elevations as much as 200 ft above modern sea level, but suggest that tectonic uplift or aggradation during nonglacial intervals may be responsible.

Unit $Qc_w$ is a poor aquifer; water wells are typically drilled through it and developed in older outwash below. Laminated clay in unit $Qc_w$ makes it a hydrologic barrier, causing springs at the top of the unit. Silts and clays along Big Valley are probably Whidbey Formation. Sparse age data from unit $Qc_o$ imply the relative age, but we have no direct age estimates for this unit from within the map area. We rely on luminescence age estimates from nearby quadrangles to infer the age of this unit; they range between 82.5 ±3.89 ka and 134 ±9.74 ka (Contreras and others, 2012a,c). These dates correspond with dates provided in Easterbrook (1994) for the Whidbey Formation (Easterbrook and others, 1967) less than 10 mi to the northeast of the map area.

### *Pre-Fraser Deposits, Undivided*

Qc **Pre-Double Bluff nonglacial deposits, undivided (cross section only)**—Predominantly silty clay, sand, and gravel with minor peat and wood; brown-gray and blue-gray; very dense and hard. The few wells that penetrated this unit encountered sand and silt with organic matter, suggestive of nonglacial strata. Unit Qc is less than 100 ft thick in the area of the cross section. It 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 others, 2008) or much older; we have no age control.

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 metamorphic and granitic clasts, indicating a northern source. The unit may reflect multiple glacial advances. Unit Qpd is found on the eastern side of Hood Canal between Lofall and Vinland (sec. 28, T27N R1E) where it includes northern-source diamict of unknown age. In the cross section, it is depicted as glacial drift older than Double Bluff Drift. It could be significantly older (Birdseye and Carson, 1989), but we have no age control. This unit closely resembles unit $Qgd_d$ mapped in nearby quadrangles (Contreras and others, 2012a,c), but exposures did not allow us to confidently differentiate it from Possession, Double Bluff, or older glacial deposits.

***Deposits of the Double Bluff Glaciation (MIS 6)***

$Qgd_d$ **Double Bluff Drift (cross section only)**—Diamicton; gray to blue gray; very dense. The few wells that penetrated this unit encountered diamicton suggestive of significant glacial strata. Unit $Qgd_d$ as depicted in the cross section is as much as 100 ft thick. It is found stratigraphically above and below 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). Unit $Qgd_d$ is inferred to have been deposited during MIS 6 but without age control. We tentatively correlate it with the Double Bluff Drift on Whidbey Island (Easterbrook and others, 1967).

## Tertiary Sedimentary and Volcanic Rocks

In 1972, two oil wells were drilled to the east of the map area along a structural uplift termed the Kingston arch (Johnson and others, 1994). The Union Oil Co. Pope and Talbot No. 18-1 well was drilled less than 2 mi east of the map boundary (see Fig. 1 on map sheet) and the Mobil Oil Corporation Kingston No. 1 well was drilled less than 6 mi east. The Pope and Talbot No. 18-1 encountered sedimentary rocks at approximately 1,350 ft below ground surface and the Kingston No. 1 at 1,720 ft. The Kingston No. 1 has been studied more than the Pope and Talbot well, so we rely primarily on information from the Kingston well (Rau and Johnson, 1999) to characterize sedimentary rocks depicted in the cross section. Based on field notes of Howard Gower, Brocher and Ruebel (1998) thought the sedimentary rocks in the Pope and Talbot well were likely Blakeley Formation, but provided few additional details. Rau and Johnson suggested that the upper part of the Blakeley Formation was eroded off the Kingston arch because they did not find evidence for the upper Blakeley Formation in the well, and exposures on Bainbridge Island and seismic interpretations supported this. We were unable to determine from the literature much about the formations encountered in the Pope and Talbot well, so we are unsure if the sedimentary rocks here were also eroded.

Hanson (1976) mapped the basalt near Shine as the Crescent Formation. Yount and Gower (1991) mapped bedrock near the Hood Canal Bridge as lower Eocene Crescent Formation and the sedimentary rocks from the Kingston well as “undifferentiated marine and nonmarine sedimentary rocks (upper Eocene and Oligocene), Blakeley Formation and Blakely Harbor Formation”. We relied on Yount and Gower’s work and depict these rocks in the cross section as “undifferentiated marine and nonmarine siltstone” because we had little additional information on these rocks and they are not exposed in the map area. We relied on Hanson and Yount and Gower for the one small exposure of basalt near Shine and mapped it as basalt of the Crescent Formation.

ΦEm **Undifferentiated marine and nonmarine siltstone and sandstone (upper Eocene to lower Oligocene) (cross section only)**—Marine siltstone and sandstone; light gray to gray and gray-brown. These sedimentary rocks were reported from the Union Oil Co. Pope and Talbot well No. 18-1 drilled in 1972.

$Ev_c$ **Crescent Formation (early to middle Eocene)**—Basalt; dark gray to greenish black; commonly includes amygdules of zeolite, opaque minerals, and chlorite-group minerals. Unit $Ev_c$ is found in an isolated outcrop along the shore of Squamish Harbor near Shine and in water wells and borings as far east as the Hood Canal Bridge. Magnetic anomalies, seismicity, and tilted Olympia-age silts suggest that a fault associated with the Kingston arch brings Crescent basalt to the surface here. We tentatively assign this exposure to the Upper Crescent Formation (Cady and others, 1972; Arnold, 1906).

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# Appendix A. Pollen Data

Analysis of two pollen samples depicted on the map as significant sites S1and S2. Counted and analyzed by Estella Leopold from the University of Washington.

| | **Significant site** | **S1** | **S2** |
|---|---|---|---|
| | **Sample no.** | 15-K-211-A | 46-K2-622 |
| | **Latitude and longitude (decimal degrees)** | 47.865702<br>–122.643428 | 47.807797<br>–122.744730 |
| | **elevation** | 9 ft | 9 ft |
| | **Radiocarbon age (conventional radiocarbon age)** | 37,840 ±380 yr BP | 25,850 ±120 yr BP |
| **Identified pollen species** | *Abies* (fir) | X | 7 |
| | *Acer* | | 1 |
| | *Alnus* | X | 1 |
| | *Artemisia* | | 1 |
| | *Asteraceae* | | 2 |
| | *Betula* | | X |
| | charcoal | X | |
| | *Chenopodiaceae* | | 2 |
| | fern spores | X | 5 |
| | herb pollen | | |
| | *Larix* | | 3 |
| | *Picea* | X | 16 |
| | *Pines* | X | |
| | *Pinus* | | 6 |
| | *Poaceae* | | 2 |
| | *Populus* | | 2 |
| | *Pseudotsuga* | X | |
| | *Selaginella cf densa* | | 7 |
| | *Tsuga* | | 2 |
| | *Tsuga heterophylla* | X | |
| | *Tsuga cf canadensis* | | |
| | non-tree pollen | | 18 |
| | **Interpretation** | Mixed conifer forest with climate similar to today or a dry environment based on abundance of pine. Forest perhaps had frequent fires. | Mixed conifer forest… maybe a cooler setting (no *Pseudotsuga*) because this time frame may not have been a true warm period. Lots of non-tree pollen. Surprised at the dry-loving flora. Not necessarily a forest setting. Lots of herbs, fern spores, small plants. Might be open vegetation, somewhat dry. Transitional toward glaciation. Diversity may support prior to full glacial. |