GEOLOGIC MAP OF THE SKOKOMISH VALLEY AND UNION 7.5-MINUTE QUADRANGLES, MASON COUNTY, WASHINGTON

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Errata: The name of Holocene ‘alluvium’ (units Qa_m and Qoa_m) was changed to ‘marine deltaic alluvium’ to distinguish it from unit Qa. The unit labels and colors of units Qoa (Holocene to latest Pleistocene alluvium) and Qao (uppermost Olympic-source recessional outwash) were inadvertently switched on the map legend. This has been corrected. Kasper Van Wijk has been added as fourth author to Lamb (2009). Corrections were made August 8, 2011.

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Geologic Map of the Skokomish Valley and Union 7.5-minute Quadrangles, Mason County, Washington

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INTRODUCTION

The map area surrounds the Great Bend of Hood Canal in the western Puget Lowland and is covered by predominantly glacial sediment derived from the Olympic Mountains and sediment sources north of the map area. Apparent structural complexity at the intersection of the Tacoma fault, Seattle uplift, Dewatto basin, Saddle Mountain fault, Lucky Dog structure (proposed herein), and perhaps other structures (Hood Canal fault, Olympia fault) suggests that statements about the depth and character of bedrock beneath the area may be speculative. Jones (1996) estimated sedimentary thickness above Tertiary bedrock at mostly between 600 and 900 ft, ranging from about 1000 ft in the southeast to about 100 ft in the northwest. Our review of well logs yielded no evidence to contradict these estimates. Tabor and Cady (1978) mapped Crescent Formation basalt in the North Fork Skokomish valley within about 1000 ft north of the west half of the Skokomish Valley quadrangle. Magnetic data (downloaded Feb. 10, 2010, from http://geo-nsdi.er.usgs.gov/ metadata/open-file/02-361/WA/WA_3082.faq.html#what.1) and unpublished gravity data (Richard Blakely, U.S. Geological Survey, written commun., 2010) suggest that further east, basaltic bedrock ends or quickly drops to much deeper depths. Data and interpretations of Lamb and others (2009) suggest similar conclusions.

Repeated Pleistocene glacial incursions into the map area deposited most of the unconsolidated sediment. Glacial drift deposited by Cordilleran (hereinafter “northern-source”) and alpine glaciers of the Olympic Mountains (hereinafter “Olympic-source”) determined the lithologic composition of the sedimentary units. Northern- and Olympic-source sediments resemble each other more in the map area than in most other parts of the Puget Lowland because on their way into the map area, Cordilleran ice sheets picked up sediment of Olympic provenance, and Green and Gold mountains, about 16 mi northeast of the map area, introduced additional rocks that resemble Olympic provenance and were characterized by Reeve (1979), Clark (1989), Yount and Gower (1991), and Haeussler and Clark (2000). In addition, Cordilleran ice sheets deposited Cordilleran sediment in the foothills of the Olympic Mountains west of the map area, so that deposits from Olympic-sourced glaciers and rivers in the map area commonly include rocks of Cordilleran provenance that they picked up en route to the map area.

Unconformities, weathering, paleosols, and field relations with deposits outside the map area suggest a broad age range for the pre-Fraser sediments in the map area and more stratigraphic complexity than we could demonstrate or untangle in this project, especially along the walls of the Skokomish and North Fork Skokomish valleys and the western and southern shores of Hood Canal. Previous workers have located the type sections for the Olympic Skokomish Gravel (location SGTS; Molenaar and Noble, 1970) and the northern-sourced Annas Bay Drift (location ABTS; Easterbrook and others, 1988) within the map area, and that of the Olympic Clark Creek Drift (Easterbrook and others, 1988) 2.3 mi north of the map area. We incorporated these units into other map units (see unit descriptions and Polenz and others, 2010). Previous workers suggested that some deposits in and near the map area are of mid- or early Pleistocene age (Carson, 1976; Naeser and others, 1984; Westgate and others, 1987; Easterbrook and others, 1988; Birdseye and Carson, 1989; Smith and others, 2007). We have arrived at similar conclusions, primarily due to new age control data (Table 1) and analysis of and correlation to a tephra exposure just north of the Skokomish Valley quadrangle (Polenz and others, 2010). Despite the new age estimates, much more work will be needed to develop a truly satisfactory model of the pre-Fraser stratigraphy, in part because the map area occupies the intersection of several known and suspected active faults.

STRUCTURE

Tectonic Setting

Located in the Cascadia subduction zone forearc, the Great Bend area straddles at least three regions of active uplift and subsiding basins. The structures bounding these regions accommodate margin-parallel shortening due to oblique convergence at the subduction zone (Johnson and others, 2004). Roughly 5 mi north of the Great Bend and parallel to western Hood Canal, the Saddle Mountain deformation zone marks the western boundary of crustal shortening of the Puget Lowland (Blakely and others, 2009). The southernmost region, the Olympia uplift, is apparent in geomagnetic and gravity data as a structural high bounded by the Olympia structure, which trends northwest–southeast across southern Puget Sound and may underlie the area southwest of the Great Bend (Danes and others, 1965). The Tacoma and Dewatto basins lie between the Olympia uplift and the Seattle uplift to the north. East of the Great Bend, the Tacoma fault, with south-directed reverse offset, marks the boundary between the Tacoma basin and Seattle uplift (Johnson and others, 2004). Prior studies have documented the Tacoma fault as extending across the southern Kitsap peninsula to the south shore of Hood Canal just east of the Union quadrangle (Sherrod and others, 2003b; Logan and Walsh, 2007; Nelson and others, 2009; Derkey and others, 2009). The Tacoma fault may extend into the map area but remains undocumented there. The Dewatto basin is located beneath the western part of the Tahuya peninsula, but its structural boundaries are not as well constrained as those of the Tacoma basin (Polenz and others, 2010). Bounded by the Tacoma fault and the Seattle fault, the Seattle uplift exposes bedrock at Green and Gold mountains west of Bremerton. The north-directed, reverse offset Seattle fault was inferred to cross Hood Canal north of the Lilliwaup quadrangle, based on aeromagnetic data (Blakely and others, 2009), but seismic surveys of the western Seattle fault suggest that the fault bends to the southwest, and it is unclear where or if the fault crosses the canal (Andrew P. Lamb, Boise State Univ., written commun., 2010).

Many studies produced radiocarbon-dated evidence for post-glacial coseismic land level changes, likely in association with M>6.0 earthquakes on the aforementioned structures. Dates for the most recent coseismic events associated with these structures are thought to be as follows: Olympia structure, ~900 A.D. (Sherrod, 2001); Tacoma fault, 770–1160 A.D. (Sherrod and others, 2003a); Seattle fault, 900–930 A.D. (Atwater, 1999); and Saddle Mountain fault zone, 700–1000 A.D. (Carson, 1973; Witter and others, 2008). Additional pertinent references, including some referring to older events, are included in the structural discussion of the supplement to this report (Polenz and others, 2010).

Evidence for Post-Glacial Tectonic Effects

A HOLOCENE ACTIVE STRUCTURE ACROSS THE LOWER SKOKOMISH VALLEY

We introduce a northwest-trending structure that shows evidence of tectonic activity within the past ~6000 years. We informally name it the Lucky Dog structure. The available data include Holocene ground deformation that we interpret as structural activity, and while we suspect a shallow fault of indeterminate dip and northeasterly vergence, the evidence could be accommodated by faulting, folding, or both. The main evidence lies in Skokomish Valley floor deformation that formed a 26 ft-high, northwest-trending berm across the northern three-fourths of the valley and confined the modern Skokomish River to a narrow corridor along the southern valley margin. This berm was first noted as a possible tectonic feature by Brian Collins of the University of Washington (Ralph Haugerud, U.S. Geological Survey, written commun. 2006). Southwest dips in pre-Fraser sediment northwest of the valley further support the presence of a structure. The structure remains poorly understood and probably is complex. We use a queried, approximately located fold symbol across the valley floor to represent the observed deformation and add a queried, approximately located and concealed, northeast-vergent reverse fault roughly parallel to and northeast of this fold. We located the fault as shown on the basis of geomagnetic data and a possible fault exposure in sediment at the north end of its mapped extent. Northwest of the valley, we show the fold as approximately located, queried, and concealed anticline, based on southwesterly dips in sheared, pre-Fraser sediment. The fold could, however, be a monocline or tilting due to faulting without notable folding. The length and character of the structure are not herein determined. Multiple lines of evidence for the structure are introduced below. More detailed information and discussion are provided in Polenz and others (2010).

Coring of the bog to the southwest (age-date site M438) suggests 26 ft of uplift on the structure relative to alluvial sediment beneath the bog. A radiocarbon sample from the core (Table 1, Lucky Dog bog core, age-date site M438) approximately dates the onset of bog-like conditions to A.D. 1200 to 1280. Analysis of lidar elevation data across the structure and delta reveals valley floor steepening (compared to the area near the active Skokomish River channel and delta) from the crest of the structure east to the delta (*see* fig. 4 of Polenz and others, 2010). This steepening suggests that 18 ft of relative land-level change took place between the crest of the Lucky Dog fold and the modern shore. An uplifted, relict shore is present along the way. Work in progress by Maria Martin (Univ. of Wash.) will quantify uplift on the Skokomish delta that was dated to A.D. 780 to 1000[1] (Table 1, age-date site M434, delta peat site), followed some decades thereafter by subsidence (Table 1, age-date site M436, delta beach stump). Where the crest of the Lucky Dog fold meets the northwestern valley wall (age-date site J287), pre-Fraser sediments dip as much as 42 degrees to the southwest, likely due to fault-controlled folding. Similar sediment is level-bedded 500 ft to the southwest (see horizontal bedding symbol). The next unnamed valley to the northwest contains similarly deformed pre-Fraser sediment on trend with the Lucky Dog fold and level-bedded sediment to the southwest, suggesting that deformation related to the Lucky Dog structure extends northward. Consideration of historic flood records in the context of other evidence for tectonic activity in the Skokomish Valley suggests that tectonic land-level changes may contribute to frequent flooding on the Skokomish River (Polenz and others, 2010).

Along the north side of the Skokomish Valley, 1.6 mi southwest of the crest of the anticline, an unconformity between pre-Fraser units dips gently west-northwest along Sunnyside Road, dropping 55 ft over 0.7 mi (apparent dip slope 0.85°). The unconformity slopes from the lowland to the Olympics, whereas streams that could have eroded the unconformable surface would most likely have drained the Olympic range and sloped from the Olympics to the lowland. This suggests that the unconformity has been tilted, although the axis and fulcrum of such tilting are unconstrained, and we have no information that would specifically relate this apparent tilting to the Lucky Dog structure.

SYNCLINE NEAR TAHUYA

A syncline inferred from two strike and dip measurements in older pre-Vashon lacustrine silts southeast of the Tahuya River is shown on the map. The apparent fold axis trends about S22°W, plunging 5 degrees. See Polenz and others (2010) for further discussion.

DESCRIPTION OF MAP UNITS

Surficial deposits in the map area generally consist of a mix of two provenances: (1) Olympic-provenance basalt-clast and sandstone sediments, and (2) a broadly similar but more diverse northern-provenance mix that additionally incorporates more than 5 percent plutonic and metamorphic lithic clasts indicative of Cordilleran provenance (North Cascades of Washington and (or) the Coast Ranges of British Columbia). Most upland surficial deposits are relatively unweathered, but variations in weathering of clasts, both

Table 1. Age control data from the map area. Uncertainty values preceded by '±' are one standard deviation (68% confidence interval) and age ranges reported as 'number-to-number' span two standard deviations (that is, 2σ = 95% confidence interval). Radiocarbon 'greater than' age statements (for example, >43,500 B.P.) include a 2-sigma variance against background radiation. Uncertainty statements reflect random and lab errors; errors from unrecognized sample characteristics or flawed methodological assumptions (for example, ^{14}C sample contamination from younger carbon flux; incomplete pre-depositional re-setting of luminescence samples) are not known. ^{14}C, radiocarbon analysis; ^{14}C AMS,

Age-date site	**Quadrangle**	**Site name**	**Analytical method**	**Age Estimate (^{14}C yr B.P. or ka)**	**^{13}C/^{12}C (o/oo)**	**Material dated**
M438	Skokomish Valley	Lucky Dog bog core	^{14}C AMS	780 ±40 B.P. (0.750–0.670 ka)	-26.9	plant material
M436	Skokomish Valley	delta beach stump	^{14}C	1050 ±60 B.P. (1.070–0.900 and 0.860–0.820, and 0.810 ka)	-25.4	cellulose from Douglas-fir[2] (*Pseudotsuga menziesii*) root, analysis on tree rings 34 to 43, counted inward from bark
			computation of estimated time of tree death	1.032–0.862 and 0.822–0.782 and 0.772 ka		
M434	Skokomish Valley	delta peat site	^{14}C AMS	1,130 ±40 B.P. (1.160–0.950 ka)	-25.2	five *Ranunculus* (wetland plant) seeds
TCN14	Skokomish Valley	Hood Canal School	^{14}C AMS	7,740 ±50 B.P. (8.600–8.420 ka)	-26	charred material, apparently wood
M831	Union	quarry dredge log	^{14}C	13,210 ±80 B.P. (15.870–15.400 ka)	-23.9	cellulose from western hemlock[2] (*Tsuga heterophylla*) log, analysis on tree rings 99 to 108, counted inward from bark
			computation of estimated time of tree death	15.767–15.297 ka		
M906	Skokomish Valley	Above US101 & Sunnyside Rd	^{14}C	41,710 ±2320 B.P.	-29.1	organic sediment
J231	Skokomish Valley	lower N. Fork Skokomish	^{14}C AMS	>43,500 B.P.	-25.4	degraded, microscopic plant fragments
M958	Union	Cranberry Creek	^{14}C AMS	>43,500 B.P.	-26.5	plant material
M495	Union	SR106 road-level peat	^{14}C	>47,000 B.P.	– – –	peat
T1245	Union	Summertide Resort	IRSL[3]	>245 ka	– – –	silty fine sand (apparent flood plain setting) from above (glacial outwash?) sand and gravel section
M470	Skokomish Valley	Purdy cut-off pit	IRSL[3]	>250 ka	– – –	sand with silt; apparent flood plain setting
J287	Skokomish Valley	Lucky Dog fold beds	IRSL[3]	no luminescence signal; sample lacks suitable minerals or is too old for technique, or was not reset before burial	– – –	sand from interbedded section of sand and gravel

[1] Some sample geologic units on this table differ from the map unit at the sample location, either because the sample came from the subsurface, or because the sample unit exposure was too small to show on map and was incorporated into a surrounding master unit.
[2] Tree species identified by Kathleen Hawes (South Puget Sound Community College).

radiocarbon analysis by atomic mass spectrometry; IRSL, infrared stimulated luminescence analysis. One-sigma ^{14}C age estimates (including AMS) are in radiocarbon years before 1950 (^{14}C yr B.P.) or as reported by lab or prior publication; ^{14}C ages stated in ka are in calendar years before 1950 divided by 1000. One-sigma ^{14}C ages (including AMS) are ‘conventional’ (that is, adjusted for measured $^{13}C/^{12}C$ ratio) if a $^{13}C/^{12}C$ ratio is shown; other entries may be ‘measured’ or ‘conventional’. Elevations are in feet as estimated in this study using Puget Sound Lidar Consortium lidar grid elevations projected to State Plane South, NAD 83 HARN, supplemented by visual elevation estimates on bluffs. Lidar elevation statements were not adjusted to account for systematic projection differences relative to base map.

Geologic unit	Lab no.	Elevation (ft)	Reference	Notes
Qp	Beta 273145	9.75 ±1	this report	Plant material extracted from core sample of organic-rich silt 4 in. beneath base of modern peat bog, 9 ft 6 in. to 9 ft 8 in. below bog surface. Sample marks time shortly before onset of peat accumulation at site. Lab reports 2-sigma calendric age as A.D. 1200 to 1280.
Qp	Beta 273144	6 ±2	this report	Tree rooted in freshwater peat soil that is overlain by organic-rich saltwater mud; both layers are now in intertidal zone and being exposed by active beach erosion 6000 ft NE of intersection of US101 and SR106. Lab reports 2-sigma calendric age as A.D. 880 to 1050 and 1090 to 1130 and 1140.
				Tree death is herein estimated at 38 calendar years younger than Cal B.P. (calendar year) age reported by lab.
Qm	Beta 263045	5.5 ±1	previously unpublished, NEHRP Award 07HQGR0009	Sample (seeds) harvested from the basal 0.5 in. of a 7-in.-thick peat buried beneath 2 ft of intertidal saltmarsh mud. Peat overlies 11 in. of sand (includes silt layer) interpreted as a liquefaction feature, and that in turn overlies at least 3 in. of intertidal(?) mud. Lab reports 2-sigma calendric age as Cal A.D. 780 to 1000.
Qoa	Beta 272798	~-43	this report	Geotechnical core sample from 70 ft below surface, with small amount of apparent charred wood. Lab reports 2-sigma calendric age as BC 6650 to 6470.
Qgd	Beta 273994	227 ±10	this report	Sampled from log dredged up by gravel quarry operation from “4 ft-thick blue clay” beneath “15-25” ft of Vashon recessional outwash gravel. Clay suggests lake setting, which could be Vashon recessional, full-glacial (sub-ice), or advance. Western hemlock favors but does not require nonglacial tree growth conditions (Leopold and others, 1982). Lab reports 2-sigma calendric age as BC 13,920 to 13,450.
				Tree death is herein estimated at 103 calendar years younger than Cal BP (calendar year) age reported by lab.
Qpp (in Qpu_{op})	Beta 271634	210 ±20	this report	Lab cautions that “^{14}C activity was extremely low” and that the “most conservative interpretation of age … is >43500”.
Qapd (paleosol within unit)	Beta 272772	86 ±3	this report	Two-ft-thick, red, horizontal band (apparent paleosol) in channel left cutbank, N. Fork Skokomish River, 12 ft above Sept. 2, 2009, water level. Lab cautions that “^{14}C activity was extremely low” and the “most conservative interpretation of age is infinite”.
Qpu_{op}	Beta 271635	101 ±2	this report	Lab cautions that “^{14}C activity was extremely low” and the “most conservative interpretation of age is infinite”.
Qpp (in Qpu_{op})	UW-48	34 ±3	Fairhall and others, 1966	Approximate location of ~2.5 mi SW of Union, and 47°19.7′; 123° 07.7′) indicates up to 100 ft NE or 300 ft SW of plotted location. Source reported elevation as “ca. 5 ft above road” and “ca. 25 ft”. Lidar indicates road level between 28 and 30 ft.
Qapd	T-1245	60 ±5	this report[4]	Tan, very fine sand to silt, interlayered with fines, from center of ~8 ft section of inter- bedded sand and fines, bracketed by sandy gravel above and below. Till of Olympic(?) source is exposed ~10 ft upsection from the sand and fines, or 14 ft above the sample. A separate Olympic-source till is exposed 30 to 35 ft below the package of sand and fines.
Qpu_{op}	57-M-470-E	47 ±4	this report[4]	Light yellowish brown to variegated sand with laminae of fines (image 324) from center (6 ft above base) of ~13 ft to 15 ft-high, apparent low-energy channel to flood plain section of alternating sand + fines, each up to 10 in. thick, and most <6 in. thick (image 316); sampled ~6 ft above woody debris from same site. Outcrop is near-vertical and most likely manmade, NW-facing surface exposed in small gravel pit. Sample distance from pre-disturbance surface unclear, but should exceed 4 ft.
Qpu_{op}	89-j-287-B	52 ±2	this report[4]	Sampled ~20 ft above road in 4 to 6 in. (stratigraphic thickness), stiff sand above hackly clay and below pea-gravelly sand to sandy pea gravel. Site is on steep roadside bank—unclear if natural bank or manmade cut. Stiff and compact, pale red ranging to orange and yellow, steeply (34–49°) SW-dipping, apparent low-energy channel to flood plain setting.

[3] Analysis performed on k-feldspar grains, fine silt fraction (5–10 micron) by multiple aliquot additive dose technique.
[4] Analysis by Shannon Mahan (U.S. Geological Survey).

within specific units and across units, are common and often increase lower in the stratigraphic section. Weathering and interstitial secondary clay content also tend to increase in coarse-grained units with higher permeability, in sediment derived from the Olympics, and at or below paleosols. Weathered units range in color from red to brown and yellowish brown. Some exposures include a mix of unweathered and weathered sediment. Such mixing can result from in-place weathering but also appears to partly reflect the presence of Cordilleran clasts alongside proximally sourced clasts of Olympic Mountains provenance. We attribute the mixing to incorporation into northern-source sediment of altered sediment previously shed off the Olympic Mountains north of the map area and ophiolitic Tertiary bedrock from Green and Gold mountains (Reeve, 1979; Clark, 1989; Yount and Gower, 1991; Haeussler and Clark, 2000).

While northern sediment can thus contain sediment of Olympic provenance, sediment derived from the Olympic Mountains can also contain up to 5 percent northerly derived granitics and metamorphics. Because of these relatively subtle distinctions, determining the source of glacial sediment sometimes required petrographic examination of thin sections. Petrographic examination revealed the relative abundance of either the polycrystalline quartz and high-grade metamorphic rock characteristic of Cordilleran provenance, or the angular sands of plagioclase feldspar, clinopyroxenes, and predominantly monocrystalline quartz (chert or vein filling) characteristic of Olympic provenance. Sediments that included 5 to 9 percent diagnostically Cordilleran clasts were classified as ‘northern-source’, and sediments containing only 0 to 2 percent Cordilleran clasts were classified as ‘Olympic-source’. Deposits with 2 to 5 percent Cordilleran clasts are common and were generally assigned to an Olympic or northern source based at least in part on field relations.

We sought to show as geologic units those deposits that form a sufficiently thick surficial cover to be of geotechnical significance, generally a thickness of 5 ft or more, although where stiff, impermeable, or geotechnically challenging units (for example, till or peat) were encountered or we sought to illustrate a geologic process, we locally mapped thinner deposits. In most areas, we relied considerably on geomorphology, field relations, and where available and helpful, subsurface records. We used the Udden-Wentworth scale (Pettijohn, 1957) to classify unconsolidated sediments. U.S. Geologic Survey 7.5-minute topographic maps were used as base maps, but contact locations other than marine shorelines were generally refined by reference to lidar, aerial photos, and field observations.

Quaternary Unconsolidated Deposits

HOLOCENE NONGLACIAL DEPOSITS

af **Artificial fill**—Clay, silt, sand, gravel, organic matter, and rip-rap; placed to elevate and reshape the land; may be engineered or nonengineered; shown where fill is readily verifiable and relatively extensive and appears sufficiently thick to be geotechnically significant (>5 ft); excludes roads.

ml **Modified land**—Local sediment, ranging from clay to gravel and diamicton, mixed and reworked by excavation and (or) redistributed to modify topography; shown where relatively extensive, masking underlying geology, and geotechnically significant (>5 ft); excludes roads, except across water basins and along the south shore of Tahuya peninsula, and abandoned pits where underlying units can be identified; includes aggregate pits active at time of mapping.

Qb, Qob **Beach deposits**—Transient sand, pebbles, pebbly sand, cobbles, silt, clay, and shells; clasts typically moderately to well rounded and oblate; locally well sorted; loose; derived from shore bluffs, streams, and underlying deposits. Unit Qb is active in the modern environment. Its deposits are generally transient, with beach erosion at times exposing underlying units. Subunit Qob resembles unit Qb in every way, but is older and forms elevated relict deposits. The age of unit Qob is constrained to less than about 6000 years because prior to that, sea level was significantly lower.

Qm **Marsh deposits**—Organic sediment and (or) loose clay, silt, and sand in tidal flats and coastal wetlands; saltwater to brackish equivalent of unit Qp; includes buried layers of freshwater peat in some areas, due to relative sea-level changes.

Qa_m, Qoa_m **Marine deltaic alluvium**—Gravel, sand, and mud; includes some organic saltmarsh deposits; clasts typically well rounded; moderately to well sorted and loose; stratified to massively bedded; clasts and matrix generally fresh; deposited in marine deltaic streams and on adjacent tidal flats; separated from unit Qa by presence of brackish water and tidal influence. Subunit Qoa_m resembles unit Qa_m in every way, but is older and forms relict deposits. The age of unit Qoa_m is constrained to less than about 6000 years because prior to that, sea level was significantly lower.

HOLOCENE TO LATEST PLEISTOCENE NONGLACIAL DEPOSITS

Qp **Peat**—Organic and organic-rich sediment; includes peat, muck, silt, and clay; typically in closed depressions; freshwater equivalent of unit Qm, but some peat areas near sea level also include minor brackish influence. Unit Qp was mapped in all recognized upland wetland areas and flat surfaces in closed depressions unless a different unit or standing water was specifically identified. Where field data were unavailable, unit Qp was mapped on the basis of topography, aerial photos, or prior mapping. The unit is predominantly Holocene but locally ranges to late Pleistocene.

Qls **Landslide deposits**—Cobbles, pebbles, sand, silt, clay, boulders, and diamicton in slide body and toe; angular to rounded clasts and grains; unsorted; generally loose, jumbled, and unstratified, but may locally retain primary bedding; commonly includes liquefaction features. Absence of a mapped slide does not imply absence of sliding or hazard. Some polygons include exposures of underlying units in scarp areas; elsewhere, head scarps are identified by a hachured scarp symbol across upslope map units. The unit is predominantly Holocene but may include some late Pleistocene deposits. A map boundary mismatch between the Shelton and Union quadrangles resulted where Schasse and others (2003) mapped unit Qgo at the expense of a landslide that was too small to show within the Shelton quadrangle.

Qmw **Mass wasting deposits**—Cobbles, pebbles, sand, silt, clay, boulders, and diamicton; generally unsorted, but locally stratified; typically loose; shown along mostly colluvium-covered or densely vegetated slopes that are potentially or demonstrably unstable; locally includes exposures of underlying units that either could not be mapped confidently or are too small to show, as well as debris fans, alluvial fans, and landslides. The unit is common along the flanks of recessional outwash channels. Absence of a mapped mass-wasting deposit does not imply absence of slope instability or hazard. The unit is predominantly Holocene but locally includes late Pleistocene deposits. A map boundary mismatch between the Shelton and Union quadrangles resulted where Schasse and others (2003) did not map a mass-wasting deposit that was too small to show within the Shelton quadrangle.

Qa, Qoa **Alluvium**—Gravel, sand, and silt, with some clay and peat; clasts typically well rounded; typically moderately to well sorted and loose; stratified to massively bedded; clasts and matrix generally fresh, but some exposures iron-stained; deposited in streams and on adjacent flood plains and terraces. Except in small drainages where streams have not yet eroded through Vashon deposits, the sediment source is primarily older Olympic sediment exposed upstream. Shear-wave velocity profiles east of the map area confirm that unit Qa tends to form a more diverse deposit than at least some deposits of unit Qgic (Polenz and others, 2009). However, the unit may locally include some recessional outwash (unit Qgo) and other late Pleistocene deposits. Subunit Qoa resembles unit Qa in every way, but is older and forms elevated relict terraces. Near Annas Bay, unit Qoa should not be older than about 6000 years because prior to that, sea level was significantly lower, which resulted in an erosional setting. Map boundary mismatches with the Shelton quadrangle to the south and Mason Lake quadrangle to the east resulted where Schasse and others (2003) mapped unit Qgo at the expense of limited Johns Creek valley floor alluvium and Derkey and others (2009) mapped unit Qgo at Deer Creek because unit Qa within their quadrangle was too small to show.

Qaf, Qoaf **Alluvial fan deposits**—Cobbles, pebbles, sand, silt, and boulders; typically poorly sorted and stratified; forms concentric lobes where streams emerge from confining valleys, and reduced gradients, channel morphology changes, and (or) increased substrate permeability cause sediment load to be deposited. Especially along the base of smaller steep drainages, deposition is commonly sudden, hazardous, and associated with significant storm events, such as the Great Coastal Gale of December 1–3, 2007. The unit is predominantly Holocene but locally ranges to late Pleistocene. Subunit Qoaf identifies relict fans that resemble unit Qaf in every way, but have stopped accumulating deposits. Such older fans are typically dissected by a modern stream channel that is deep and steep enough to preempt addition of modern sediment to the fan surface. A map boundary mismatch between the Shelton and Union quadrangles resulted where Schasse and others (2003) did not distinguish between alluvial fans and other alluvium.

PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

Deposits of the Vashon Stade of the Fraser Glaciation (northern source)

Qgo **Vashon recessional outwash**—Gravel and sand, with some silt and clay; clast rounding and sorting diverse, but most commonly subrounded and moderately sorted; clasts and matrix generally fresh, but some exposures iron-stained; loose, but where not separated by till, difficult to distinguish from the typically more compact unit Qga. Unit Qgo is stratified and typically 10 to 30 ft thick (subunit Qgog is thicker), based on exposures and well logs. Unit Qgo was deposited by Vashon meltwater in outwash channels or isolated basins. It stratigraphically overlies till. Most deposits are ice-proximal, as illustrated by a “jumping” outwash channel a few miles east of the map area (see fig. 2 of Polenz and others, 2009), and difficult to separate from unit Qgic, locally resulting in gradational boundaries and poor distinction between units Qgic and Qgo (and subunits). In the Skokomish Valley quadrangle, unit Qgo covers large perched terraces along both sides of the North Fork Skokomish valley, where it is probably dominated by gravel (unit Qgog) but was mapped as undivided outwash (unit Qgo) due to insufficient data density to support subdivision by texture. In the Union quadrangle, unit Qgo primarily forms small terraces that fill, and are locally incised into, troughs within the fluted upland. Many of these grade at their southern terminus into at least partially deltaic ice-contact deposits that seem geomorphically related to water surface levels in larger outwash channels (mapped as Unit Qgog) to the southwest. Elsewhere, unit Qgo is locally divided into:

Qgog **Vashon recessional outwash gravel**—Mostly gravel with clean, sandy matrix; ranges to or includes lenses and beds of sand and silt; gray to tan, locally iron-stained to red and yellow, but clasts and grains substantially unweathered; clasts moderately to well rounded; moderately to well sorted; loose and generally less compact than, but in some exposures difficult to distinguish from, advance outwash gravel (unit Qgag); typically 10 to 50 ft thick. Geomorphic relations suggest that thickness may locally exceed 100 ft. In the Skokomish Valley quadrangle, unit Qgog covers extensive, southeast-trending outwash channel plains that extend from the southern margin of the Skokomish Valley southeast to Shelton (2.5 mi south of the map area) and Oakland Bay at the south end of the Union quadrangle. We disagree with the notion of Bretz (1910) and Thorson (1981) that these channels were associated at their upper end with an ice-dammed lake that would have filled the Skokomish Valley to a water surface higher than that of Lake Russell and instead interpret their presence and character as evidence that such a lake did not exist (Polenz and others, 2010). At the southwest end of the Skokomish Valley quadrangle, unit Qgog includes bedded and channelized outwash gravel of mappable thickness (>5 ft) that appears to somehow drape underlying flutes without fully obliterating the fluted surface morphology (see fig. 2 of Polenz and others, 2010). A map boundary mismatch between the Shelton and Union quadrangles resulted where Schasse and others (2003) mapped undifferentiated unit Qgo and did not separately identify gravel-dominated deposits in

Vashon recessional outwash. The underlying geologic interpretation is the same in both quadrangles.

Qgos **Vashon recessional outwash sand**—Mostly sand, with some lenses and beds of pebbles and silt; mostly matrix-free; gray to tan; clasts moderately to well rounded; moderately to well sorted; loose and generally less compact than, but in some exposures difficult to distinguish from, advance outwash sand (unit Qgas); typically 5 to 10 ft thick. Most deposits were placed by small low-energy streams or are slackwater deposits graded to an adjacent, larger outwash channel. At the north end of Oakland Bay in the southeast corner of the Union quadrangle, the unit blankets the gentle valley side as bottom sediment from a proglacial lake.

Qgoaf **Vashon recessional alluvial fan deposits**—Cobbles, pebbles, sand, silt, and boulders; typically poorly sorted and stratified; forms concentric lobes where outwash streams once emerged from confining valleys, and reduced gradients, channel morphology changes, and (or) increased substrate permeability caused sediment load to be deposited. Unit Qgoaf identifies relict alluvial fans that resemble unit Qoaf in every way, but no longer receive fresh deposits and are constrained by cross-cutting or other field relations to a Vashon recessional setting. The deposit post-dates Vashon ice in its location—the apparent depositional agent was meltwater.

Qgof **Vashon recessional lake beds**—Glaciolacustrine silt that commonly ranges to fine sand or locally clay with sparse dropstones (pebble size or larger) mostly in structureless exposures; medium gray where fresh and light tan to light orange where oxide-stained; grains and clasts generally angular to subangular; well sorted; rhythmically bedded (varved?) to structureless; in some exposures, bed tops are thin and brown to gray, and bed bottoms are 1- to 3-in.-thick and lighter in color; loose, may be locally stiff, but not usually compact; deposited in an ice-dammed lake setting at the end of the Fraser Glaciation. At least 23 possible varves were counted in one 12-ft-thick exposure at Oakland Bay in the southeast end of the Union quadrangle, and 6 ft (minimum) of only faintly rhythmic exposure was noted in the Skokomish Valley quadrangle. The limited number of beds suggests a short existence for the glacial lake(s) in which unit Qgof was deposited. Mappable areas of the unit were noted around Oakland Bay in the southeast corner of the Union quadrangle, where the deposits are associated with Lake Russell (and Lake Leland?) (Bretz, 1910) and were observed only below about 180 ft elevation. Unlike Bretz (1910) and Thorson (1981), we found no reason to infer a significant ice-dammed lake, except perhaps Lake Russell, along the south side of the Skokomish Valley (see Polenz and others, 2010), which may explain why we also found no notable deposits of unit Qgof near the Great Bend. The only notable deposit of unit Qgof that we recognized in the Skokomish Valley quadrangle is midslope along the south side of the Skokomish Valley, 1.6 mi east of Purdy Creek, where Bretz (1910) and Thorson (1981) inferred an ice-dammed lake with a water surface above that of Lake Russell. Field relations suggest to us, however, that unit Qgof at the south side of the Skokomish Valley represents a small, local lake separated by ice from the outwash channels that Bretz (1910) and Thorson (1981) cited in support of Lake Skokomish (see Polenz and others, 2010). Slope failures in similar deposits around Henderson Bay, northeast of Olympia (20 mi southeast of the map area), suggest that the unit is prone to sliding, even at low slope angles, where lateral support has been removed (Polenz, unpub. data). A map boundary mismatch between the Mason Lake and Union quadrangles resulted where Derkey and others (2009) did not acknowledge unit Qgof on top of Vashon till (unit Qgt).

Qgol **Vashon recessional glacial lake–deltaic outwash**—Gravel, sand, and locally fines; gray to brown; loose; moderately to well sorted and clean; formed by glaciofluvial reworking of upslope units into a systematic, ice-dammed-lake-marginal deltaic assemblage of gravelly glaciofluvial topset beds near the top, gravelly to sandy foreset beds in the center, and quiet-water lake-bottom (bottomset) beds dominated by sand at the base; bottomset beds grade laterally into unit Qgof. Unit Qgol was mapped at Oakland Bay, where it is 150 ft thick and forms the north end of the Shelton delta (Thorson, 1981; Polenz and others, 2010). A map boundary mismatch between the Shelton and Union quadrangles resulted where Schasse and others (2003) included lake marginal outwash deposits with the more general outwash unit Qgo.

Qgik **Vashon ice-contact kames and kame deltas**—Gravel, sand, some silt, and scattered lenses of diamicton; mostly loose; medium to very thickly bedded or massive; moderately to well stratified; commonly contains localized delta foreset beds, crossbedding, cut-and-fill structures, and oversteepened or slumped bedding. These elevated fluvial-deltaic deposits were mapped where sedimentary structures, geomorphology, and (or) geologic setting imply lateral ice buttressing. Stagnant ice occupied the Skokomish Valley and the Great Bend portion of Hood Canal during ice recession, resulting in perched ice-contact deposits, including kames, veneering parts of the valley walls. Their presence along the south side of Hood Canal provides one reason to doubt that a sizeable ice-dammed lake with a water level significantly above that of Lake Russell occupied the Great Bend area at the end of the Fraser glaciation (*see* Polenz and others, 2010).

Qgta **Vashon ablation till**—Unsorted, unstratified mix of gravel, sand, silt, and clay; large erratic boulders of plutonic or metamorphic (Cordilleran) rock common; mostly gray, but locally ranging to tan, light brown, or orange; typically unweathered; clasts commonly striated and faceted, with angular or rounded edges; loose; constitutes melt-out deposit directly from stagnant, wasting glacial ice. Unit Qgta generally forms a 2- to 6-ft-thick blanket atop lodgment till where unit Qgt is mapped, but it was mapped separately where evidence pointed to a thicker deposit. Its thickness rarely exceeds 10 ft.

Qgic **Vashon ice-contact deposits**—Sand, gravel, lodgment till, and flow till, with minor silt and clay beds; tan to gray; variably sorted; loose to compact; massive to well stratified; locally includes oversteepened beds that either reflect sub-ice flow or developed as collapse features or due to glaciotectonic (or tectonic?) deformation; ranges in thickness from a few feet (common on upland surfaces between 200 and 600 ft elevation) to a few hundred feet along flanks of large basins, where ice-contact deposits are commonly mapped as unit Qgik. Unit Qgic was deposited by meltwater or ice or both, generally late in the glaciation, and is commonly accompanied by stagnant-ice features, such as kettles and hummocky topography, ripples on flutes, disrupted surfaces on and between flutes, eskers (subunit Qge), and subglacial or subaerial outwash channels. Such features are widespread in the map area, and many resemble those illustrated by Polenz and others (2009, figs. 1-3). Where stagnant-ice features are found, lodgment till, if present, is commonly only a few feet thick, locally ranges to the “sub-glacially reworked till” noted by Laprade (2003), and is generally more permeable than a well-developed blanket of lodgment till. See discussion in Polenz and others (2009) of similarities between units Qgic and Qgo (and its subunits Qgos, Qgof, and Qgol).

Map boundary mismatches with the Mason Lake and Shelton quadrangles to the east and south resulted where Derkey and others (2009) mapped Vashon till (unit Qgt), Vashon recessional outwash (unit Qgo), or alluvium (unit Qa), and Schasse and others (2003) mapped unit Qgt or Vashon advance outwash (unit Qga). We mapped unit Qgic in those areas based on topographic irregularities and field observations that suggest the low areas between flutes contain stagnant-ice deposits that are looser and more permeable than intact till sheets. We disagree with some previous unit Qgo mapping in areas between flutes or where channels crosscut flutes, because such crosscutting suggests subglacial features. Some of the channels contain kettles, again favoring unit Qgic over unit Qgo. Unit Qga was previously mapped in some topographically low areas with hummocky topography that we see as an indication of stagnant ice. Unit Qa was mapped in a small area near Deer Creek in the Mason Lake quadrangle. The deposits are perched above the creek, suggesting to us that unit Qgic is a better fit. Locally divided into:

Qge **Vashon esker deposits**—Sand and gravel; tan to brown; clasts moderately to well rounded; moderately to well sorted, with good porosity and permeability; loose; deposited subglacially by Vashon meltwater in areas occupied by stagnant ice; forms low, elongate, sinuous hills on fluted uplands or subglacial outwash channels, and locally merges into channel incisions that help increase the infiltration capacity of the fluted uplands by locally cutting through underlying till (*see* fig. 1 of Polenz and others, 2009).

Qgt **Vashon lodgment till**—Unsorted, unstratified (but locally banded) mix of clay, silt, sand, gravel, and sparse boulders; typically supported by a sandy matrix; mostly gray, but locally ranging to tan, light brown, or orange; typically unweathered; commonly includes clasts or clumps plucked from underlying units; clasts commonly striated and faceted, with subangular or rounded edges; compact, with well-developed facies resembling concrete, but near the surface commonly hackly and (or) looser and covered by 1 to 6 ft of loose ablation till; deposited directly by glacial ice. Large (erratic) boulders of plutonic or metamorphic (Cordilleran) rock are common on till surfaces. Some exposures include interlayers and lenses of sand and gravel, locally with shears and joints. Till commonly forms a patchy and seemingly randomly distributed cover, up to several tens of feet thick, with 5 to 20 ft most common. It typically dominates, but is also locally discontinuous on, fluted surfaces, with individual drumlins measuring 0.03 to 0.3 mi wide by 0.3 to 1.3 mi long and the long axis aligned with ice flow. Till is typically in sharp, unconformable contact with underlying units, most commonly advance outwash (unit Qga). Unit Qgt lies stratigraphically below unit Qgo. It is tempting to interpret the concrete-like properties of well-developed lodgment till as evidence for an effective aquitard. However, variable till thickness and gradational association with more permeable ice-contact deposits and outwash channels in the map area suggest that in the map area the aquitard is commonly leaky. Unit Qgt may include unrecognized exposures of older till.

Qga **Vashon advance outwash**—Pebbles, cobbles, sand, and beds and lenses of silt and clay; gray to tan; clasts typically well rounded and well sorted; clean (<5% silt or clay in matrix), except in less-sorted and more angular ice-proximal deposits; generally compact (*see* fig. 4 of Polenz and others, 2009), but commonly cohesionless; very thinly to very thickly bedded; contains planar and graded beds, cut-and-fill structures, trough and ripple crossbeds, and foresets; thickness typically between 100 and 300 ft, with the unit top elevation rising gently across the map area from ~200 ft in the southeast to ~600 ft in the northwest, generally coinciding roughly with the surface elevation suggested for the “great Lowland fill” of Booth (1994); deposited as proglacial fluvial and deltaic sediment during Vashon glacial advance and typically overlain by unit Qgt along a sharp, unconformable contact. Exposures are generally gravel dominated, but some are insufficient to confirm gravel dominance or are more evenly divided between gravel, sand, and (rarer) fines. Such exceptions were common along the slopes above the North Fork Skokomish River, within about 1.5 mi south of the town of Union, within about 3 mi of the southeastern corner of the Union quadrangle, and on the Tahuya peninsula. Sand dominates the southern end of one long and skinny polygon along the northeastern channel margin of a recessional outwash channel near the southwest corner of the Skokomish Valley quadrangle. Widespread debris slides and debris flows associated with the Great Coastal Gale of December 1–3, 2007, and other significant storms contained ample gravel from unit Qga, thus confirming that it is prone to rapid, hazardous landslides. Springs are common at the apparent base of the highly permeable unit, indicating that the well-sorted, nearly matrix-free unit is an important aquifer. If correct, our suspicion that the fluted upland surface above is a “leaky” aquitard suggests that this aquifer may be sensitive to contamination (see also unit Qgt; Polenz and others, 2010, suggest a way to test this suspicion). Unit Qga was generally identified based on stratigraphic position beneath Vashon till, the presence of northern-source clasts or matrix, and paucity of weathering. It is otherwise undated and may locally include pre-Vashon northern outwash. A boundary mismatch between the Union and Mason Lake quadrangles near Hood Canal resulted where Derkey and others (2009) mapped unit Qls. We acknowledged the instability and mapped mass wasting deposits downslope, but mapped the upper slope, where ridges expose seemingly undisturbed thick gravel, as unit Qga. However, the gravel may have been deposited as a kame next to stagnant ice. A discrepancy also exists between the Union quadrangle and the Shelton quadrangle (Schasse and others, 2003), where unit Qgo was mapped in the valley walls of Johns Creek. Our identification of unit Qga was based in part on recent gravel pit exposures that did not exist when the Shelton quadrangle was mapped.

Qgd **Vashon drift, undivided**—Heterogeneous patchwork of stratified and unstratified sand, silt, clay, gravel, and diamicton; may locally include till, subglacial outwash, advance outwash, proximal recessional outwash, and ice-dammed-lake sediment; gray to tan; loose to compact; typically forms geomorphologically complex patchwork of mounds, terraces, incipient to fully developed channels, closed depressions, and erosional exposures of older units; predominantly Vashon Drift but may include older drift; shown where map scale or exposure do not support stratigraphic division. While in many ways similar to unit Qgic, unit Qgd typically includes more recessional outwash deposits and post-ice incisions, but fewer stagnant-ice indicators (eskers, subglacial drainage channels, and kettles). Unit Qgd is most widespread in the uplands of the Skokomish Valley quadrangle north of the Skokomish Valley, where till plain morphology is generally well developed but displays relatively little relief, a surficial patchwork of localized, recessional reworking of ablation till is common, and few exposures were available to confirm a thick or continuous sheet of lodgment till.

Pre-Vashon Glacial Deposits

Pre-Vashon Olympic-source drift of probable Fraser age (may include pre-Fraser deposits)

Exposures of generally unweathered or only faintly weathered Olympic-source outwash and till are widespread immediately beneath Vashon Drift in the map area north of the Skokomish Valley, especially in the upper valley walls of the North Fork Skokomish River. This Olympic drift is herein presumed to be of probable early Fraser age (Booth and others, 2004, global marine oxygen isotope stage 2—hereinafter MIS 2) on account of its exposures immediately subjacent to Vashon Drift and paucity of significant clast and till matrix weathering. However, its age is otherwise unconstrained, and it may predate MIS 2. The alpine ice advance that triggered deposition of this drift may have extended to the Tahuya peninsula, where a single polygon of unit Qad? between 250 and 300 ft elevation includes Olympic till and outwash. If the alpine till there is of early MIS 2 age, the exposure implies that immediately prior to the Vashon Stade, alpine outwash formed a braid plain across the paleo–Hood Canal, if such an inlet had previously existed. However, it is likely that a prior Wisconsinan Olympic glacial advance would have already filled any paleo–Hood Canal because at least farther north in the Olympic Mountains, prior Olympic glacial advances appear to have extended farther downslope than the early MIS 2 event (Jessica Hellwig, Univ. of Illinois, written commun., 2010). Consequently, the drift mapped herein as units Qao, Qat, and Qad, and especially the queried polygon of unit Qad? on the Tahuya peninsula, may represent a pre-MIS 2 Olympic-ice advance.

Qao **Uppermost Olympic-source recessional outwash**—Cobble to pebble gravel with occasional boulders and a (generally sparse) sandy to clayey matrix; matrix typically clay-rich and vesicular; gray to reddish brown, with commonly heavy iron-staining but generally unweathered clasts; compact; moderately sorted; generally level-bedded with widespread, gentle crossbeds, but ranging to structureless and locally bordering on diamicton; dominated by Olympic basalt (~67%) and sandstone (~33%), with less than 5% Cordilleran plutonic and metamorphic clasts. Along the western valley wall of the North Fork Skokomish River 0.9 mi south of the northern quadrangle boundary, 70 ft of unit Qao overlies an Olympic till, with the contact at about 455 ft. At the same latitude on the east side of the valley, 16 ft of the unit was observed atop a similar till, with the contact at ~435 ft. Elsewhere, no Olympic till was observed in direct association with the outwash, and it is unclear if the outwash is recessional, advance, or both, but it was mapped separately from unit Qad due to continuous or near-continuous exposure in the apparent absence of intervening till. Unit Qao was mapped in the upper, western sideslope of the North Fork Skokomish valley, about 0.4 to 1.4 mi south of the northern quadrangle boundary and was noted on the east sideslope at the same latitude, but due to map scale, was included with unit Qad there. It was also mapped between about 400 and 500 ft elevation in the westernmost two unnamed tributaries on the north side of the main stem Skokomish River east of the North Fork Skokomish River (secs. 4, 5, 8, and 9, T21N R4W). We believe that the unit formed a braid plain of Olympic outwash on the eastern flank of the Olympic Mountains.

Qat **Uppermost Olympic-source till**—Unsorted, unstratified (but locally banded) mix of clay, silt, sand, and gravel; typically supported by a sandy matrix; mostly gray, but typically slightly darker and more reddish or brownish than Vashon till; typically unweathered or only faintly weathered; compact, with well-developed facies resembling concrete; deposited directly by glacial ice; commonly includes clasts or clumps plucked from underlying units. Some clasts are striated and faceted, with angular or rounded edges. Sparse boulders are common within the till. Some exposures include interlayers and lenses of sand and gravel, locally with shears and joints. Observed exposures are up to 6 ft thick and were found in the upper valley walls of the North Fork Skokomish River, where some exposures are included with unit Qad. On the west side of the valley, we noted this till at about 450 to 455 ft, east of the valley at about 430 to 435 ft. The unit may have extended to the Tahuya peninsula (see discussion above at beginning of section). Unit Qat is typically in sharp, unconformable contact with underlying and overlying units and lies stratigraphically below unit Qao and above unit Qaa. It may include unrecognized exposures of older till.

Qaa **Uppermost Olympic-source advance outwash**—Cobble to pebble gravel with occasional boulders and a (generally sparse) sandy to clayey vesicular matrix; gray to reddish brown, with commonly heavy iron staining but generally unweathered clasts; clasts mostly subrounded; moderately sorted; compact; generally level-bedded with widespread, gentle crossbeds, but ranging to structureless and locally bordering on diamicton; dominated by Olympic basalt (~67%) and sandstone (~33%), with less than 5% Cordilleran plutonic and metamorphic clasts. Along the western valley wall of the North Fork Skokomish River, 0.9 mi south of the northern quadrangle boundary, about 35 ft of unit Qaa underlies an Olympic till, with the contact at about 450 ft. On the east side of the valley, 37 ft of the unit was observed beneath a similar till, with the contact at ~430 ft, about 1.3 mi south of the northern quadrangle boundary. Where no Olympic till was observed in direct association with Olympic outwash directly subjacent to Vashon Drift, the outwash was mapped as unit Qao and may include unit Qaa. Unit Qao was mapped in the upper, western sideslope of the North Fork Skokomish valley, about 0.4 to 1.4 mi south of the northern quadrangle boundary, and was noted on the eastern sideslope at the same latitude, but due to map scale, was included with unit Qad there. We believe that unit Qaa formed a proglacial gravel outwash braid plain derived from an alpine ice advance on the southeastern Olympic Mountains.

Qad **Uppermost Olympic-source drift, undivided**—Till and outwash consisting of cobble to pebble gravel with occasional boulders and a (generally sparse) sandy to clayey matrix; combines units Qao, Qat, and Qaa where map scale or limited exposures prevented separate mapping of the component units.

Pre-Fraser Olympic-source glacial deposits

Qapo **Pre-Fraser Olympic-source outwash gravel**—Cobble to pebble gravel with occasional boulders and a sandy to clayey oxidized matrix; gray to light orange-brown, typically darker and more reddish than northern outwash, even in gray exposures; clasts mostly subrounded; moderately sorted; compact; generally level-bedded with widespread, gentle crossbeds, but ranging to structureless and locally bordering on diamicton; dominated by Olympic basalt (~67%) and sandstone (~33%), with less than 5% Cordilleran plutonic and metamorphic clasts. Unit Qapo is variably weathered and locally includes fresh clasts but elsewhere appears more or less entirely saprolitized. The thickness of mapped exposures is poorly constrained but may locally exceed 160 ft along the side walls of the North Fork Skokomish valley. Unit Qapo is widespread along both sides of the North Fork Skokomish valley, where most exposures were included with unit Qapd, either because Olympic till was clearly present in addition to the outwash but map scale prohibited separate display, or because available exposures did not clearly reveal whether till was present. The observed exposures of unit Qapo (including those included with unit Qapd) are stratigraphically constrained by field relations to a pre-Fraser age, and weathering of many exposures suggests great age, but no other age control data constrains the mapped exposures within the map area. Well-developed paleosols are locally present within the unit (see also unit Qapd) and suggest time-significant depositional discontinuities. It therefore appears likely that unit Qapo incorporates outwash from multiple Olympic glacial advances. Some exposures may include Clark Creek Drift, but insufficient age control prevented definitive determination. This is further discussed in the supplement (Polenz and others, 2010).

Qapt **Pre-Fraser Olympic-source till**—Unsorted, unstratified (but locally banded) mix of clay, silt, sand, gravel, and sparse boulders; gray to brown, typically darker and more reddish than northern till, even in gray exposures; compact, with well-developed facies resembling concrete; deposited directly by glacial ice; commonly includes clasts or clumps plucked from underlying units; some clasts striated and faceted, with angular or rounded edges. Some exposures include interbands and lenses of sand and gravel, locally with shears and joints. Observed exposures vary in thickness. On the eastern sidewall of the North Fork Skokomish valley, well-developed exposures of largely unweathered lodgment till between ~200 and ~250 ft elevation reach at least 25 ft in thickness, with the top 3 ft locally weathered to a red, strongly developed paleosol. On the west side of the river, some exposures between 100 and 150 ft elevation may locally be 50 ft thick. Thinner tills were noted elsewhere and generally included with undivided unit Qapd on both sides of the valley and elsewhere in the map area. Although we were unable to demonstrate it in any individual section, we suspect that multiple Olympic glacial advances are represented by unit Qapt, as was noted farther north by Carson (1980). Exposures at beach level 8 mi north of the Union quadrangle indicate that at least one, perhaps the Clark Creek Drift, extended to the Tahuya peninsula (*see also* additional discussion in Polenz and others, 2010). A younger Olympic till near the north end of the Union quadrangle was mapped as unit Qad but may be of pre-Fraser age (*see also* Pre-Vashon Olympic-source drift of probable Fraser age). Unit Qapt tends to have sharp, unconformable contacts with underlying and overlying units and is stratigraphically bracketed by unit Qapo and unit Qapd.

Qapd **Pre-Fraser Olympic-source glacial drift, undivided**—Till and outwash consisting of cobbles and pebbles with occasional boulders and a sandy to clayey matrix; combines units Qapo and Qapt where map scale or limited exposures prevented separate mapping. We suspect that unit Qapd captures multiple Olympic ice advances, based on multiple intervening paleosols (at least three at the south end of the east side of the North Fork Skokomish valley, where they are identified by line symbols) and till exposures of varying thickness at varying elevations and with varying degrees of weathering, although stratigraphic relations between these exposures are insufficiently established to fully demonstrate multiple ice advances. At significant site J221, along the eastern bank of the North Fork Skokomish River, a weathered exposure of a 10-ft-thick section of thin-bedded to laminated silt and clay forms a gently east-dipping, gentle anticline. The exposure was previously mapped as glaciolacustrine by Carson (1976) and is in sharp contact with an underlying 3^{+} ft of weathered gravel of unknown provenance. Both the gravel and the overlying silt and clay may be entirely weathered to clay. Unit Qapd includes the type section of the Clark Creek Drift along US 101, 3 mi north of the Skokomish Valley quadrangle. The age and identification of the Clark Creek Drift there and elsewhere in the map area are further discussed in Polenz and others (2010).

Pre-Fraser northern-source glacial deposits

Assuming that Easterbrook and others (1988) correctly assessed the age of the Annas Bay Drift at its type section along US 101 at the north end of the Skokomish Valley quadrangle (location ABTS), some pre-Fraser northern drift may date to about 1 Ma (*see also* discussion of age of deposits in map area by Polenz and others, 2010).

Qpo **Pre-Fraser northern-source outwash**—Cobble to pebble gravel with occasional boulders and typically >5% sandy to clayey matrix; locally includes beds, lenses, and layers of sand or fines; typically weathered to reddish brown, but locally ranging to gray; clasts typically well rounded and well sorted, except in less-sorted and more angular ice-proximal deposits; compact; very thinly to very thickly bedded, with planar and graded beds, cut-and-fill structures, trough and ripple crossbeds, and foresets; clasts commonly weathered, some even saprolitized, but fresh clasts may predominate in some exposures; clayey matrix and iron and manganese coating in some exposures are thick enough to harden and provide increased cohesion to the outcrop, but more commonly the overall mass is weakened by weathering. The thickness of unit Qpo may reach 300 ft in the Union quadrangle on the south side of Hood Canal. Close to 200 ft may locally be present north of the Skokomish River, but the continuity of the unit throughout the section there has not been adequately substantiated, and previous workers have noted interfingering, complex relations between northern and Olympic drift in this area (Birdseye and Carson, 1989; Easterbrook and others, 1988). Unit Qpo appears to be widespread elsewhere in the subsurface, but its thickness is poorly constrained. The varying degrees of weathering and apparent interfingering of unit Qpo with Olympic drift indicate that unit Qpo includes deposits of multiple glaciations.

Qpos **Pre-Fraser northern-source outwash sand**—Sand, with sparse pebbles in some exposures; fine grained, locally ranging to silt; light gray; compact; horizontally laminated in clast-free, locally gently folded exposures of up to 20 ft thick; possible tectonic significance of folding unresolved (folded exposure on trend with (?) axis of deformation observed in relation to Lucky Dog structure farther southeast); elsewhere gently crossbedded. The unit was observed exclusively on the west side of Hood Canal at the north end of the Skokomish delta along an unnamed drainage that straddles the boundary between townships 21N (sec. 3) and 22N (secs. 34 and 35) (significant site M544). At the east end of the valley, the unit is exposed in sharp, unconformable contact with overlying, more weathered, compact Olympic gravel (unit Qpu_{op}). A map boundary mismatch with the Shelton quadrangle to the south of the Union quadrangle resulted where Schasse and others (2003) did not recognize pre-Fraser deposits in Johns Creek and instead mapped unit Qgo. The deposits are herein interpreted as pre-Fraser because they are compact and weathered and exposed low in the valley wall, similar to those in Cranberry Creek that provided an “infinite” radiocarbon age estimate.

Qpt **Pre-Fraser northern-source till**—Unsorted, unstratified (but locally banded) mix of clay, silt, sand, gravel, and sparse boulders; may include interbands and lenses of sand and gravel; gray to brown, typically lighter and less reddish than Olympic outwash; compact, with well-developed facies resembling concrete; deposited directly by glacial ice; commonly includes clasts or clumps plucked from underlying units; some clasts striated and faceted, with angular or rounded edges. The till is commonly sheared and jointed. Observed exposures vary from 2 to 20 ft in thickness. Varying degrees of weathering suggest that multiple northern glaciations are represented by unit Qpt, and although we were unable to demonstrate it in any individual section, previous workers have indicated multiple pre-Fraser northern tills within the map area (Birdseye and Carson, 1989; Easterbrook and others, 1988). Unit Qpt is typically in sharp, unconformable contact with underlying and overlying units and is stratigraphically bracketed by unit Qpo, as well as by unit Qpd. Most exposures of unit Qpt were included in map polygons of unit Qpd or shown as lines within other polygons.

Qpd **Pre-Fraser northern-source drift, undivided**—Till and outwash consisting of cobble to pebble gravel with occasional boulders and a sandy to clayey matrix; combines units Qpo and Qpt and is shown where map scale or limited exposures prevented separate mapping of the component units. Unit Qpd includes the type section of the Annas Bay Drift (location ABTS; Easterbrook and others, 1988).

Pre-Fraser glacial deposits of indeterminate provenance

Qpl **Pre-Fraser glaciolacustrine sediment, paleomagnetically reversed**—Silt, sand, and clay; gray to tan; compact, generally laminated; may locally contain sparse dropstones. Unit Qpl was recognized only along Frigid Creek in the northwest corner of the Skokomish Valley quadrangle. The unit was characterized by Westgate and others (1987) as magnetically reversed, based on exposures in a 135-ft-thick glaciolacustrine section described by Birdseye and Carson (1989) along a right-bank tributary of Frigid Creek, 0.1 mi north of the map area between 420 and 285 ft elevation. (Lidar suggests 20 ft lower elevations for all points, such that 420 ft $\rightarrow$ 400 ft by lidar; the following elevation statements are unadjusted from the source reference.) The section includes a gap between 340 and 290 ft and underlies a ^{14}C-infinite peat (Birdseye and Carson, 1989; Westgate and others, 1987; Easterbrook and others, 1988). A tephra at 380 ft yielded a fission track age estimate of 0.89 ±0.29 Ma (Naeser and others, 1984), and Westgate and others (1987) suggested that the tephra correlates to the Lake Tapps tephra at the Salmon Springs Drift type section of Crandell and others (1958). The implications for the rest of the map area of these age estimates and correlations are discussed in Polenz and others (2010).

Pre-Fraser Olympic-source glacial and nonglacial deposits, undivided

Qpu$_{op}$ **Pre-Fraser Olympic-source glacial and nonglacial deposits**—Mostly gravel, ranging to sand, silt, clay, and diamicton, including some tills and paleosols; tan to reddish brown, or gray in some exposures; gravel clasts typically pebble to small cobble size, with sandy matrix that is in many exposures suffused with and (or) weathered to clay; compact; poorly sorted in most exposures, but ranging to well sorted. Fresh clasts can be found in the unit, but overall weathering exceeds that of the overlying Fraser Drift and typically that of northern-source deposits of similar age, such as unit Qpo. Some exposures contain abundant saprolitized clasts and secondary clay matrix. Bedding is readily apparent in most exposures and is mostly horizontal with minor crossbedding, except where the Lucky Dog structure intersects the unit and beds dip southwesterly up to 52 degrees. Along about a mile of valley wall on the north side of the Skokomish Valley, unit Qpu$_{op}$ is separated by a seemingly planar unconformity from its underlying, deformed subunit Qpu$_{opl}$. A gentle west-northwest drop in the elevation of the unconformity suggests tilting (*see also* subunit Qpu$_{opl}$). Clasts in the unit are of mostly Olympic provenance, but some exposures include northern gravel and till. Where possible, such exposures are identified by lines (labeled as separate units). Unit thickness exceeds 200 ft and may exceed 300 ft, but the upper end of the unit is too poorly constrained in too many polygons to support a well-founded assertion of the latter thickness. Exposures of the unit are clustered along the slopes of the Skokomish Valley and the south side of Hood Canal up to about 1 mi east of the town of Union, suggesting an association with a paleo–Skokomish Valley that geographically resembled the modern valley. The unit includes the type section of the Skokomish Gravel (Molenaar and Noble, 1970) at the boundary between the Skokomish Valley and Union quadrangles south of Annas Bay (location SGTS), but we have not limited unit Qpu$_{op}$ to the Skokomish Gravel and believe that we have mapped as other units (Qapo and Qapd) some deposits that Molenaar and Noble would have intended to be included with the Skokomish Gravel. Our reasoning is explained in Polenz and others (2010) and is based in part on new age control that conflicts with Molenaar and Noble's assignment of the Skokomish Gravel to the Olympia nonglacial interval (MIS 3). Locally divided into:

Qpu$_{opl}$ **Pre-Fraser Olympic-source glacial and nonglacial deposits, lower facies**—Gravel, sand, silt, clay, and diamicton, including some till; tan to reddish brown, or gray in some exposures; gravel clasts typically pebble to small cobble size, with sandy matrix that is in many exposures suffused with and (or) weathered to clay; poorly to well sorted; compact. Fresh clasts can be found in some exposures, but at least some clasts are weathered in nearly all exposures, and some exposures are dominated by saprolitized clasts and secondary clay matrix. Sedimentary bedding is readily apparent in most exposures and undulates, seemingly randomly, across single outcrops or from one to the next, with typically gentle to moderate dips. The unit is dominated by Olympic-provenance material, but some exposures include northern gravel and till because the exposures were too localized to support separate polygons and lateral continuity could not be established, even over short distances. Unit thickness is at least 75 ft at the base of the slope below location BCS2, where the unit extends from the Skokomish River at 31 ft to a seemingly planar unconformity that separates the unit from the overlying, undivided Qpu_{op} at 106 ft. Unit Qpu_{opl} was identified only along about 1 mi of the northern valley wall of the Skokomish Valley. It was separated from the master unit Qpu_{op} based on the unconformity that marks its top and the pervasive, gentle to moderate, and seemingly random (?) deformation of its beds. This deformation stops abruptly at the unconformity, and the overlying beds of unit Qpu_{op} generally appear flat and undeformed at outcrop scale, leading us to suspect that unit Qpu_{opl} is significantly older than the overlying Qpu_{op}. The unconformity dips gently west-northwest along the bluff, dropping to 55 ft over 0.7 mi (*apparent* dip slope 0.0125; 0.7°). The west-northwesterly slope of this apparent dip seems inconsistent with the roughly easterly slope one might expect for deposits from a river that drains from the Olympic Mountains to the Puget Lowland, thus suggesting tilting of both unit Qpu_{opl} and the overlying beds at the base of unit Qpu_{op}.

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