Supplement to Geologic Maps of the Lilliwaup, Skokomish Valley, and Union 7.5-minute Quadrangles, Mason County, Washington—Geologic Setting and Development Around the Great Bend of Hood Canal

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Supplement to Geologic Maps of the Lilliwaup, Skokomish Valley, and Union 7.5-minute Quadrangles, Mason County, Washington—Geologic Setting and Development Around the Great Bend of Hood Canal

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Pleistocene incursions into the Puget Lowland of northern-source (hereinafter “northern”; also commonly referred to as “Cordilleran) and Olympic Mountains source (hereinafter “Olympic”; also commonly known as “alpine”) glaciers repeatedly eroded and deposited large volumes of sediment in the map area (Skokomish Valley, Union, and Lilliwaup 7.5-minute quadrangles). Nonglacial periods dominated by fluvial erosion of upland surfaces and alluvial deposition in paleo-valley floors (much like in the present setting) also contributed to the character and distribution of sediment in the area. Despite several new ^{14}C and luminescence age estimates, we were mostly unable to confidently subdivide this sediment by age but note that unconformities, differential weathering, paleosols and field relations with deposits outside the map area suggest a broad sedimentary age range. Two sedimentary exposures just north of the map area are known to be magnetically reversed, suggesting early Pleistocene (Matuyama) age (Westgate and others, 1987; Easterbrook and others, 1988). At one of these sites, glacio-lacustrine sediment and an Olympic drift downsection from it along a tributary drainage to Frigid Creek just north of the Skokomish Valley quadrangle rank among the oldest known Quaternary deposits above sea level in the Puget Lowland. Besides the paleomagnetically reversed signature of the glacial lake sediment, the assertion of early Pleistocene age for the Frigid Creek exposure—and probably others in the area—rests on analysis of and correlation to a tephra noted by Birdseye and Carson (1989) amidst the Frigid Creek glacio-lacustrine sediment. In addition, we compiled existing and obtained several new age estimates from the map area (Polenz and others, 2010, table 1). Yet the discussion below of tephra data coupled with the knowledge that the map area occupies the intersection of several known and suspected active faults, and the reality that the lithologic character of northern and Olympic sediments resemble each other much more in the map area than in most other parts of the Puget Lowland illustrate that much more work will likely be needed to develop a truly satisfactory model of the pre-Fraser stratigraphy in the area.

PRE-FRASER SEDIMENTS

Age Control for and Correlations among Pre-Fraser Sediments:

FISSION-TRACK AGE CONTROL AND TEPHRA AND PALEOMAGNETIC DATA

Glaciolacustrine sediments along Frigid Creek just south of the northwest corner of the Skokomish Valley quadrangle offer the best case for assignment of pre-Fraser deposits in the map area to a specific formation. Birdseye and Carson (1989) noted that these same glaciolacustrine deposits slightly north of the map area are down-section from outwash deposits of Olympic provenance, which in turn are downsection from peat that yielded a ^{14}C age estimate of >41,000 B.P., thus establishing a pre-Fraser age for the underlying Olympic outwash and glaciolacustrine deposits. Naeser and others (1984) reported a 0.89 ±0.29 Ma fission track age for tephra from the same glaciolacustrine beds (also just north of the map area), thus suggesting an early Pleistocene age for the section. Westgate and others (1987) used this fission track age estimate (now stated as 0.9 ±0.15 Ma) and chemical analyses of the Frigid Creek tephra, including analyses of some trace and rare earth elements, to advocate correlation to the 0.84 ±0.22 Ma (also fission track) Lake Tapps tephra at the Salmon Springs Drift type section (Crandell and others, 1958; reassigned to a “middle Quaternary” age by Easterbrook and others, 1981). Westgate and others (1987) further cited consistently magnetically reversed signatures of the glaciolacustrine silt above and below the Frigid Creek tephra to advocate correlation to the Salmon Springs type section, where Easterbrook and others (1981) had documented paleomagnetic signatures immediately upsection of the Lake Tapps tephra that were unstable and included both magnetically reversed and normal orientations in silt that Crandell and others (1958) characterized as nonglacial.

Thus, the fission track age statements are consistent with correlation of the Frigid Creek and Lake Tapps tephras, although their error bars would also permit separate origins. Similarly, the magnetic signatures permit correlation, but also a possible difference, especially considering that the Frigid Creek tephra is overlain by 40 ft of glaciolacustrine silt (Birdseye and Carson, 1989), whereas the Lake Tapps tephra underlies nonglacial (Crandell and others, 1958) silt. In contrast to the chemical correlation between the Lake Tapps and Frigid Creek tephras that Westgate and others (1987) advocated, Naeser and others (1984) asserted that the two tephra compositions differ. Given these potential discrepancies, we note the strong possibility of a Salmon Springs Drift association for the Frigid Creek glaciolacustrine deposits but map them as unit Qpl (pre-Fraser glacio-lacustrine silt and clay, reversely magnetized), thus permitting the possibility of a separate identity of broadly comparable age.

0.2 mi west of stratigraphic column 2 of Birdseye and Carson, 1989 (Polenz and others, 2010, Skokomish Valley quadrangle: top of Birdseye and Carson’s column marked on map by location BCS2), we sampled a tephra (Fig. 1; geochemistry sample site J136 in Polenz and others, 2010; hereinafter “power line tephra” in reference to its easily located exposure at Birdseye and Carson’s stratigraphic column—location BCS2—where a Bonneville Power Administration transmission line crosses the northern Skokomish Valley wall). Birdseye and Carson suggested that this tephra correlates to the Frigid Creek tephra, and, by implication perhaps also the Lake Tapps tephra. If valid, the correlation would also require a Salmon Springs Drift age for the deposits exposed at similar elevation for about 0.8 mi west and at least 0.2 mi east of the power line, which consist predominantly of Olympic gravel but also include some gravel of apparent Cordilleran and Green and Gold mountains provenance (hereinafter “northern” source). Moreover, an unconformity that is well-exposed 15 ft below the power line tephra at the power line (downslope from stratigraphic column location BCS2) and marks the contact between unit Qpu(op) and its underlying subunit Qpu(opl) would suggest that about 75 ft of underlying section predates the Salmon Springs Drift (see also mapped extent of Qpu(opl) and unit descriptions for unit Qpu(op) and its sub-unit Qpu(opl), Polenz and others, 2010). However, aside from the uncertainties that accompany the Salmon Springs Drift association of the Frigid Creek tephra, questions also surround the correlation of the power line tephra to the Frigid Creek tephra:

Figure 1. Power line tephra at geochemistry sample site J136 of Polenz and others, 2010. Like the Frigid Creek tephra, this tephra consists of a couplet, with the lower, thinner tephra bed being marked by the white line at the top of the rock pick. The upper, thicker tephra is marked by the Nejiri Gama (gardening tool) at the top of the image. Microprobe analysis (discussed herein) was performed on a sample of the upper tephra only.

Birdseye and Carson (1989) advocated correlation of the Frigid Creek and power line tephras, citing petrographic, stratigraphic and major element chemical attributes, including differential weathering patterns. However a fresh electron microprobe analysis of the power line tephra (Table 1) prompted our analyst to dismiss a Lake Tapps association (Franklin Foit, written commun., 2010). Foit instead noted high similarity coefficients (0.97) between the power line tephra and either the Shevlin Park Tuff (age unpublished), or the Summer Lake tephra bed FF (165 to 190 ka), both from the Summer Lake area in south central Oregon (Franklin Foit, written commun., 2010).

Table 1. Major element geochemical values for power line and Frigid Creek tephras

Tephra reference name	Oxide	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	MnO	Cl	Total[^]	Original total	No. of shards analyzed
power line (J136)	percent	68.68	15.81	3.71	0.67	5.77	2.31	0.77	2.11	no data	0.17	100	93.65	19
	standard deviation	0.73	0.31	0.14	0.06	0.26	0.11	0.08	0.23		0.02		1.73	
Frigid Creek[*]	percent	78.3	12.6	0.89[#]	0.2	3.4	3.7	n.d.	0.78	no data	0.14	100		18*
	standard deviation	0.4	0.2		0.03	0.4	0.1	--	0.12		0.04			
Lake Tapps[&] 3367, 11/22/1990 UT-88 T315-3	percent	77.27	12.94	0.88	0.15	4.02	3.77	0.15	0.79	0.03	no data	100	92.97	29
	standard deviation[&]	0.41	0.14	0.07[&]	0.04	0.13	0.09	0.02	0.04	0.02				
Shevlin Park[&] 3710, Oct 92 SPAT-4 T343-3	percent	68.45	15.63	3.83	0.69	5.91	2.34	0.83	2.2	0.11	no data	99.99	95.18	9
	standard deviation[&]	0.61	0.16	0.06[&]	0.05	0.24	0.06	0.05	0.17	0.03				
Columbia Canyon[&] BPT-CC T126-1	percent	69.34	15.31	3.7	0.67	5.7	2.3	0.72	2.12	0.13	no data	99.99	96.36	20
	standard deviation[&]	0.6	0.53	0.04[&]	0.07	0.18	0.04	0.04	0.04	0.03				

[*] Average per F. Foit (written commun., 2010) of three analyses reported by Westgate and others (1987), who reported n= 8, n=5, and n=5 shards per analysis.

[#] Westgate and others (1987) reported iron as FeO (0.71 for n=8; 0.87 for n=5; 0.81 for n=5); converted to Fe_2O_3 by F. Foit.

[&] Lake Tapps, Shevlin Park, and Columbia Canyon: unpublished data, USGS Tephrochronology Laboratory, Menlo Park, CA 94025, written commun. from Andrei Sarna-Wojzicki to M. Polenz, March and April, 2010. Major element oxide totals normalized by Andrei Sarna-Wojzicki. Standard deviations unadjusted from unnormalized data. Unnormalized iron expressed as FeO.

[^] Analyses normalized to 100 weight percent. Original totals: not stated for power line and Frigid Creek tephras; Lake Tapps 92.97%; Shevlin Park 95.18%; Columbia Canyon 96.36%.

Foit's suggestion of a possible Oregon Cascades provenance is reinforced by Andrei Sarna-Wojcicki, whose comparison of the power line tephra chemistry to known tephras in the U.S. Geological Survey Tephrochronology Project database similarly identified the Shevlin Park Tuff (Table 1) with a 0.97 similarity coefficient. However, Sarna-Wojcicki also provided a 0.983 similarity coefficient to the pumice of Columbia Canyon (Table 1), which is exposed west of Bend, Oregon, and stratigraphically underlies the Shevlin Park Tuff but overlies the ~400 ka Lava Island tuff (Andrei Sarna-Wojcicki, written commun., 2010), thus suggesting a possible age for the power line tephra somewhere between the age of the Shevlin Park Tuff and 0.4 Ma, if the Oregon Cascade connection is valid. While Birdseye and Carson (1989) had noted that apparent eolian differentiation in the Frigid Creek and power line tephras favored a distal eruption, Tom Sisson, in comparing the microprobe data of Foit to his own database of known tephras, suggested a possible association with Mount St. Helens, based on high levels of Na_2O and Na_2O/K_2O (Thomas Sisson, written commun., 2010). We prefer to interpret these somewhat conflicting views as evidence that a Shevlin Park tuff-age to 0.4 Ma, Oregon Cascade origin may be the best match for the power line tephra, but any correlation of the power line tephra remains speculative. A thorough analysis of the tephra chemistry, including trace and rare earth elements may well shed additional light on the volcanic source and correlation to other known tephras, and a direct age estimate for the tephra should ideally be explored, but neither was possible within this project.The proximity of the map area to deposits that are known to be magnetically reversed and the uncertainty that surrounds the above summarized attempts to correlate these deposits with deposits in the map area presents a quandary for assigning age estimates to the pre-Fraser deposits in the map area: on one hand, at least some deposits in the map area clearly are early Pleistocene in age. Indeed, some may pre-date those known to be early Pleistocene. On the other hand, the age control from near the map area demonstrates an age predating that of the Frigid Creek tephra only for the glaciolacustrine deposits that underlie this tephra along Frigid Creek and extend into the northern end of the Skokomish Valley quadrangle, where they were mapped as unit Qpl. Everywhere else in the map area, sedimentary ages have been effectively unconstrained except by stratigraphic relations among the mapped units and a single ^{14}C infinite age estimate obtained by John Noble from peat 5 ft above SR 106 near the boundary between the Skokomish Valley and Union quadrangles (Polenz and others, 2010, table 1 and age-date site M495). Moreover, the presence of the early-Pleistocene deposits at Frigid Creek is part of a story that, along with fossils of spawning sockeye salmon in comparable sediments 2 mi west thereof (Smith and others, 2007), hints at a long-established, cyclical pattern of valley-filling sedimentation, mostly during glacial times, alternating with re-excavation of more or less the same valleys at the end of the glaciations. While much of the valley fill in the Skokomish and North Fork Skokomish valleys will likely get removed during each erosional interlude, small slivers of sediment from each cycle are likely to persist and add to the complexity of geologic exposures along the valley walls, such that a diverse set of sedimentary ages should surprise no one. In that context, it is noteworthy that the degree of weathering of deposits in and near the map area varies widely, consistent with a broad range of sedimentary ages, and prior workers have advocated the presence of deposits dating to multiple Olympic and northern glacial incursions (Birdseye and Carson, 1989; Easterbrook and others, 1988). Yet their distribution and stratigraphic ordering has remained largely unconstrained.

Correlation of Map Units

Exposures along the valley walls and the slopes above Hood Canal in the map area are mostly restricted to isolated patches of sediment. With few exceptions, we were unable to identify marker beds that would have permitted us to confidently follow stratigraphic layers over more than a few hundred or a few thousand feet. Moreover, in most cases, we knew little about the age of each patch. Given these limitations and the conceptual possibility (see above discussion of Fission track age control, and Tephra and paleomagnetic data) of almost randomly scattered deposits of diverse ages, the ages of our pre-Vashon map units are defined to be broadly inclusive. Previous workers have assigned some deposits within the map area to the Salmons Springs Drift (Crandell and others, 1958), Annas Bay Drift (Easterbrook and others, 1988), Clark Creek Drift (Easterbook and others, 1988), and Skokomish Gravel (Molenaar and Noble, 1970). The type sections of the Skokomish Gravel (included with unit Qpu(op); location SGTS, Polenz and others, 2010) and the Annas Bay Drift (included with unit Qpd; location ABTS, Polenz and others, 2010) are located within the map area. However, since we define the age ranges for our pre-Vashon units much more broadly—typically constrained only to a pre-Fraser age, but commonly including deposits that are very likely—and in a few cases demonstrably—much older than Vashon Drift, the pre-Vashon map units are not based on the previously noted Salmon Springs Drift, Clark Creek Drift, Annas Bay Drift or Skokomish Gravel, and deposits from each of these previously defined units may be part of more than one of our map units.

PRE-VASHON GLACIAL DEPOSITS

Pre-Fraser Olympic-Source Glacial and Nonglacial Deposits, Undivided

The lower slopes of the Skokomish Valley and the southern shore of the Hood Canal east of the town of Union are dominated by deposits of mostly (but not exclusively) Olympic provenance, which are represented primarily by units Qpu(op) and Qpu(opl) but also include the glacial units Qapd, Qapo, and

Qapt in those areas (see also section on pre-Fraser Olympic source glacial deposits). Weathering varies greatly among these exposures and is generally correlated to elevation, but only crudely. Exposures are scattered, and traceable marker beds are mostly lacking. Sedimentary structures, grain size distributions, isolated till exposures, and relative abundance or paucity of organic matter among these exposures indicate that the exposures include both glacial and non-glacial deposits. These deposits are combined into map unit Qpu(op).

Although age control data remain sparse and arguably provide only minimum age estimates, new age control data permit some revision to previous interpretations, and limited stratigraphic distinctions permit some additional notes and recognition of a subunit. Unit Qpu(op) contains the type section for the previously defined Skokomish Gravel (Molenaar and Noble, 1970). The upper end of the type section is shown as stratigraphic column location SGTS ("Skokomish Gravel Type Section", Polenz and others, 2010). We have not limited map unit Qpu(op) to the Skokomish Gravel, however. Aspects of Molenaar and Noble's characterization align with our field observations from some exposures. These include the overall thickness of at least 200 ft, strongly weathered appearance in outcrop, but apparently lesser oxidation in well records, distinctly stronger weathering than the overlying northern till and outwash, and, at least near the Skokomish Gravel type section, an Olympic source gravel package above about 80 ft in elevation[1] that includes sparse clasts of northern source that quickly thin out upsection. Like us, Noble and Molenaar recognized that similar sections of Olympic gravel are present elsewhere in the area and not all are likely to be of the same age. Unlike Molenaar and Noble, we doubt that deposition of the Skokomish Gravel type section correlates to the Olympia nonglacial interval (MIS 3; Booth and others, 2004) and the early phases of the Fraser Glaciation (which, according to Booth and others, 2004, equated to MIS 2). We base our skepticism partly on a subjective sense that many exposures, at least in the lower ~80 ft of the section along SR 106 east and west of the town of Union and along Purdy Cutoff Road further west (and therefore apparently assigned to the Skokomish Gravel by Molenaar and Noble), are more strongly weathered than would be likely for deposits of MIS 3 age. More importantly, in addition to the ^{14}C-infinite age estimate that John Noble obtained from a peat 5 ft above SR 106 (Polenz and others, 2010, table 1, sample M495), we obtained a luminescence age estimate for a sandy deposit slightly northwest and almost directly downslope of the top of Molenaar and Noble's type section, at about 47 ft elevation in a small, private quarry 0.3 mi southeast of the intersection of SR 106 and Purdy Cutoff Road (Polenz and others, 2010, table 1, sample M470)—by every indication, a deposit that Molenaar and Noble would have included with the Skokomish Gravel. The age estimate indicates a minimum age of 250 ka, however, placing it early in MIS 7 or earlier.

Because we have been unable to identify marker beds that would lend themselves to unambiguously associating the beds from which we obtained our luminescence age control sample with similar deposits more than a few hundred to a few thousand feet distance in any direction, and because we still lack age control for the upper parts of the Skokomish Gravel type section, we note that the Skokomish Gravel clearly is not limited to deposits of an MIS 3 age, if it even includes any, but we resist the temptation to use the >250 ka age estimate to either redefine the age of the Skokomish Gravel or define another unit with a minimum age that corresponds to the age estimate for our sample. We instead define the age of map unit Qpu(op) simply as pre-Fraser and note that it clearly includes some deposits that are much older. We note that deposits within this map unit are not limited to nonglacial or glacial deposits, nor are they limited to Olympic deposits, though those clearly dominate. Map unit Qpu(op) is therefore less restrictive than the Skokomish Gravel, although it is dominated by deposits that are by their character compatible with the Skokomish Gravel, and our unit Qpu(op) appears to accommodate all deposits that Molenaar and Noble intended to include in the Skokomish Gravel. We did, however, map some gravel sections that may be compatible with the Skokomish Gravel separately as Qapo or Qapd where we had reason to believe that they were of glacial association. In effect, we found the Skokomish Gravel to be unmappable as unit and in need of revision regarding the age it was defined to belong to. For these reasons, we abandoned use of this unit for our mapping.

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[1] All elevation statements were measured on a digital elevation model courtesy of the Puget Sound Lidar Consortium. Within the limits of map accuracy, these are indistinguishable from USGS topographic base map contour elevations.

Aside from the area beneath the Skokomish Gravel type section, two areas that we included in unit Qpu(op) are noteworthy in that stratigraphic field relations and other characteristics indicate more than an undifferentiated pre-Fraser age. One of these is a localized (?) exposure at significant site M667 (Polenz and others, 2010) on the south shore of Hood Canal east of the town of Union, where a 30 ft section of interbedded gravel and sand at SR 106 road level was mapped as Qpu(op). Some clasts in this exposure were rotten beyond lithologic recognition. The rest convinced us that, despite a few apparent granitic clasts, the deposit is of probable Olympic provenance. Sedimentary structures indicate a fluvial setting that is compatible with the (nonglacial) low gradient alluvial setting of the modern Skokomish valley floor, in contrast to the less weathered, overlying Olympic source deposits of apparently glacial affinity, which comprise a 50 ft section of interbedded gravelly debris flow deposits and channel gravel, suggesting a steeper braid plain marked by rapid sedimentation. These Olympic glacial deposits were included with unit Qapd and are in turn overlain by a roughly 100 ft section of pre-Fraser, northern source gravel (unit Qpd) that thickens to over 200 ft within about a mile to the east, where it includes a northern source till. This pre-Vashon, northern source drift is notably less weathered than the underlying Olympic drift but also more weathered than the 200 ft section of Vashon advance outwash that extends to the top of the slope at 400 ft.

We noted the section at significant site M667 because within this map area, it provides a rare (?), easily recognized and orderly section of deposits that are progressively more weathered downsection, with distinct breaks in the degree of oxidation at each unit boundary, and a clear stratigraphic progression that requires unit Qpu(op) to be at least MIS 5 in age. Considering the severe degree of weathering in Unit Qpu(op) at this site, the general recognition that MIS 4 was a relatively mild glaciation (Mix, 1987) and the regional paucity of evidence that the Possession ice front extended significantly south of Tacoma (Lea, 1984; Troost, 1999; Troost and others, 2003), coupled with the observation that an ice sheet that barely advanced past Tacoma may have been prevented from reaching the Great Bend by Green and Gold mountains (northeast of the Great Bend), it is not far-fetched to speculate that the pre-Vashon northern source drift in this section may date to MIS 6 or before, and that therefore unit Qpu(op) would date to MIS 7 or older.

The second area of stratigraphic note within unit Qpu(op) is located on the north side of the Skokomish Valley beneath stratigraphic column location BCS2 and from there west for about a mile along the road near the base of the slope (Sunnyside Road). This section is noteworthy in that the road level exposures, while otherwise resembling the roughly level-bedded, upsection deposits within unit Qpu(op), are contorted, dipping gently to moderately, in seemingly random manner. The top of the contorted lower section is marked by a planar unconformity that drops gently but apparently steadily westward from ~106 ft elevation beneath stratigraphic column location BCS2 to ~55 ft 0.7 mi to the east. We interpret the unconformity as probably time-significant break and have therefore separated the lower section into sub-unit Qpu(opl). The presumption that the predominantly Olympic source deposits in this area should generally slope to the east, away from the Olympic Mountains, suggests that the unconformity records tectonic tilting of the sediment above and below the unconformity. Additional characterization of the unit, the unconformity, and the apparent tilting is provided in the unit description (Polenz and others, 2010), and speculations on the age of unit Qpu(opl) are provided in the discussion on fission track age control, and tephra- and paleomagnetic data.

We obtained sedimentary age analyses from unit Qpu(op) in two locations along US 101 on the west side of the Skokomish Valley. The more northerly of these is a luminescence age analysis that was sampled on the west side of the intersection between US 101 and SR 106, just above the “Lucky Dog” Casino sign (age-date site J287, table 1 and map of Polenz and others, 2010). At this site, Robert Carson (Whitman College, unpub. manuscript, 1980) had aptly characterized sandy to fine pebbly sediment as weathered but not rotten, less consolidated than any bedrock in the southeastern Olympics, and “not typical”. We might add only that for the degree of oxidation of the sand, the deposit struck us as uncommonly clean, that is, essentially lacking a clay matrix, which reinforces the “atypical” character of the exposure. Weldon Rau had informed Carson in 1972 that he had been unable to find microfossils in a sample from this exposure (Robert Carson, unpub. manuscript, 1980). Unusual, steep westerly dips in the sedimentary strata suggest the possibility that particularly old sediment may be exposed near the crest of an apparent anticline associated with the Lucky Dog structure (Polenz and others, 2010, and structure discussion herein). The luminescence analysis is both unhelpful and consistent with this notion. It yielded no age estimate because the Olympic-sourced, basaltic sand and silt deposits provided at best marginally sufficient quantities of k-feldspar for analysis (the same would hold true for quartz), and the k-feldspar that was targeted for analysis provided no detectable luminescence signal—consistent with either a deposit too old to permit dating with this technique, or too lacking in the necessary feldspar, or consisting of sand and silt particles that were not subjected to resetting of their luminescence signal prior to deposition. Based on the sedimentary characteristics of the exposure, we deem incomplete resetting unlikely at this site. However, we cannot dismiss the possibility that the sample simply lacked sufficient k-feldspar for analysis, such that the lack of a detectable luminescence signal, while consistent with the possible presence of a deposit of early Pleistocene or older age, does not require such an advanced sedimentary age, even though it would fit beautifully with the expectation that one might encounter especially old sediment near the crest of the Lucky Dog fold.

The second new age analysis from unit Qpu(op) alongside US101 was sampled from a peaty clay at about 200 ft elevation in an unnamed drainage above where US 101 reaches the northern edge of the Skokomish Valley (age-date site M906, map and table 1 of Polenz and others, 2010). The lab returned a nominally finite age estimate of about 42,000 ^{14}C yrs before present for this site, suggesting a MIS 3 sedimentary age. However, the finite age statement of the lab cannot include evaluation of all sources of possible errors, and at the stated age, an infusion of less than one percent of modern carbon would turn a sample that in fact is too old for the technique into one that would yield a nominally finite ^{14}C age estimate. Therefore, even a limited, naturally occurring infusion of more recent carbon could, if present provide an artificially “finite” ^{14}C age estimate. Consequently, we suggest that this age estimate is best interpreted as a minimum sample age.

One additional, new ^{14}C age estimate from unit Qpu(op) was obtained from soft, leafy plant fragments in a clay that is interbedded with pea gravel along the channel of Cranberry Creek in the southern Union quadrangle (age-date site M958, map and table 1 of Polenz and others, 2010; map shows presence of uit Qpu(op) as line unit only, due to map space limitations). This ^{14}C infinite ^{14}C age estimate from an elevation of 100 ft was less than 100 ft below the fluted upland surface and most of the overlying slope likely consists of Vashon advance outwash. In this setting, the sample fits a pattern of nearly exclusively ^{14}C infinite deposits immediately beneath the Vashon drift, that appears to dominate the southern Puget Lowland from the Nisqually Delta to Tumwater and Shelton (Schasse and others, 2003; Walsh and others, 2003a,b,c) south of the map area, and east of the map area spanning several 7.5-minute quadrangles from the Lake Wooten, and Mason Lake to the Belfair, Vaughn, and Burley 7.5-minute quadrangles and, with a single exception at Cutts Island, also including the Fox Island 7.5-minute quadrangle (Derkey and others, 2009a,b; Logan and others, 2006; Logan and Walsh, 2007; Polenz and others, 2009 a,b). Like Walsh and others, (2003a,b,c) we speculate that this apparent pattern is systematically related to a MIS 3 paleo-environment that was more conducive to erosion than deposition in the area (see Walsh and others, 2003a,b,c for a conceptual summary of the rationale), except that in the Great Bend area, and especially in the more northerly parts of the map area, Olympic Mountains glaciation events during MIS 3 may have introduced undated pulses of glacial sedimentation.

Pre-Fraser Glacial Deposits of Indeterminate Provenance

Unit Qpl—the only map unit constrained to early Pleistocene (Matuyama) age

Reversely magnetized, glaciolacustrine beds above and below the Frigid Creek tephra extend from the Frigid Creek tephra exposure (Birdseye and Carson, 1989; Westgate and others, 1987; Easterbrook and others, 1988) into the northwest corner of the Skokomish Valley quadrangle, where it is unclear whether the tephra and the beds above the tephra are present. This implies a well-established Matuyama age (Cox and others, 1964) for these lake beds, probably in the order of a million years (Naeser and others, 1984; Westgate and others, 1987; Easterbrook and others, 1988; see also discussion above on fission track age control, and tephra and paleomagnetic data). Because no other pre-Vashon lakebeds of mappable extent and demonstrably glacial origin, much less reverse magnetization, were recognized in the map area but their presence is eminently significant, the Frigid Creek lakebeds were mapped as their own unit.

Pre-Fraser Northern-Source Glacial Deposits

Map units dedicated to pre-Fraser northern source glacial deposits by Polenz and others (2010) include undifferentiated drift (Qpd), till (Qpt), gravel-dominated outwash (Qpo), and sand (Qpos). Some pre-Fraser northern source glacial deposits are hiding amidst other units, primarily Qpu(op), however. The strongest case for the presence of deposits from multiple pre-Fraser northern glaciations may rest in the previously described stratigraphic column 2 of Birdseye and Carson (1989; slope below stratigraphic column location BCS2 of Polenz and others, 2010) on the northern Skokomish Valley wall, although much of this section was obscured at the time of our field work, and we could not verify the presence of at least two pre-Vashon northern tills on that slope. Robert Carson (Whitman College, unpub. manuscript, 1980) also noted two pre-Vashon, northern tills further north. Advance and recessional outwash are not separated because in most cases, it is not clear which deposit a given exposure belongs to. As is the case with outwash of the Fraser glaciation, one can reasonably expect that advance outwash dominates, however.

Map unit Qpd includes the type section along US 101 north of the Skokomish Valley of the previously mapped, northern source Annas Bay Drift (stratigraphic column location ABTS, Polenz and others, 2010), defined by Easterbrook and others (1988) as correlative to the early Pleistocene Salmon Springs Drift. Easterbrook and others had assigned an early Pleistocene age to the exposure indirectly, by asserting that it is correlative to a magnetically reversed, Olympic drift near sea level at Capstan Rock, 12 mi north-northeast of their type section and on the east side of Hood Canal. Easterbrook and others assigned the Olympic Drift at Capstan Rock to the Clark Creek Drift, which they also identified beneath the magnetically reversed glaciolacustrine deposits and tephra at Frigid Creek. Easterbrook and others further noted complex interfingering of the Clark Creek Drift and Annas Bay Drift on the north side of the Skokomish River and concluded that both the Clark Creek and the Annas Bay Drifts are correlative to the Salmon Springs Drift and therefore early Pleistocene. We accept this possibility but were also unable to verify it beyond the fact that the type section of the Annas Bay Drift is more compact and weathered than most in the map area. We are less confident in correlation of the Annas Bay Drift type section within our map area to the magnetically reversed drift at Capstan Rock. We therefore included the type section in unit Qpd, thus requiring only that it be pre-Fraser, but leaving open the possibility that it is indeed early Pleistocene. We applied the same rationale to other deposits throughout our map area that may have been previously identified as Annas Bay Drift and therefore assigned these to any pre-Vashon unit that otherwise appeared to suit the deposits, and we did the same with deposits that might have been previously associated with the Clark Creek Drift or the Salmon Springs Drift for the same reason that we were unable to verify correlation of the deposits at hand to exposures that demonstrably possess the age asserted by Easterbrook and others for the units in question.

Pre-Fraser Olympic Glacial Deposits

Map units dedicated to pre-Fraser Olympic source glacial deposits by Polenz and others (2010) include undifferentiated drift (Qapd), till (Qapt), and gravel-dominated outwash (Qapo). We recognized these deposits as widespread along the North Fork Skokomish valley walls, and it is quite possible that many of the deposits shown along the north side of the Skokomish Valley and the west side of the Skokomish Delta as units Qao, Qad, Qpu(op) and Qpo (Polenz and others, 2010) include deposits that would be better classified as pre-Fraser Olympic drift (see also section on pre-Fraser Olympic source, undivided glacial and non-glacial deposits). The deposits in those areas were assigned to the above mentioned other units because at least in the lower slopes more than 2 mi east of the North Fork Skokomish River, exposures commonly suggested a nonglacial setting marked by more common inclusion of organic matter, flood plain sand, silt, clay and peat, and sedimentary structures that suggest a lower-energy alluvial valley floor rather than the steeper-sloping, rapid-sedimentation braid plain setting that likely dominated during Olympic glacial advances. This change in the character of the deposits along at least the lower slopes suggests that there may be a significant, roughly north-trending (?) boundary 2 mi east of the North Fork Skokomish River that would separate more glacially dominated deposits to the west from more nonglacial deposits further east, and the presence of such a boundary may be reflected in a crudely defined, westward drop in geomagnetic intensity readings across this boundary. However, the density of insightful field data more than 50 ft above US 101 and the road along the north side of the Skokomish Valley (“Sunnyside Road”) was generally sparse, well records are basically nonexistent for this area, and the above suggestions therefore remain speculative.

Pre-Fraser Olympic drift was also recognized as widespread along the western shore of the Tahuya peninsula (Contreras and others, 2010), and some exposures of it are present on both sides of the Hood Canal at the Great Bend and east thereof (Polenz and others, 2010).

Like most pre-Fraser units, the pre-Fraser Olympic source glacial units are explicitly not limited to a single glaciation, and we suspect that multiple pre-Fraser Olympic glaciations are represented among the deposits in the map area, although we were unable to demonstrate that in any individual section. One reason for suspecting deposits from multiple glaciations is that the degree of weathering varies widely among these units. Another is the presence of at least three apparent paleosols at different elevations in a single section on the south end of the North Fork Skokomish Valley (noted on the map and in the Qapd unit description of Polenz and others, 2010). At least one (additional?) paleosol that is exposed at somewhat lower elevation (~85 ft) about 1,000 ft further north along the North Fork Skokomish River, is too old for radiocarbon dating (~12 ft above river level, age-date site J231 and table 1 in Polenz and others, 2010). On the Tahuya peninsula, a preliminary luminescence age estimate from silty flood plain (?) deposits exposed at about 60 ft elevation within unit Qapd indicates an age of >50 ka (age-date site T1245 and table 1 in Polenz and others, 2010). Finally, it must be noted that deposits mapped as "probable" Fraser age units Qad, Qaa, Qat, and Qao may pre-date the Fraser glaciation. If so, then some sections within the map are would demonstrate the presence of deposits from multiple Olympic drifts of pre-Fraser age.

THE FRASER GLACIATION AND HOLOCENE

Pre-Vashon Olympic-Source Glacial Deposits of Probable Fraser Age (may include pre-Fraser deposits)

Map units dedicated to Olympic source glacial deposits of "probable Fraser" age by Polenz and others (2010) include undifferentiated drift (Qad), advance outwash gravel (Qaa), till (Qat), and gravel-dominated outwash (Qao). We recognized these deposits as widespread along the North Fork Skokomish valley walls (Polenz and others, 2010) and the north side of the Skokomish Valley within 2 mi east of the North Fork Skokomish River (see also discussion above of pre-Fraser Olympic source glacial deposits). A few patches of Olympic outwash near the upland surface along the southern and western shores of the Tahuya peninsula were also mapped as probable Fraser age deposits (Contreras and others, 2010; Polenz and others, 2010). All of these deposits lack age control and were assigned to a probable Fraser age only on the basis of minimal weathering and their stratigraphic position immediately subjacent to Vashon drift. To the extent that these deposits are correctly assigned to the Fraser Glaciation, they correlate to MIS 2 (Booth and others, 2004).

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

Map units dedicated to Vashon Stade, northern source glacial deposits by Polenz and others (2010) include undifferentiated drift (Qgd), gravel-dominated advance outwash (Qga), till (Qgt), ablation till (Qgta), undifferentiated ice contact deposits (Qgic), eskers (Qge), kame deposits (Qgik), undifferentiated recessional outwash (Qgo), recessional outwash gravel (Qgog), recessional outwash sand (Qgos), glacial lake-marginal, deltaic recessional outwash (Qgol), recessional glacial lake bottom silt (Qgof), and recessional outwash alluvial fans (Qgoaf). Like elsewhere in the Puget lowland, Vashon drift deposits dominate the upland surface and much of the upper slopes along Hood Canal and the Skokomish Valley.

While the Fraser glaciation is generally equated to MIS 2 (Booth and others, 2004), previous studies have suggested that the incursion into the Puget Lowland of ice from the Puget lobe of the Cordilleran ice sheet did not, geologically speaking, last long. Indeed, confining ^{14}C data from north of Seattle and the southern Puget Lowland paradoxically suggest that some areas north of Seattle may have been post-glacially ice free 13,600 ^{14}C yrs B.P. (Porter and Swanson, 1998; Booth and others, 2004) whereas ice had not yet covered portions of the southern Puget Lowland 13,400 ^{14}C yrs B.P. (Walsh and others, 2003a). The data that underpin this puzzling chronology are from east of the map area, however, and it is not clear that the western Puget Lowland followed an identical chronology. A new radiocarbon age estimate (age-date site M831, map and table 1 in Polenz and others, 2010) from a Western Hemlock log that was dredged up from "blue" clay underneath recessional outwash in the map area provides a locally derived perspective that is at once intriguing and inscrutable. The log is spectacularly preserved, with even bark intact, suggesting a host deposit of fat clay that provided a thoroughly anoxic depositional environment. The log is not, or at most minimally flattened, suggesting either that it was not glacially overridden, or requiring that the surrounding clay acted as ductile host around the more rigid (?) wood, thereby permitting it to retain its round cross section. Quarry dredge operators estimated that the clay layer that contained the log is about four ft thick. In short, it is not clear from the limited stratigraphic information whether the clay was deposited before, after (or even during?) the presence of Vashon ice in the area. Based on the set of tree rings that was analyzed (growth rings 99-108, counted from bark inward), the age estimate of 13,210 ±80 ^{14}C yrs B.P. suggests that the tree died between about 15,770 and 15,300 calendar years ago—so close to the height of the incursion of Vashon ice into the region that it we do not know if the tree grew and died before or after the presence of the Vashon ice. Additional paleo-environmental characterization of the source clay, and perhaps of the deposits that underlie it, would be required to provide further insight, but the age estimate appears generally consistent with the suggestion from elsewhere in the southern Puget Lowland that Vashon ice arrived in the area neither much before, nor much after 13,300 radiocarbon years ago.

Leaky Till, Vashon Stratigraphy, Springs, and Groundwater Nitrogen Levels

Haugerud (2009) suggested that "decapitation" of the Puget ice lobe due to collapse of the Juan de Fuca ice lobe triggered formation of widespread dead ice features between Olympia and northern Whidbey Island. Many such features were noted, and some were illustrated, around Belfair 6 to 12 mi east of the map area, where Polenz and others (2009b) noted that the former presence of stagnant ice was associated with

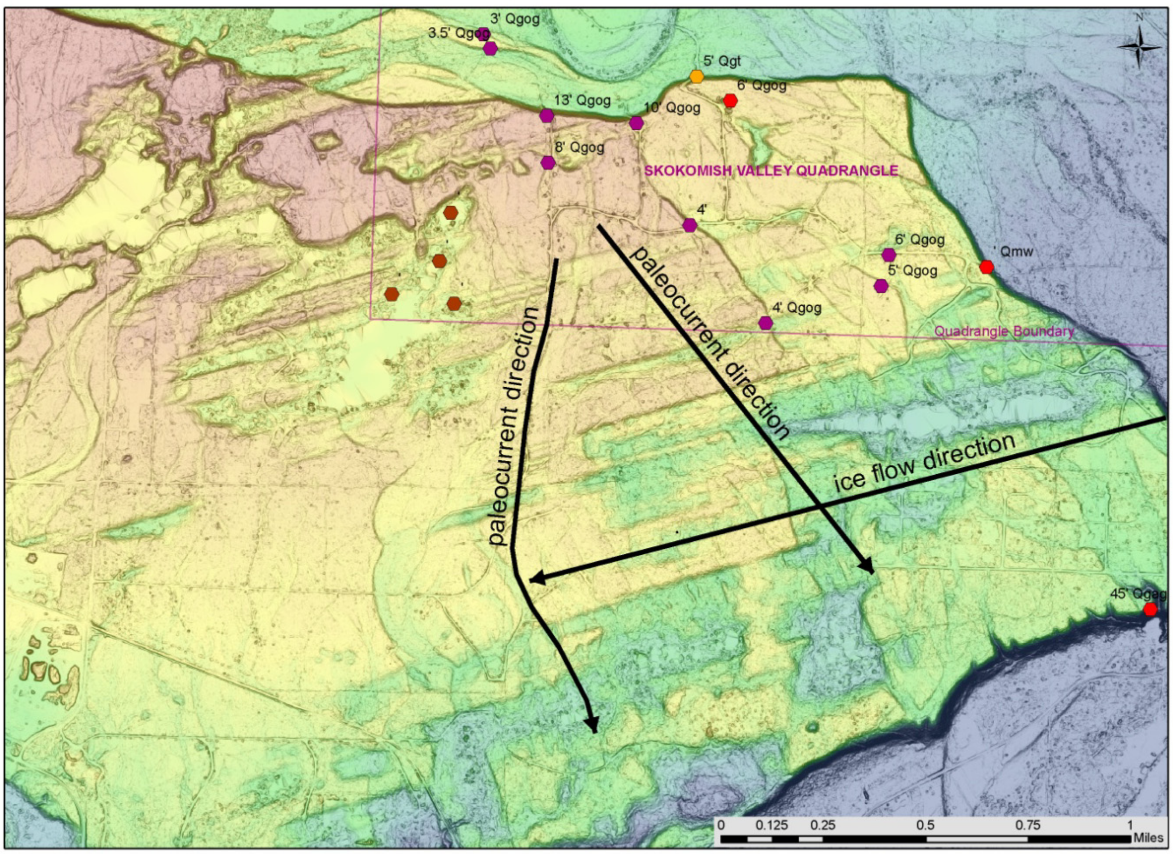

Figure 2. Fluting overprinted by outwash: At the southwest corner of the Skokomish Valley quadrangle, southwest trending flutes are clearly apparent beneath a blanket of south-directed outwash that is apparent in braided stream channels. Kettling and other ice-contact features are apparent in upper left (northwest). Elsewhere, faint depressions hint at additional kettling, suggesting that much of the fluted surface is more permeable than a continuous sheet of lodgement till would be. For unknown reasons, the cover of recessional outwash, over 10 ft thick in some exposures, blankets the underlying flutes like snow, rather than obliterating the fluted morphology by eroding peaks and filling valleys. Five feet of Vashon lodgement till is exposed in a high channel cutbank (upper center). Forty-five feet of underlying advance outwash is exposed in another cutbank (lower right). Did the outwash channels form atop a thin sheet of ice that protected the underlying flutes? Yet bedding is intact in at least some outwash exposures. Red points, gravel; purple points, gravel-sand mixture; orange point, Vashon lodgement till; brown points, wetland. Lidar hillshade image simulates vertical sun angle. Color corresponds to elevation: brown = high; blue = low.

subglacial channels that locally perforated the till. Polenz and others (2009) further mapped some areas of poorly developed till and “sub-glacially re-worked till” (Laprade, 2003) as ice contact deposits (unit Qgic) and, less commonly, as outwash (unit Qgo) or undifferentiated drift (unit Qgd). Similar trends and other enigmatic combinations of ice- and water-related landforms and deposits (for one example, see Fig. 2) are apparent around the Great Bend and were similarly mapped (Contreras and others, 2010; Polenz and others, 2010). Many of these areas are marked by morphologic irregularities (some only subtle) within the fluted upland, but some have so far escaped systematic recognition and were either detected on the basis of fortuitous field exposures or may have gone unrecognized, most likely mapped as till (unit Qgt). It is therefore clear that even a well-developed till plain surface provides little assurance of a well-developed aquitard that would slow, filter, and otherwise limit surface water infiltration and thereby help protect underlying aquifers. In short, the till plain appears to be leaky.

Recognition that the till plain is leaky implies that surface drainage direction need not predict subsurface drainage direction. Cooperation of our mapping efforts with concurrent water quality studies (Robert Turner, oral and written commun., 2009 and 2010) has led to the recognition that the map area provides an opportunity to conduct a targeted test of the importance of the leaky till hypothesis. Such a test could simultaneously provide insight into groundwater pathways, residence time, and the importance of the presence or absence of a leaky till plain for groundwater resource protection. It could also help better characterize the aquifer characteristics of the Vashon advance outwash—without question among the most widely used aquifers in the map area and elsewhere in the Puget Lowland. Moreover, the same test may help point to the relative importance and role of groundwater chemistry as partial determinant of water quality in Hood Canal.

Based on field observations, mid-slope springs on both sides of the Skokomish Valley, but especially on the south side, tend to be associated with the apparent base of drift deposits from the Fraser Glaciation. This recognition coupled with measurement of nutrient levels from springs in the area may be used to develop an improved understanding of groundwater pathways and controls on nutrient loading. Specifically, radiocarbon dating of water samples from the springs at the apparent base of the Fraser glacial deposits and from drinking water wells in the area would reveal groundwater residence times in the Fraser deposits. If groundwater dates from the springs point to post-development infiltration, this would indicate high hydraulic conductivity in the upper aquifer and facilitate identification of anthropogenic sources of high nutrient or other pollutant loads where those are present. If, however, the spring water dates are pre-historic, then the hypothesis that a leaky till plain and highly conductive underlying Fraser deposits are quickly transmitting the spring water would need to be re-evaluated. This would also require a re-assessment of the geologic substrate and indicate that that elevated nutrient concentrations in some springs and their effects on Hood Canal are less likely to be anthropogenic.

Holocene and Late Pleistocene Nonglacial Deposits, and Holocene Nonglacial Deposits

“Holocene and Late Pleistocene Nonglacial Deposits” are separated from “Holocene Nonglacial Deposits” because the former need not be limited to the Holocene but may include some late Pleistocene deposits, as the Holocene began, by international convention, 11.7 ka ago (International Commission on Stratigraphy, 2009, International Stratigraphic Chart), whereas the influence of the Fraser glaciation locally may have waned a bit earlier. These map units include peat (Qp), landslides, (Qls), undifferentiated mass wasting deposits (Qmw), alluvium (Qa, and Qoa where relict), and alluvial fans (Qaf, and Qoaf where relict). Strictly Holocene deposits include marine-deltaic alluvium (Qa(m), and Qoa(m) where relict), coastal salt marsh deposits (Qm), and beach deposits (Qb, and Qob where relict). In addition, manmade fill and modified land are mapped as Holocene units.

We present four previously unpublished radiocarbon age estimates from among these units. Three of these relate directly to the structural setting of the lower Skokomish Valley and Skokomish delta (see structure section). The fourth was sampled from early Holocene alluvium (Qoa) 70 ft beneath the Hood Canal School (age-date site TCN14, map and table 1 in Polenz and others, 2010), where charred material (probably wood) was included in a geotechnical boring sample. The sample was deposited in sandy silt alluvium, apparently in a setting that resembles either the modern Skokomish Valley floor or the modern Skokomish delta surface. Microfossil analysis revealed no foraminifera (Elizabeth Nesbitt, Univ. of Wash., written commun., 2010), and preliminary analysis suggested that diatoms are likewise sparse or absent (analysis by Maria E. Martin), so it remains unclear whether the depositional setting was deltaic or freshwater fluvial. The sample can therefore not be tied to paleo-sea level, although it may approximate it. However, the sample is overlain by 70 ft of Holocene alluvium and thus places a long-term constraint on the minimum volume of sedimentation that the Skokomish River has placed in the valley floor since the time of sample deposition ~8,500 calendar years ago. The constraint is complicated by the possibility that the Lucky Dog structure may have thickened the alluvial section at the borehole site. If so, then a minimum sediment thickness estimate is provided by the 70 ft thickness of alluvium above the sample site less the 26 ft relief (see structure discussion) between the surface at the borehole location and the base of the adjacent bog to the west (age-date site M438, map and table 1 in Polenz and others, 2010). Therefore, at least 44 ft, and perhaps as much as 70 ft of alluvium has accumulated in the Skokomish Valley over the past 8,500 years. If the Lucky Dog structure repeatedly raised the valley floor east of the Lucky Dog bog, additional alluvium would have gotten trapped west of the structure, thus potentially thickening the alluvium west of the structure. A maximum sediment volume estimate is therefore not implied by the available data. But a minimum volume estimate could be generated from the 44 ft minimum alluvial thickness, the width of the valley, and the volume of delta sediment above the paleo-alluvial plain implied by the sample. Such a sediment volume estimate may provide an interesting long-term comparison to historic attempts at assessing the impact of land use practices on sediment load in the modern Skokomish River.

Late Vashon Pro-Glacial Lakes, Deltas and Outwash Channels

Like elsewhere in the Puget Lowland, Vashon recessional outwash (unit Qgo and subunits Qgog, Qgos, Qgol, and some polygons of unit Qgik) in the map area is typically found on glaciofluvial terraces that are incised below the glacially fluted upland surface but also perched at various elevations above modern valley floors, commonly by several hundred feet, as along the flanks of the North Fork Skokomish valley and in the northwestern uplands of the Lilliwaup quadrangle. The meltwater streams that deposited the outwash generally seem to have been graded to base levels that were controlled either by ice-dammed lakes or by ice itself. Proximity to residual ice is illustrated, for instance, by a “jumping” outwash channel documented by Polenz and others (2009) near Belfair (a few miles east of the map area). Similar features can be found in this map area, and the close association of recessional outwash deposits in the map area is further illustrated by the commonly gradational boundaries between outwash terrace deposits (unit Qgo and subunits) and ice contact deposits (units Qgic, Qge) (Polenz and others, 2010). This clearly is also the case in the southeastern Union quadrangle and the southern Skokomish Valley quadrangle, where the most extensive outwash deposits in the map area occupy braided channels and terraces. These channels and terraces extend from the southern margin of the Skokomish Valley southeast to downtown Shelton (2.5 mi south of the map area) and Oakland bay (southeast corner of the Union quadrangle), where the meltwater streams that cut the channels terminated into glacial Lake Russell and formed voluminous, clean, deltaic aggregate deposits that were mapped, along with the outwash channel deposits to their north, as undifferentiated Vashon recessional outwash unit Qgo by Schasse and others (2003). The deltaic deposits were noted as the “Shelton Delta” by Bretz (1910) northwest of the Shelton port area and by Thorson (1981) northeast of the Shelton port area. The north end of Thorson’s Shelton Delta extends into the Union quadrangle, where it forms unit Qgol (previously included with unit Qgo by Schasse and others, 2003). The presence of the channels and their alluvial deposits was first recognized by Native Americans, who noted that in “myth times”, the Skokomish River used to flow to Oakland Bay (Elmendorf and Kroeber, 1992).

The southeast trending outwash channels between the Skokomish Valley and Shelton and Oakland Bay originate at multiple elevations between 530 and 240 ft at the southern margin of the Skokomish Valley. They were previously interpreted by Bretz (1910) and Thorson (1981) as evidence for a glacio-recessional lake that preceded the arrival of Lake Russell and filled the Skokomish Valley and nearby Hood Canal to a level above the 220 ft water surface inferred for Lake Russell in the inner Hood Canal (section on “Glacial Lakes of Hood’s Canal”, Bretz, 1910; “Lake-Skokomish”, “Hanks Lake Spillway”, “Kent Lake Spillway”, “Clifton Channel” and “Belfair Delta”, Thorson, 1981).

We believe that the outwash channels along the Skokomish Valley provide no evidence for such a lake. Widespread and in places extensive kame deposits (unit Qgik) are draped along the Skokomish Valley walls and imply that the modern valley occupies a basin of comparable dimensions that existed and was ice filled late in the Vashon stade. Although this observation does not rule out the possibility that the basin was subsequently filled by outwash and/or ice-dammed lakes before being re-excavated to form the modern

Skokomish Valley, the bathymetry of the Hood Canal near the Skokomish delta indicates that the Canal did not absorb the volume of sediment that would have had to be removed from the Skokomish Valley if recessional outwash had indeed filled the valley. It follows that the subglacial basin at the Skokomish Valley was not subsequently filled by outwash.

We also encountered evidence that all but perhaps the very lowest one of the outwash channels that extend from the Skokomish Valley southeast towards Shelton are not associated with a lake in the Skokomish Valley. Near the upper margin of the south side of the Skokomish Valley, several relict, glaciofluvial terrace fragments are perched along the valley wall. Since the subglacial Skokomish basin was not substantially filled with outwash when the ice receded (see above), the streams that formed these terrace fragments must have meandered partially atop ice that filled the basin.

Some of these terraces are continuous with the outwash channels that extend from the Skokomish Valley to Oakland Bay and Shelton. All of the relict terraces and outwash channels except perhaps the very lowest one (on which we were unable to demonstrate more than 6 ft of outwash near the head of the channel) are generally covered with more than 10 ft of Vashon recessional outwash gravel, indicating that the terrace-forming streams carried a significant bedload. Continuity of some of the outwash channels with terraces that formed partially atop ice and the presence of substantial gravel bedload at the head of the channels imply that the channels flowed from an ice surface onto the upland surface. Unlike Bretz (1910) and Thorson (1981), who interpreted the outwash channels as evidence for a proglacial lake or lakes that filled the Skokomish Valley and Hood Canal to 350 ft (Bretz) or 501 ft (153 m) and 234 ft (71.3m) (Thorson), we therefore see all but the very lowest of these channels as evidence for the absence of an appreciable late glacial lake with a water surface higher than that of Lake Russell in the lower Skokomish Valley, and we do not see the lowest channel as requiring a proglacial lake to a 240 ft level, either, although that may have been present and seems to us to be compatible with an expected Lake Russell water level, considering that lidar places the elevation of the Shelton delta at 200 to 210 ft (as opposed to the 170 ft (51.5 m) noted for that delta by Thorson (1981).

The notable evidence for an ice-dammed lake or lakes that we saw in the Skokomish Valley includes a small delta at roughly 310 to 320 ft elevation 0.4 mi east of the intersection of US101 and SR106 in the northern part of the Skokomish Valley quadrangle (Polenz and others, 2010, significant site M646). This delta is nested amidst ice contact deposits and could easily relate to a small, local lake.

At the south side of the Skokomish Valley 1.5 mi east of the western map boundary of the Skokomish Valley quadrangle, we noted a draping of up to about 5 ft of lake sediment (unit Qgof) below about 340 ft elevation. This deposit is located directly beneath the upstream end of the most elevated of the above noted outwash channels and therefore post-dated it. It is also elevated well above the upstream ends of the lower channel heads that negate the presence of a larger lake at similar elevations in the area. We infer that the deposit resulted from a small, local lake that post-dated formation of the most elevated outwash channels but also was geographically isolated from (and pre-dated?) formation of the less elevated channels at Purdy Canyon to the east, where the Skokomish Valley must have still been ice-filled, at least to a somewhat lower elevation.

Near the north end of the Skokomish Valley quadrangle, we noted some isolated, probable shoreline fragments on the western slope of the Hood Canal basin between about 220 and 240 ft, and in the Lilliwaup quadrangle, some weakly expressed terracing in ice contact deposits in the Dewatto valley is apparent at a similar elevation. Both of these features seem a bit low to be part of the same lake, if any, that may have been associated with the lowest outwash channel at the south end of the Skokomish Valley, unless rebound tilt was non-uniform in this area or unrelated post-glacial tectonic land level changes further complicated the picture, which seems possible.

The observations and inferences above do not negate the possible presence of the larger proglacial Lake Russell throughout nearby Hood Canal. To the north and northeast, evidence for a larger proglacial lake is considerable, with at least four glaciolacustrine deltas at close to 310 ft elevation (Eldon, Upper Fulton Creek, Mc Kenna, and Kitsap Lake; Thorson, 1981). In addition, lidar data reveal isolated terrace fragments and widespread ice contact and outwash terraces that seem to grade to a water surface near 300 ft around Belfair (Polenz and others, 2009b) and in the upper Tahuya River valley east of our map area. Indeed we might add the above mentioned apparent shoreline fragments at 220 to 240 ft and the weak terracing at about the same level in ice contact deposits in the Dewatto valley. A few other ledges among ice contact deposits on the north side of the Skokomish valley may also conceivably relate to water at similar elevation, and it may be no coincidence that at a maximum elevation of 240 ft, the highest point of the lowest outwash channel between the Skokomish Valley and Oakland Bay is close to the same level as the Clifton Channel that Bretz noted as connection between the Hood Canal and Lake Russel, especially if allowance is made for possible, postglacial tectonic land level changes. Indeed, as attractive as the Clifton channel seems as Lake Russell connector in light of its 220 ft channel floor elevation, it curiously lacks the sharply defined cutbank morphology that characterizes other outwash channels, leading us to speculate that it may have instead been an earlier, subglacial channel, and that for establishing a connection between ice dammed water in Hood Canal and Lake Russell to the south, the 240 ft channel between the Skokomish Valley and Oakland Bay may be a more attractive candidate.

Yet the overriding feature of the Great Bend portion of the Hood Canal is that the Great Bend area, at least in the Skokomish Valley, offers evidence against a large proglacial lake with a water surface above that of Lake Russell, and relatively little evidence for Lake Russell. This pattern contrasts with the east end of the Hood Canal basin, where extensive and thick glaciolacustrine deposits dominate the Union River valley and extensive outwash terraces are graded to a similar base level at Mission Creek (Polenz and others, 2009b) and in the Tahuya Valley (Derkey and others, 2009a), and the Clifton Channel and Belfair Delta have been cited as evidence for a Lake Russell water surface at about 220 ft (Bretz, 1910; Thorson, 1981). It is possible that this paucity of evidence at the Skokomish Valley stems from the fact that the Skokomish is a large and dynamic river that has aggraded at least 70 ft during the Holocene, thereby potentially concealing glaciolacustrine deposits at lower elevations, and that similar deposits elsewhere on the floor of Hood Canal remain hidden beneath the sea. In contrast, the Union River valley several miles east of our map area and Oakland Bay at the southeast end of our map area are full of glaciolacustrine sediment (units Qgof, and parts of Qgic) and provide little evidence for substantial post-glacial valley floor alteration by the underfit streams that occupy them.

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 caused by northward translation of the forearc into the older, more stable rocks of southwestern Canada. This northward movement is driven by oblique convergence at the subduction zone (Johnson and others, 2004).

Roughly 5 mi northwest of the Great Bend and parallel to the western shore of Hood Canal, the Saddle Mountain deformation zone marks the western boundary of crustal shortening of the Puget Lowland. This > 25 mile long zone encompasses the Saddle Mountain East and West, Frigid Creek, and Canyon River faults. Characterizations of these faults have documented dip-slip offset with the sense of motion determined by adjacent regions of uplift and subsidence to the east (Blakely and others, 2009). The Saddle Mountain East and West faults produced a magnitude 6.5-7 earthquake between 700 and 1000 A.D. (Carson, 1973; Hughes, 2005). This quake possibly was coeval with the last Seattle fault earthquake at 900-930 A.D. (Atwater, 1999).

The southernmost region, the Olympia uplift, is apparent in potential field data as a structural high that is bounded on the northeastern side by the northwest-trending Olympia structure across southern Puget Sound (Danes and others, 1965). This structure may underlie the area SW of the Great Bend. The geophysical anomalies defining the Olympia structure are likely due to faulting or folding of Eocene bedrock, but its exact nature remains to be constrained (Magsino and others, 2003). Magsino and others (2003) noted that evidence for an earthquake in the vicinity of the structure around 900 A.D. (Sherrod, 2001) could be interpreted by as suggestion that the Olympia structure may be a post-glacially active fault.

The Tacoma and Dewatto basins lie between the Olympia uplift and the Seattle uplift to the north. East of the Great Bend area, the Tacoma fault, with south-directed reverse offset, marks the boundary between the Tacoma basin and Seattle uplift (Johnson and others, 2004). The last major offset on the Tacoma fault occurred around 770-1160 A.D. (Sherrod and others, 2003a). 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 (Blakely and others, 1999; Sherrod and others, 2003b; Logan and Walsh, 2007; Nelson and others, 2009; and Derkey and others, 2009).

Located beneath the western part of the Tahuya peninsula, the Dewatto basin is represented by an aeromagnetic and gravity low whose structural boundaries are not as well constrained. Modeling of the geophysical data and a seismic profile suggest that the Dewatto basin is a syncline with no evidence for faulting (Lamb and others, 2009).Bounded by the Tacoma fault and the Seattle fault, the Seattle uplift exposes bedrock at Green and Gold Mountain west of Bremerton. The north-verging, 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 (Lamb and others, 2009).

The above noted studies of the structures in and near the map area collectively document that the map area and its vicinity are tectonically active, and episodic seismic shaking and sudden land level changes are to be expected. In the steep-walled basin of Hood Canal, sudden land level changes and ground shaking may trigger submarine landslides and tsunamis. Consideration of bathymetric surface irregularities coupled with recent exploration by remotely operated submarine vehicle confirm that submarine landslides have occurred in Hood Canal (Fig. 3; Walsh and others, 2009; Cakir and others, in press).

Evidence for Post-Glacial Tectonic Effects

THE LUCKY DOG STRUCTURE AND SKOKOMISH DELTA

Surface deformation from the Lucky Dog structure is easily identified in topographic data as an asymmetric landform across the Skokomish Valley floor that was first noted by Brian Collins (Ralph Haugerud, written commun., 2006). The landform consists of a gentle berm (hereinafter “Lucky Dog berm”) that trends N35W approximately 1.5 mi inland from the active beach (see Fig. 4). The topographic crest of the landform lies adjacent to a southwest-facing escarpment and decreases in elevation from 35 ft at its northwest end to 15 ft at its southeast end, where it either plunges beneath or is truncated by the modern Skokomish channel. The elevation of the bog (water) surface immediately to the southwest of the escarpment is approximately 18 ft, such that the crest of the berm rises up to about 17 ft above the bog. From the crest towards the northeast the land surface slopes ~0.4° for approximately 3000 ft before leveling to ~0.2° until the shoreline (see profile line A-A' in Figs. 4 and 5 and in Polenz and others, 2010). Based on lidar data, the total loss in elevation, from crest to shoreline, across this profile is 24 ft. This contrasts with only 6 ft of elevation loss along the modern Skokomish River floodplain, from just south of the Lucky Dog structure to the shore (see profile line B-B' in Figs. 4 and 5 and in Polenz and others, 2010). Assuming that the flood plain and delta surfaces along profile A-A' formed in a fluvio-deltaic setting that resembled the modern Skokomish river and delta, the kinked profile and the difference in elevation loss suggest that the crest has been uplifted 18 ft relative to the delta since deposition of the flood plain and delta surfaces. These surfaces are graded to sea level, and sea level has approximated modern sea level throughout the past ~6,000 years (Dragovich and others, 1994) but was lower prior to that time (Dragovich and others, 1994). It follows that the flood plain and delta surfaces are at most about 6,000 years old, and any deformation of these surfaces cannot be older that about 6,000 years. Coring of the bog to the southwest of the structure revealed mud above interlayered mud and sand 11 ft below the surface. This mud, lying below the peat, may represent alluvial conditions before the formation of the bog or the onset of swamp-like conditions, presumably caused by damming of the valley by uplift on the Lucky Dog structure. A radiocarbon sample taken from just below the peat dates to A.D. 1200 to 1280 (see table 1 in Polenz and others, 2010, critical site M438). The elevation of this sample (9 ft) compared to the crest of the structure (35 ft) suggests 26 ft of relative uplift since this date, assuming that the crest and sample location were level at that time. When considering the maximum relief on the modern Skokomish valley floor (~10 ft), the amount of relative uplift could be limited to 16 ft if the crest and sample location were not originally level.

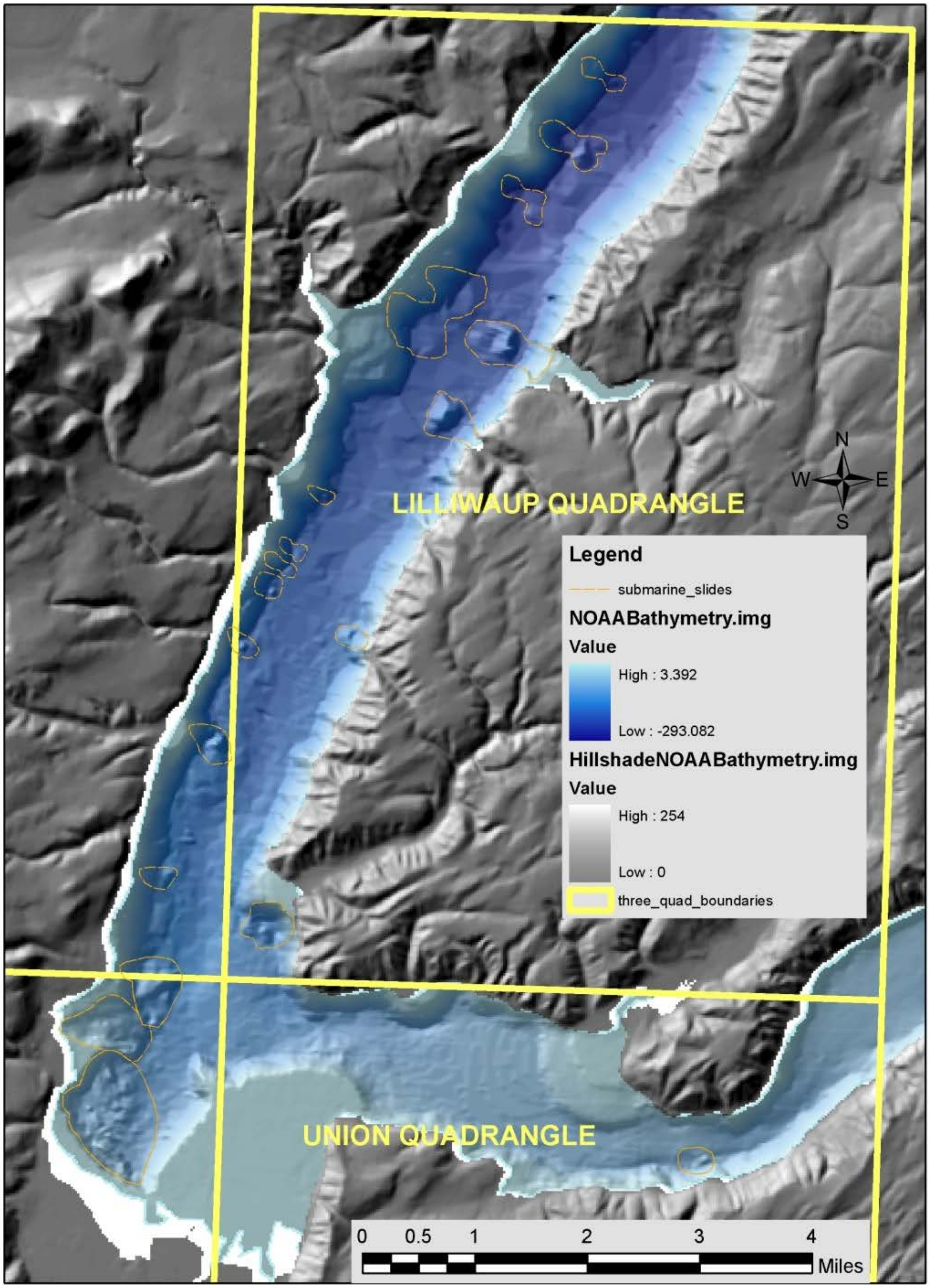

Figure 3. Bathymetry of southwestern Hood Canal: Orange polygons outline apparent submarine landslides. The slide areas were identified from bathymetric imagery similar to this figure, and some were confirmed as landslide areas by ROV submarine exploration (Walsh and others, 2009; Cakir and others, in press).

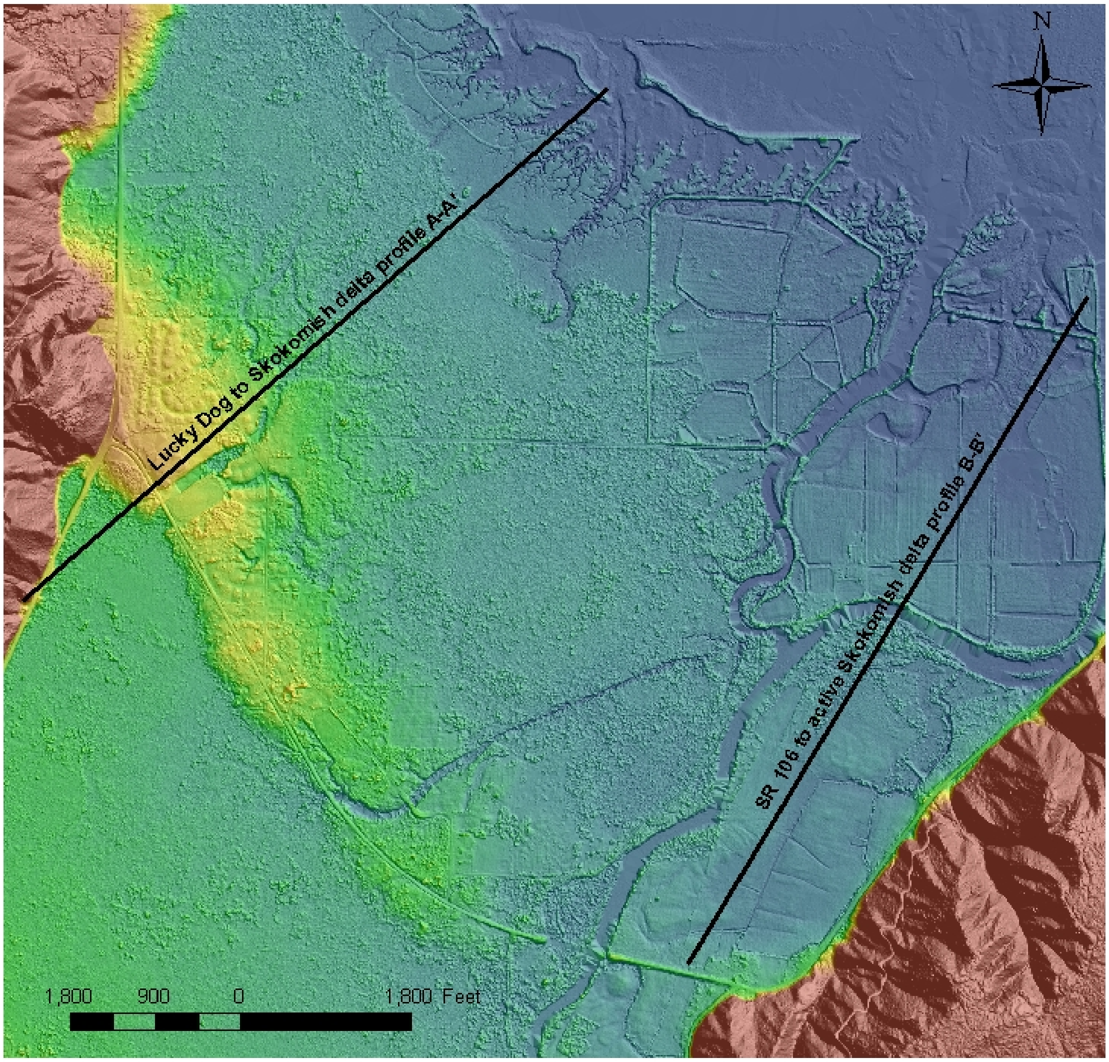

Figure 4. Lidar DEM and hillshade of Lucky Dog structure. Profile lines A-A' and B-B' identify location of profiles in Figure 5. Color ramp stretches from 5 to 45 ft, blue to red. Illumination angle is 45 degress from the northeast. The gentle berm (see text above) is expressed as the northwest-trending brown-yellow-green lineament across the center-left of the image.

Land level changes are also apparent in the outer Skokomish delta. Work in progress by Maria E. Martin (Univ. of Wash.) will document quantified uplift based on detailed stratigraphy that includes a freshwater peat layer between layers of intertidal mud. The emergence of the delta from brackish to freshwater conditions is dated to A.D. 780 to 1000 based on an AMS sample from the base of the peat (see table 1 in Polenz and others, 2010, delta peat site, M434, previously unpublished data courtesy of Maria E. Martin, Univ.of Wash., under USGS NEHRP Award 07HQGR000). Northwest of this site a Douglas-fir (*Pseudotsuga menziesii*) stump (as identified by Kathleen Hawes, South Puget Sound Community College) is rooted in the peat layer. The death of the tree, based on a combination of radiocarbon data and tree ring analysis, dates to sometime between A.D. 920 and 1180 (see table 1 in Polenz and others, 2010, Delta beach stump, M436). At the location of the stump, the duration of freshwater conditions is constrained to be at least 68 years due to the age of the tree (from tree rings) at the time of its death. Tight spacing of the outermost 30 annual growth rings of the tree sample could be an indication that the tree became stressed by the onset of marine conditions decades before succumbing to them. At this time it is unknown whether the transition back into marine conditions represents tectonic subsidence, subsidence due to settling and compaction, submergence due to rising sea levels, or some combination thereof.

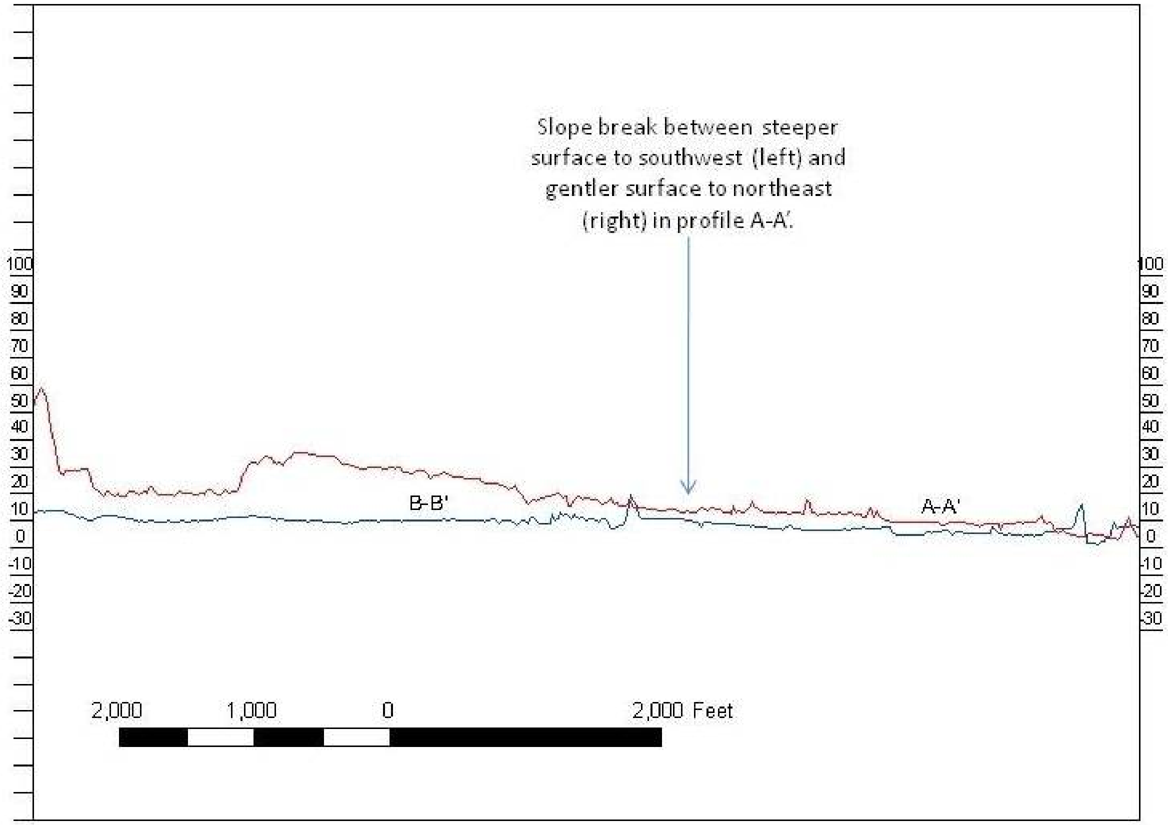

Figure 5. Profiles of land surface along profile lines A-A' (upper line) and B-B' (lower line) (20X vertical exaggeration; elevation in feet shown above ticks along vertical axes on both sides of the figure). The juxtaposition of the two profiles reveals that the modern flood plain and delta (A-A') are marked by a gentler slope than their older equivalent. We suggest that the difference may be best explained by tectonic activity of the Lucky Dog structure.

Where the crest of the Lucky Dog berm meets the northwestern valley wall, undivided pre-Fraser sediments at an elevation of 60 to 110 ft contain beds that dip southwest by as much as 42° (Fig. 6). Similar deposits are level bedded 500 ft to the southwest, on the bog side of the escarpment. A similar distribution of steeply southwest-dipping beds along the trend of the Lucky Dog fold and flat sediments southwest thereof is exposed in pre-Fraser sediments in a small, northeast-oriented valley 1,500 ft farther northeast. The mapped length of the Lucky Dog fold was extended northwest to this valley on account of these deformed pre-Fraser sediments. It is unclear if or how sediments are deformed northwest of the documented extent of the Lucky Dog fold (upper left in Fig. 6; see also northwestern limit of fold in Polenz and others, 2010), due to a lack of suitable exposures containing measurable attitudes. Lidar data reveal a number of possible topographic lineaments on the uplands northwest of the Lucky Dog berm, but it is difficult to determine if these lineaments are tectonic or glacial in origin. The character and location of folding, in the context of the northeast side up sense on the Lucky Dog berm, are consistent with a monoclinal or anticlinal, reverse offset fault-propagation fold (Fig. 7). However, while we have little remaining doubt that the data point to the presence of a tectonic structure that has been active sometime during the past 6,000 years, the specific interpretation of a northeast-verging reverse fault associated with a fault propagation fold and a possible (southwest verging) back thrust at the Lucky Dog berm remains speculative, and the folding and fault(s?) are therefore shown queried (Fig. 7 and Polenz and others, 2010).

Geophysical data lend some insight to the Lucky Dog structure and surrounding area. Aeromagnetic data reveal a magnetic low underlying the Skokomish delta. The southwestern margin of this magnetic low is parallel to and ~1,600 ft northeast of the Lucky Dog berm (Blakely, written commun., 2010). The magnetic contact defining the southwest edge of the magnetic low (as determined by Blakely’s curvature analysis) extends southeast until truncated by a magnetic contact underlying the southern

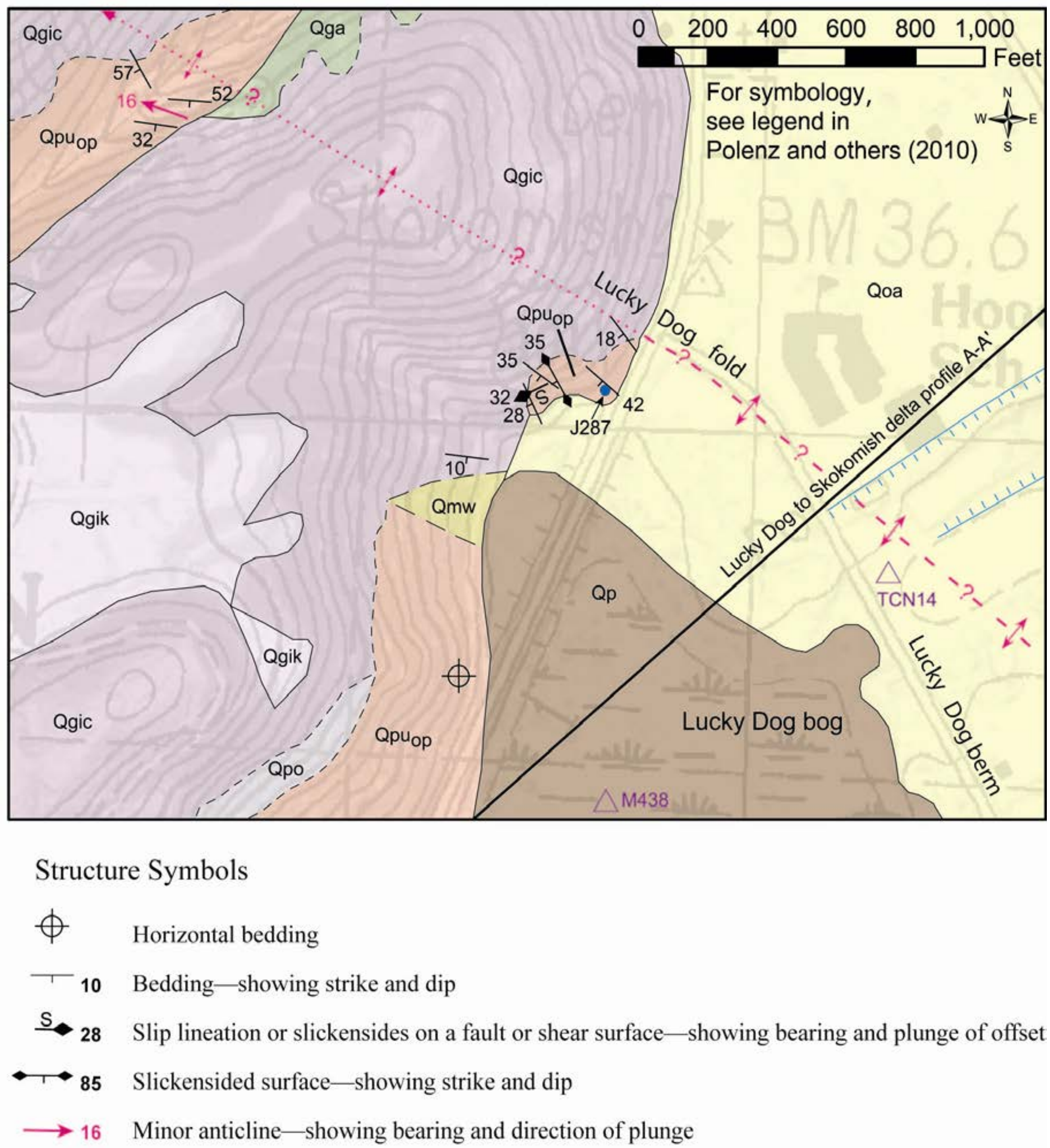

Figure 6. Structural features recognized along Lucky Dog structure at north end of Skokomish Valley. Some bedding and structural orientations are averaged from multiple, closely clustered measurements.

Skokomish Valley wall. To the northwest, this magnetic contact extends about 2 mi beyond the Skokomish Valley before being truncated by a northeast trending magnetic contact near the northern border of the Skokomish Valley quadrangle. Blakely speculates that the magnetic low may be a fault controlled basin, although he cautions that such a basin is not apparent in sparse gravity data. In this context, Blakely postulates that the Lucky Dog berm may be the surface expression of a back thrust in the hanging wall of a deeper, concealed, basin controlling, northeast verging thrust fault. Our version of this interpretation is illustrated in Figure 7. The Lucky Dog fault alignment presented in Polenz and others is based on our reading of the geophysical data Blakely provided us, but it also happens to point at the northern terminus of the mapped fault extent with a complex outcrop that we were unable to fully explain and had speculated during our field work may be a fault exposure (Fig. 8). Based on this (inconclusive) outcrop, we show the fault as inferred and shallow rather than concealed.

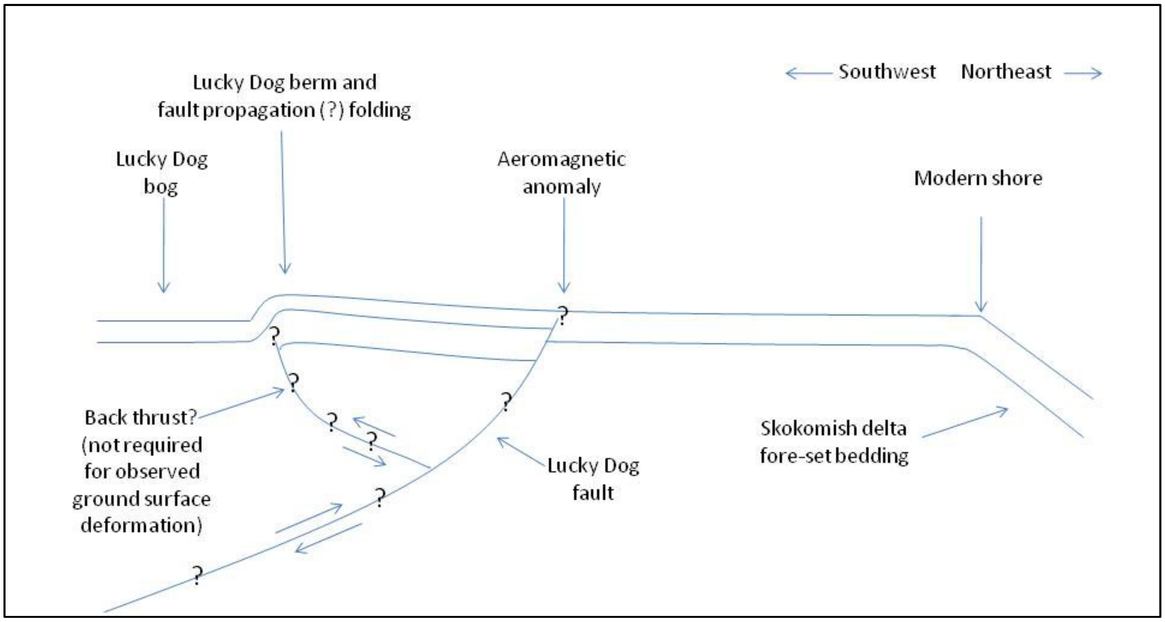

Figure 7. Schematic illustration of one interpretation of structural setting to explain surface and subsurface deformation and geophysical data in and around the lower Skokomish Valley and the Skokomish delta. Subsurface lines other than faults represent assumed bedding orientations in Skokomish Valley alluvium.

In light of the evidence for tectonic activity in the Skokomish Valley it is reasonable to suspect that unusually frequent flooding of the Skokomish River may be related. Generally the recurrence interval for bankfull stage is expected to be between 1.5 and 3 years (figs. 16-15, Dunne and Leopold, 1978; Dingman, 1984). The Skokomish River reliably exceeds bankfull annually (Dunn, 1942; Sover and Montgomery, 2001; Hawes, oral commun., 2010). Prior studies point to land use changes and the damming of the North Fork during the 20th century as the primary cause. Stover and Montgomery (2001) describe ongoing channel aggradation of the mainstem of the Skokomish River due to increased sediment load from heavily logged areas in the South Fork drainage, combined with decreased transport capacity in the mainstem due to damming of the North Fork. Channel modifications and constrictions on the mainstem may play an additional role in channel aggradation (Bakke, written commun., 2009). Despite these 20th century modifications to the Skokomish River system, there are records of annual flooding back to A.D. 1914, prior to any major anthropogenic disturbances (Dunn, 1942). This could be evidence that a tectonic or other natural process contributes to frequent Skokomish River flooding; however, the paucity of historical records makes this difficult to confirm. The persistent frequency of flooding favors gradual land level changes (creep) over sudden land level changing events as a possible tectonic contribution to flooding on the Skokomish River. The presence of a tectonic influence does not preclude the aforementioned causes but merits consideration as a contributing factor.

HOOD CANAL FAULT

Our geological mapping produced no data to satisfactorily prove or disprove the existence of the Hood Canal fault. Magnetic data and recent models by Lamb and others (2009) and Richard J. Blakely (written commun., 2008) cast doubt on the existence of the Hood Canal fault due to the lack of a magnetic anomaly where Crescent basalt, if offset, should produce an anomaly. Due to poor exposures of units on the west side of the Hood canal, contacts are not well defined (and are shown as questionable or inferred). The cross section within the Lilliwaup quadrangle gives the appearance of a vertical offset across the canal. This appearance of offset is likely an artifact of the poorly constrained contacts. The best constrained contact (between the Vashon advance outwash (unit Qga) and the pre-Fraser continental glacial drift (unit Qpd) does not appear to be vertically offset. The Hood Canal fault was included in the cross section largely because of the work to of Brian J. Haug (1998) whose interpretations of high resolution seismic data consistently show the Hood Canal fault along many lines across the canal.

Figure 8. View to northwest of east-facing rock face on private land at north end of mapped extent of postulated Lucky Dog fault. The light colored line that extends from the pick to the right before curving up across the center of the image reveals evidence of possible shearing and juxtaposes bedded gravel of unit Qpu(op) to the south (left) against a younger (?) diamicton to the north (right and below). The exposure was not conclusively characterized as faulted, however.

TACOMA FAULT, DEWATTO BASIN AND MAPPED FOLDS

Sparse structural measurements provide for poorly constrained and inferred structures in the Lilliwaup and Union map areas. However, along the southern boundary of the Lilliwaup quadrangle and the northern end of the Union quadrangle, multiple structural measurements consistently show apparently systematic deformation of older glaciolacustrine units (units Qpd and Qapo). These units dip to the north or northeast along the map boundary and are likely good evidence for deformation caused by the Tacoma fault. These deformed sediments appear to correlate with magnetic data showing a minor east-west anomaly near these deformed beds and with the continuation of the Tacoma fault as depicted in Lamb and others (2009).

Two folds were mapped in the Lilliwaup quad, one of which was projected from the Union quadrangle, where bedding orientations in lacustrine silts were found at two locations and caused us to infer a fold, but no other data was gathered to corroborate this fold. The fold was mapped as identity or existence questionable with locations approximate and concealed, due to the limited data.

The second fold in the Lilliwaup quadrangle was mapped as identity or existence questionable with the location concealed. The fold is shown as questionable due to a paucity of data; mapping of the fold relied on only six structural measurements. Three of these measurements were taken in the vicinity of Rendsland Creek, where glaciolacustrine silts dip northerly. The other three measurements were taken north of the Dewatto River, on the east side of Hood Canal and dip to the southeast. The fold was inferred and drawn to the north through the Dewatto basin (see discussion above of tectonic setting; Johnson and others, 2004), but with few constraints.

SIGNIFICANT SITE T1156 (UNION QUADRANGLE)

Deformation of likely Double Bluff age (or older?) deposits occur along North Shore road at this location. The deposits containe both glacial deposits (till, diamict and lacustrine silts) and possibly nonglacial deposits (sand with detrital wood). Both the underlying glacial till and lacustrine deposits are deformed and dip to the northeast up to 31 degrees. The deposits are dominated by northern source material. To the south (approximately 1000 feet), conjugate shears are found within the lacustrine silts and appear to have right lateral movement. This site is significant because of the deformation and the projection of the Tacoma fault into the general area.

RELICT BEACHES, TERRACES AND FANS AROUND OAKLAND BAY (UNION QUADRANGLE)

Around Oakland Bay in the southeast of the Union quadrangle, possible perched (relict) beaches, river terraces, and alluvial fans appeared to be present in lidar data but could not be confirmed because they were typically noted amongst or near ice-contact and glacial lake deposits that rendered their confident identification beyond the scope of this mapping. The possible presence of these perched features is noted herein because if confirmed, it might provide a record of previously unrecognized tectonic land level changes in this area.

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