GEOLOGIC MAP OF THE SUQUAMISH 7.5′ QUADRANGLE AND PART OF THE SEATTLE NORTH 7.5′ X 15′ QUADRANGLE, KITSAP COUNTY, WASHINGTON

By

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INTRODUCTION

Suquamish 7.5-minute quadrangle is in the center of the Puget Lowland, Washington. The quadrangle contains the northern 2/3 of Bainbridge Island and adjacent parts of the Kitsap Peninsula. Puget Sound and contiguous waterways comprise 35% of the area; maximum elevation is 137 m in the northwest corner of the quadrangle, west of Suquamish. The modal elevation is 44 m. The center of the quadrangle is 20 km west-northwest of downtown Seattle. Winslow, in the southeast corner of the quadrangle, is a 35-minute ferry ride from Seattle.

At Bremerton, 10 km southwest of Winslow, mean annual precipitation for the period 1971-2000 was 137 cm (54 inches). Average January daily low temperature was 1.5ºC (35ºF); mean August daily high was 24ºC (76ºF). The temperate climate encourages dense vegetation. Second- and third-growth forest covers most of the land. Common tree species are Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), bigleaf maple (*Acer macrophylla*), and alder (*Alnus rubra*). Undergrowth is lush: the cross-country pedestrian especially notices dense salmonberry (*Rubus spectabilis*), sword fern (*Polystichum andersonii*), salal (*Gaultheria shallon*), and—locally—exotic English ivy (*Hedera helix*). Open areas, unless grazed or mowed, are commonly filled with two exotic species of blackberry (*Rubus discolor* and *R. laciniatus*) or scrub alder.

Earliest known inhabitants of the area were coast-dwellers of the Suquampsh (or Suquamish) tribe who depended on shellfish and salmon for a large part of their diet. In the 18th and early 19th centuries their numbers were much diminished by Euro-American diseases. Their descendents have been assimilated and (or) relegated to reservations, including the Port Madison reservation at the north edge of the quadrangle. European exploration of Puget Sound commenced in 1792, when the British ships Discovery and Chatham, under the command of George Vancouver, anchored off the southeast corner of Bainbridge Island while the party explored the inland waterways. Vancouver named Puget Sound (originally, just that part of the Sound south of the Narrows at Tacoma) and Port Orchard for members of his party. In 1841 the U.S. Exploring Expedition, under the command of Charles Wilkes, spent two months mapping Puget Sound. Bainbridge Island, Point Jefferson, Port Madison, and Point Monroe are among the features they named. Wilkes named Agate Passage for the expedition's artist.

Subsequent Euro-American settlement was greatly encouraged by the California gold rush (1849), the growth of San Francisco, and consequent demand for lumber produced by tidewater sawmills, including one at Port Madison. Truck gardening, especially of strawberries, was extensive on Bainbridge Island until the Second World War, when many of the farmers were interned because of their Japanese ancestry. As of 2000 the quadrangle was home to about 30,000 people, many of whom commute by ferry, automobile, and bus to jobs in Seattle and Bremerton.

Sceva (1957), Garling and others (1965), and Deeter (1979) have produced geologic maps of all or part of Suquamish quadrangle. Yount and Gower (1991) and Yount and others (1993) compiled, and in part reinterpreted, these maps at 1:100,000 scale.

This study was undertaken in response to (1) awareness of the hazard posed by future earthquakes in the Seattle fault zone, at the south edge of the quadrangle, and the need to marshal geologic evidence for the rate and style of deformation; (2) increasing population on Bainbridge Island and consequent pressure on groundwater resources; (3) concern about landslide hazards; and (4) awareness of the role that the nearshore zone plays in supporting marine resources.

GEOLOGIC FRAMEWORK

The Suquamish quadrangle lies within the Salish Lowland physiographic province (Haugerud, 2004), a broad region in the forearc of the Cascade volcanic arc that extends from south of Olympia, Washington to north of Campbell River, British Columbia and includes both the Puget Lowland of western Washington and the Georgia Depression of northwestern Washington and southwestern British Columbia. To the east are the Cascade Range and Coast Mountains; to the west is the outer-arc high of the Coast Ranges. The Salish Lowland is the locus of late Cenozoic subsidence: Jones (1996) indicates up to 1 km of unconsolidated fill beneath some parts. The Lowland is crossed by east–west topographic highs formed by bedrock uplifts. A northern San Juan high divides the Salish Lowland into Georgia Depression and Puget Lowland sub-provinces. A southern high, which lies athwart the south end of Bainbridge Island immediately south of the map area, coincides with the Seattle fault zone along which uplift has brought Eocene rocks to elevations of 800–1200 m, 8–10 km higher than equivalent strata in the floor of the Seattle structural basin that underlies central and northern Bainbridge Island and areas to the east (Brocher and others, 2001; Blakely and others, 2002). Deformation along the Seattle fault appears to be driven by north-south shortening of the Cascade forearc (Wells and others, 1998).

Where Tertiary strata are exposed in uplifts of the Seattle fault zone, early to middle Eocene, largely submarine basalt (Crescent Formation) is overlain by thick late-middle and late Eocene fluvial to deltaic sandstone with intercalated andesitic volcanic rock (Puget Group), overlain by latest Eocene–Oligocene (Fulmer, 1975) continental shelf to nearshore tuffaceous marine strata of the Blakeley Formation. Locally, fluvial conglomerate, sandstone, siltstone, and peat of the mid-Miocene (Sherrod and others, 2002) Blakely Harbor Formation crop out. Ten Brink and others (2002; see also Brocher and others, 2004) infer that onset of deposition of the Blakely Harbor Formation corresponds to the beginning of offset on the Seattle fault.

Pleistocene glacial deposits that underlie most of the Puget Lowland have been studied for over a century (Table 1). The stratigraphy of the most recent glaciation is fairly well known. Older glaciations, interglacial periods, and the resulting stratigraphy are much less understood. Booth and others (2004) provide a useful summary and references. Willis (1898), after examining landforms and deposits in the Tacoma area, named two north-derived glacial drift sequences, a younger Vashon Drift and an older Admiralty Drift. Crandell and others (1958) recognized and named four glaciations in the southeastern Puget Lowland. From youngest to oldest, these were Vashon Glaciation, Olympia Interglaciation, Salmon Springs Glaciation, Puyallup Interglaciation, Stuck Glaciation, Alderton Interglaciation, Orting Glaciation. Only the deposits of the Vashon Drift and the preceding Olympia Interglaciation are young enough to be dated by radiocarbon means (i.e., younger than about 40,000 ^{14}C yr B.P.). On Whidbey Island, ~80 km north of the Tacoma area studied by Willis and Crandell and others, Easterbrook and others (1967) observed two drift layers beneath the Vashon Drift; they named these the Possession Drift and Double Bluff Drift, separated by non-glacial deposits of the Whidbey Formation.

As noted by most workers, Pleistocene deposits of different ages in the central Puget Lowland are compositionally similar. Observable distinctions are between north-derived (rich in volcanic, granitoid, and metamorphic rocks), east-derived (richer in volcanic debris derived from the Cascade arc, especially hypersthene of probable Mount Rainier origin), and west-derived (rich in basalt and graywacke from the Olympic Mountains) deposits, and between glacial (rapidly deposited, little or no organic material, diamict present) and non-glacial (slowly deposited, peat-bearing) deposits. With limited outcrop, even these distinctions cannot always be made and most recent studies, including this one, have resorted to widespread lumping of pre-Vashon strata.

Armstrong and others (1965) noted that regionally the Vashon Drift is associated with three episodes of Late Pleistocene ice growth, their Evans Creek, Vashon, and Sumas stades. These three stades constitute their Fraser Glaciation. The base of their Fraser Glaciation is strongly time-transgressive. In the central Puget Lowland, the Fraser Glaciation is represented only by deposits of the Vashon stade. Thus “Fraser” and “Vashon” have been used almost synonymously, but outside the central Puget Lowland “Fraser” explicitly includes events and deposits older (Evans

Creek stade, ~24,000 ^{14}C yr B.P.) and younger (Sumas stade, ~11,000 ^{14}C yr B.P.) than deposits of the Vashon stade, which in the central Puget Lowland were deposited between ~14,550 and ~13,600 ^{14}C yr B.P. (Porter and Swanson, 1998).

Immediately east of Bainbridge Island, at Fort Lawton in Seattle, Mullineaux and others (1965) formally subdivided the lower part of the Vashon Drift. They named the Lawton Clay Member (lacustrine silt and clay, commonly with varve-like layering, little or no organic debris) and the Esperance Sand Member (massive and plane-bedded sand, overlain by cross-bedded sand, locally with foreset bedding, silt and gravel, and coarsening upwards; commonly overlain by till). Their Esperance Sand Member was restricted from an earlier proposal by Newcomb (1952) that included silts and clays as a basal member.

Table 1 compares Pleistocene stratigraphies used on earlier geologic maps of Bainbridge Island with the stratigraphy used on recent geologic maps of areas in the central Puget Lowland and the stratigraphy used in this report.

ABOUT THIS REPORT

Haugerud (2009) mapped almost all post-glacial deposits, ice-contact deposits, most fault traces, and most bedding traces from detailed lidar topography collected in 1996-97 and 2000 on behalf of the Puget Sound Lidar Consortium (Harding and Berghoff, 2000; Haugerud and others, 2003). Haugerud, Evan Thoms, and Brett Cox walked almost all of the quadrangle’s shoreline, traversed many stream gullies, and inspected road cuts and construction sites to observe deposit character and collect structural data.

Mapping the extent of Vashon-age till is challenging. Throughout the central Puget Lowland, the uppermost meter of unlithified deposits is marked by extensive bioturbation, minor addition of eolian material, clayey alteration, and variable oxidation. Many road- and stream-cuts in this low-relief landscape are confined to this weathered zone. Even where the underlying material is fine-grained, the top meter is commonly pebbly. The genesis of such deposits is unclear: in some places the pebbles may be derived from up-slope exposures of pebbly deposits, but it is likely that upon deglaciation much of the landscape was littered with a thin skim of englacial and supraglacial debris that lacked the associated fine-grained material, compaction, and thickness necessary to make a mappable till. The tendency of Vashon-age till to reflect the composition of subglacial materials that lie within a few km in the ice-source direction compounds the difficulty: a sandy, brown subsoil with abundant small pebbles may be derived from underlying brown sand and gravel, or may be derived from a till derived from such a deposit. Earlier workers appear to have dealt with these difficulties by assuming that glacially-shaped uplands of the area are mantled with till unless good outcrops demonstrate otherwise. Along much of the shoreline, bluff exposures of older deposits that extend into the topmost strongly-weathered meter demonstrate that this is incorrect.

To delineate the extent of Vashon-age till, we supplemented outcrops in shoreline bluffs, stream banks, road cuts, ditches, and foundation excavations by digging or augering numerous shallow (0.5 m to 1.5 m) holes. We extracted subsurface data from the database compiled by Troost and colleagues (GeoMapNW, 2007), focusing on observations of the uppermost 10 feet (3 m) that included an interpreted stratigraphic unit (e.g., “Vashon till”, “advance outwash”), or a distinctive lithology (e.g., “till”). Field identification of till in shallow exposures and identification of till from subsurface data are both prone to error; in the many places where interpretations from the subsurface database conflicted with our field observations, we gave precedence to field observations. Because of such uncertainties, contacts between till and older units in upland areas are shown as scratch boundaries (position very uncertain).

Cross-sections were interpreted by Troost from borehole logs in the GeoMapNW (2007) subsurface database and subsequently revised on the basis of additional map data. In general, data from boreholes within 2,200 feet (670 m) of the section line were considered when interpreting sections. Borehole collar elevations were obtained by intersecting the reported map location with the lidar elevation model. Borehole logs shown on the cross sections depict the material class assigned by compilers of the GeoMapNW (2007) database.

One of the consequences of mapping on an accurate lidar base is that neither this topography nor the interpreted geology matches available base maps. We thus present this geologic map on a sparse custom base showing contours calculated from the lidar elevation model, Public Land Survey System land lines, some roads and road names, and some place names, but without streams or municipal boundaries.

This report supercedes U.S. Geological Survey Open-file Report 2005-1387 (Haugerud, 2005).

STRATIGRAPHY

GLACIAL AND NON-GLACIAL DEPOSITS

DEPOSITS OLDER THAN OLYMPIA INTERGLACIATION OF ARMSTRONG AND OTHERS (1965)

Similar physical characteristics of deposits of different ages and limited outcrops make correlation of Quaternary deposits older than the Vashon Drift uncertain. On this map we have not subdivided these older deposits, except where distinctive physical characteristics or structural position suggest correlation from outcrop to outcrop.

Unit of Rockaway Beach. A massive, fine-grained unit is interpreted to occur in the subsurface at the south end of section E. Texture and position suggest correlation with distinctive, disrupted, gray, waxy silt, clay, and fine sand that crop out about 2 km south of the quadrangle on Rockaway Beach, where it overlies the Miocene Blakely Harbor Formation (Haugerud, 2005). Disruption of the beds suggests slumping of sediments shortly after they were deposited on a subaqueous slope. The facies suggests ice-proximal deposition, thus the weak inference of a Quaternary age. As the unit is older than Vashon Drift, and is probably glacial, it is likely older than Olympia interglaciation.

Beds of University Point. Well-sorted dark gravel and associated sand, silt, and peat crop out in several locales. Gravel beds are typically no more than 1-2 m thick and most pebbles are greywacke or basalt, suggesting derivation from the Olympic Mountains to the west. Pebbles are rarely larger than 6 cm in diameter. Gravel beds commonly display good imbrication. Good outcrops show that strata are commonly organized into repeated 2- to 3-meter-thick fining-upward sequences that indicate relatively slow fluvial deposition, with channel gravels overlain by sands and succeeded by overbank silt and peat. Bluffs of this unit have a pinkish to orange-brown hue when seen from a distance. Some beds are lithified: strata at some outcrops are best described as mudstone, sandstone, and conglomerate. These deposits may have formed during several non-glacial intervals, but their similar character and relative proximity encourage us to map these beds as one lithostratigraphic unit. Presence of granitoid pebbles and lack of clayey alteration distinguish these beds from similar depositional facies in the Blakely Harbor Formation of the Bremerton East quadrangle directly south of the map area. Outcrops at University Point, on the shore of Port Orchard west of Fletcher Bay, are particularly good. Twenty-five meters of beds of University Point crop out in the bluff north of Fletcher Bay. Poor outcrop suggests as much as 65 m of section may be present on the south side of Fletcher Bay. Interpretation of subsurface data indicates a maximum thickness as great as 160 m (section D).

Deeter (1979, p. 47-58) recognized the similarity of gravel and interbedded sand, silt, and peat at University Point, at a gravel pit on Miller Road on Bainbridge Island, at a gravel pit near Hwy 305 in Sec 4, T25N, R2E, at Fletcher Bay, and north of Rolling Bay (all of which we map as University Point beds). He noted the high concentration of dark greywacke clasts and scarcity of granitoid clasts and reports that Crandell (in Levin and others, 1965) thus inferred an Olympic Mountains origin for the gravels. Nonetheless, Deeter interpreted the these strata as glacial sediments and tentatively assigned them to the Possession Drift of Easterbrook and others (1967) on the basis of infinite radiocarbon ages (W-1459, UW-449; Table 2) and on account of "difficulties in explaining alpine glaciers advancing from the Olympic Mountains across Hood Canal during an interglaciation and also because the nature of coarse gravel deposits in the lowland on an interglacial floodplain is difficult to explain especially when present day streams do not carry anything as coarse as these deposits" (Deeter, 1979, p. 55-56). These supposed difficulties are unconvincing: the beds were deposited by slowly-aggrading streams as evidenced by their good organization and common peat, they are not dominated by north-derived debris, modern streams do carry pebbles as large as 6 cm, and Hood Canal may not have existed during an earlier interglacial period.

Near Ferncliff, along the shoreline north of Rolling Bay, and between Fletcher and Manzanita Bay, University Point beds appear to stratigraphically underlie pre-Olympia glacial deposits, though direct superposition was not observed. This implies that the beds of University Point are at least as old as the Whidbey Formation. Infinite and near-infinite radiocarbon ages (Table 2) are consistent with this interpretation.

Pre-Olympia glacial deposits. Pre-Vashon, and thus pre-Olympia, glacial deposits (Qpo_g) crop out at several locales. Isolated outcrops of till and bedded silt occur northeast of Lemolo in the streambed in the center of Sec 19, T26N R2E where they underlie thick, extensive sand of pre-Vashon till age. Till crops out beneath pre-Vashon deposits on the beach between Battle and Arrow Points (SW¼ Sec 8, T25N, R2E). Folded and locally faulted diamict, gravel, and thick-bedded sand crop out in the shoreline bluffs east of Agate Point (NE¼ Sec 28, T26N, R2E). Deformed massive silt with pebbles—probable dropstones—crops out at the base of the bluff along Rolling Bay. Deeter (1979, p. 27) reported snail, clam, and barnacle fossils in these outcrops; these may be evidence for glaciomarine deposition. Till crops out along the bluff east of Ferncliff, where it underlies Lawton Clay. Along the north shore of Port Madison, till and gravel are exposed at the base of the bluff a kilometer east of Indianola (Sec 14, T26N R2E). Deeter (1979, p. 21-24) described these outcrops and reported an infinite radiocarbon age (Table 2, sample UW-447).

The stratigraphy preserved in landslide debris in the beach on the east shore of Port Orchard (Sec 29, T25N, R2E) suggests two pre-Vashon age glaciations. The debris contains oxidized gravel above pebbly till above discontinuous peat above silt and clay with dropstones.

Other pre-Olympia age deposits. Older deposits in the subsurface are assigned to stratigraphic units Qpog, Qpog$_{m}$, Qpog$_{c}$, Qpon, Qpon$_{f}$, Qpon$_{c}$, Qpo$_{f}$, and Qpo$_{c}$ on the basis of inferred depositional facies and predominant grain size: glacial, glacial-marine, and nonglacial, coarse and fine.

DEPOSITS OLDER THAN VASHON STADE OF FRASER GLACIATION OF ARMSTRONG AND OTHERS (1965)

Most of the area mapped as undifferentiated pre-Vashon age deposits (Qpv) appears to be underlain by fine quartzofeldspathic sand, pebbly sand, and gravel with lesser peat and silt, of probable fluvial and lacustrine origin. This unit is largely equivalent to coarse-grained pre-Fraser age deposits (unit Qpf$_{c}$) mapped on recent maps of nearby areas (e.g. Booth and Waldron, 2004). It is likely that unit Qpv locally includes sand, silt, and clay of early Vashon age as well as beds that, with better outcrop, could be assigned to units Qup, Qpog, Qpor, and Qpv$_{f}$. Some of the deposits mapped as Qpv are lithified and are best described as sandstone and conglomerate.

Silt and clay with associated peat crop out southeast of Agate Point. These are mapped as fine-grained pre-Vashon age deposits (Qpv$_{f}$). Except for the occurrence of peat these beds resemble the Lawton Clay (Qvlc); they could have been deposited during Olympia interglaciation.

Beds of mud, clay, and silt—locally with dropstones—exposed in the bluffs and beach at and southwest of Arrow Point are overlain by fine sand. Together the fine-grained beds and sand beds are similar to the Lawton Clay and Esperance Sand of the Vashon Drift. However, these beds are probably older than Vashon Drift, as they appear to lie beneath an older till that crops out on the beach farther southwest.

VASHON DRIFT

The Vashon stade Cordilleran ice sheet gathered in the mountains of British Columbia and flowed south, reaching its maximum southern extent near Olympia at about 16,900 calibrated yr B.P.; it covered Bainbridge Island for about 1,000 years, from 17,600 to 16,600 calibrated yr B.P. (Porter and Swanson, 1998). Ice here reached a thickness of about 1 km (Thorson, 1980).

The geomorphic effects of the ice sheet are impressive. Meltwater issuing from the advancing ice deposited clay, and silt sand, and gravel of the Lawton Clay and the Esperance Sand, as described below. The net effect was to fill low spots throughout the Lowland and produce a broad, south-sloping alluvial plain (Crandell and others, 1965; Booth, 1994). This surface is preserved, with modification, as an upland surface that is the dominant landform of the Puget Lowland. At the latitude of the Bainbridge Island this surface is at an elevation of about 140 m. The overriding glacier then eroded, shaped, and smoothed its outwash plain. The broad, anastomosing, sinuous troughs filled by Puget Sound, Port Orchard, Port Madison, and Rich Passage were eroded beneath the glacier (Crandell and others, 1965; Booth, 1994), as demonstrated by widespread blanketing by lodgement till, pervasive smoothing by south-directed flow, and the inability of post-glacial streams to erode hollows that extend far beneath any post-glacial base level. Booth (1994) suggested that erosion of the troughs was primarily by flowing subglacial water. The glacier also formed pervasive north–south flutes (elongate drumlins) with heights of 10s of meters, widths of 100s of meters, and lengths of several kilometers. These may reasonably be attributed to direct shaping by moving ice, by virtue of their parallel orientation and lack of sinuousity.

Within the map area, Vashon Drift comprises pro-glacial sediments of the Lawton Clay and Esperance Sand Members, subglacial lodgement till (Vashon till), and younger ice-contact deposits.

Lawton Clay Member. Once Vashon-age ice reached the northeast corner of the Olympic Peninsula, near Port Townsend, it dammed the Puget Lowland and turned low-elevation parts of the Lowland into one or more large lakes with an outlet at Black Lake, south of Olympia (Mullineaux and others, 1965; Waitt and Thorson, 1983; Booth and others, 2004). The Lawton Clay Member of the Vashon Drift was deposited in this (these) lake(s). Clay and silt were transported by suspension in glacial meltwater that fed the lake. Minor coarser debris was probably ice-rafted. Lawton sedimentation at any particular locale ended when Vashon-age ice approached close enough that the supplied sediment was dominantly sand. The present elevation of the Black Lake outlet is circa 42 m (Thorson, 1989; Bretz, 1913). Allowing for some Vashon-age incision of the outlet and isostatic depression by the advancing ice sheet, the likely level of this lake surface in the map area is somewhat higher than 42 m. Barring tectonism, Lawton Clay should not be present at elevations greater than the lake level and at near-lake-level elevations, Lawton Clay should be very thin. Fittingly, most recognized Lawton Clay occurs near modern sea level.

Gray to blue-gray, thinly (cm) to thickly (10s of cm) bedded silt, clay, and fine sand, locally with dropstones and lenses of sand and gravel, are mapped as the Lawton Clay Member of the Vashon Drift where evidence indicates that such beds are part of a continuous coarsening-upwards succession that culminated in Vashon-age till. Such evidence comprises (a) gradational contact with overlying uncemented fine to medium sand, and (b) occurrence at the base of laterally extensive landslide complexes that suggest the silt and clay beds and overlying sand deposits are equally extensive. Silt and clay of the Lawton Clay are common as landslide debris embedded in the modern beach. The highest Lawton Clay in the map area is at about 45 m elevation.

Esperance Sand Member. Thick, commonly homogeneous, fine to medium sand, usually poorly consolidated, locally pebbly, in places coarsening upwards, is here mapped as the Esperance Sand Member of the Vashon Drift. Recently published maps of the central Puget Lowland (e.g. Booth and Waldron, 2004; Troost and others, 2005) have mapped equivalent strata as “Vashon advance outwash deposits (Qva)”. We have revived Mullineaux and others’ (1965) nomenclature to emphasize that (1) in the Suquamish quadrangle this unit is predominantly sandy and lacks the associated gravel layers found elsewhere within Qva, and (2) we have mapped a lithostratigraphic unit with its attendant uncertainties, rather than a time-process unit.

Good exposures of Esperance Sand are present in abandoned borrow pits along SR 305 east of Lemolo. Previous workers mapped these sandy deposits as recessional outwash, but high-resolution topographic data show that the land surface here was shaped by overriding ice and has been modified little since glaciation. There is no sign of the constructional surface of a recessional outwash deposit. Esperance Sand fills a paleovalley that extended NW-SE along the present-day low between Fletcher Bay and Eagle Harbor. Similarly, Esperance Sand near Agate Passage appears to be buttressed against older deposits (Qpv) to the east. These beds are advance outwash, deposited in front of the advancing Vashon-age glacier. At lower elevations much of the unit is massive to plane-bedded, and probably was deposited by mass sediment gravity flows avalanching off advancing delta faces. At higher elevations, some of this unit is strongly cross-bedded and clearly fluvial.

In coastal bluffs the Esperance is prone to landsliding, thus exposures are commonly ephemeral. As of early 2004 there was an excellent, accessible exposure of Esperance Sand and overlying Vashon-age till in the NE ¼ of Sec 12, T25N, R1E. Subsoil developed on Esperance Sand is loose sand.

Our present understanding of Vashon-age glaciation (e.g., Booth, 1994) requires that, at the latitude of Bainbridge Island, advance outwash deposits at lower elevations (below 42+ m, i.e., at elevations below the inferred surface of the proglacial lake) cannot be fluvial; therefore we infer that subaerial fluvial deposits beneath Vashon till at lower elevations must be older than Vashon Drift

Till. The Vashon-age glacier covered much of the Puget Lowland with a thin layer of lodgement till. In the Suquamish quadrangle, this till varies from less than a meter (at which point it is unmappable) to more than 35 m thick.

There is some suggestion that the till is thicker on south-facing (down-ice flow) slopes than on north-facing slopes. Till is mostly compact diamict rich in sand and well-rounded pebbles. Most pebbles are less than 10 cm in diameter. Only rarely are clasts larger or angular. Meltwater streams carried the majority of the sediment moved (albeit indirectly) by the glacier and deposited it as outwash. Most debris in the till was reworked from overriden outwash; only a minor amount was carried within, or on top of, the ice sheet. Lenses of sorted, layered material (silt, sand, gravel) are common in the till, attesting to the near-pervasive presence of flowing water beneath the Vashon-age ice sheet. Good outcrops of Vashon-age till are common in shoreline bluffs. Particularly accessible and instructive are outcrops on the west side of Agate Passage, west of Point Jefferson, south of Battle Point, and north of Brownsville. Wave-etched outcrops commonly show foliation that is rarely evident in upland outcrops. Presumably, foliation records simple shear induced by traction from the overlying ice. Minor folds in the till, where evident, commonly have north-south axes: the rotation of folds into the transport direction indicates large shear strain. Rare clastic dikes thread some outcrops.

Cross-bedded coarse gravel near sea level southwest of Point Jefferson is mapped as a gravel facies (Qvt_g)of the Vashon-age till, as it appears continuous with the overlying till (thus may not be much older) and it is at too low an elevation to have been deposited by a subaerial stream in front of the advancing Vashon-age glacier. This gravel may have been deposited by one of the subglacial streams posited by Booth (1994).

Ice-contact deposits. North of Winslow, near Manitou Beach, and northwest of Point Bolin, surface morphology suggests that buried ice fragments melted and the adjacent deposits collapsed. These areas are mapped as ice-contact deposits.

LATE-GLACIAL DEPOSITS

The weight of the Vashon-age ice sheet induced significant isostatic subsidence at the time of glaciation. As the ice sheet retreated it dammed extensive ice-marginal lakes in the Puget Lowland (e.g., Bretz, 1913). As the mass of the waning ice sheet decreased, isostatic uplift lagged, as recorded by now-elevated shorelines and marine deposits. Thorson (1989) further described and analyzed these features, and interpreted post-glacial rebound with an up-to-the-north gradient of about 1 meter per kilometer. Most rebound occurred within a few thousand years of deglaciation (Thorson, 1989; Dethier and others, 1995; Clague and James, 2002). At the latitude of the Suquamish quadrangle, Thorson's analysis suggests present-day elevations of late-glacial lake surfaces of about 110 meters (Glacial Lake Russell) and 50 meters (Glacial Lake Bretz) and a post-ice marine limit at a present-day elevation of 20 to 30 meters. High-resolution topography locally shows shorelines developed along the late-glacial lakes, but any corresponding shoreline deposits must have been no thicker than a meter or so and are indistinguishable from other weathered and bioturbated deposits of sand and gravel.

In contrast, deposits related to late-glacial marine inundation and subsequent emergence are locally preserved. On the north side of Fletcher Bay, shoreline bluff exposures show 1 to 2 m of sorted sand, gravel, and silt. These are mapped as ***emergence gravels*** (Qeg). Elsewhere, the presence of similar deposits is inferred from subtle smoothing of the glacial land surface. These deposits are probably former beach sands and gravels, though they may include some nearshore stream deposits. Emergence gravels were not deposited by streams flowing from melting Vashon-age ice, as Bainbridge Island appears to have been ice-free earlier, at the time of glacial Lake Bretz, when shoreline knicks were developed on the north part of the island near Seabold (Sec 28 and 33, T26N, R2E) and south of the community of Port Madison (Sec 2 and 3, T25N, R2E). By the time Lake Bretz drained and Puget Sound returned to marine conditions the ice margin was almost certainly at least 20 km farther north, no closer than the northern tip of the Kitsap Peninsula.

That mappable marine shoreline deposits are present, whereas late-glacial lake shoreline deposits are not, could reflect longer inundation at lower elevations—the areas submerged by salt water after the ice melted were earlier submerged by ice-marginal lakes and the rate of isostatic rebound slowed with time. We think it is more likely that marine tides kept a significant vertical extent of the shoreline free of armoring vegetation and thus subject to wave action and more extensive reworking of underlying deposits.

HOLOCENE DEPOSITS

BEACH AND TIDE-FLAT DEPOSITS

Mapping beach deposits along Puget Sound presents an unresolved set of problems. First and foremost is lack of an adequate base map. At present, medium- and high-resolution topography for most of the Puget Lowland extends down only to the high-water line. Second, many Puget Sound beaches are underlain by pebble to cobble gravel. We do not have an efficient technique to routinely ascertain whether this sediment is a thin veneer over a beach platform eroded into older material or a thicker deposit of recently accreted material. For this study, surface materials are mapped landward of the break in slope at the high-water line, either the crest of the beach berm or the toe of the bluff. Thus the only beach deposits mapped (Qb) are the sand, gravel, and logs of accreted back-beach platforms and the associated silt, muck, and peat deposited in lagoons occluded behind beach berms and spits. Deposits farther seaward are mapped only in certain locales where older material pokes through a veneer of modern beach sediment.

On a geologic time scale it is clear that the beaches and their associated deposits are ephemeral. A good example is at the south side of Skiff Point, where soft, probable Holocene peat that was probably deposited in a marsh behind a beach berm is exposed in the upper intertidal zone in front of the present berm, suggesting that the berm here has migrated landward and (or) to the north. Extensive bulkheads along the shoreline demonstrate that many property owners are concerned that the beaches are ephemeral on a human time scale. Certainly the bulkheads are ephemeral, as they are commonly deformed by landslides, or the fill behind bulkheads is sapped by wave action, or, ironically, new beach is accreted in front of a bulkhead.

The large spits at Point Monroe and at the mouth of Miller Bay have been extensively modified for residential construction and are mapped as modified land.

LANDSLIDE DEPOSITS

Coastal landslides are particularly abundant where Esperance Sand overlies Lawton Clay along a contact at or above mean high water line. The correlation is so strong that with moderate accuracy one could infer the distribution of Esperance Sand and Lawton Clay on the basis of extensive coastal landslides. Landsliding is episodic. Regionally, extensive failures occurred following heavy rainfall on saturated soils in early 1972 and early 1997. Tubbs (1974) is an excellent reference on landsliding in this region.

Changes in details of bluff morphology between collection of lidar data in 1997 and 2000 and final field work in 2003-2004 reinforce the conclusion that landsliding is an ongoing process. Evidence for ongoing movement includes sub-angular clasts of fragile bedded silt and clay in the beach at the toe of the large slide at Yeomalt (Sec 23, T25N, R2E). However, some coastal bluffs, particularly those cut entirely in the beds of University Point, appear to be relatively stable.

We used high-resolution topographic data to map large deep-seated landslide deposits. Because the lidar data do not image shallow debris flows, commonly no more than a meter thick, that are the most common and frequent slope failures, we did not map the deposits of these events. Nor did we map colluvial debris that mantles many hillslopes.

WETLAND DEPOSITS AND ALLUVIUM

The rolling glaciated upland of the Puget Lowland, with numerous closed depressions commonly underlain by low-permeability Vashon-age till or older silt and clay, has numerous upland wetlands. Other wetlands are coastal, occluded behind beach berms and spits. In places streams have aggraded across such lows and deposited mappable amounts of alluvium. Less commonly, alluvial flats that are wide enough to map fringe streams incised into the upland surface.

We mapped wetland deposits (Qw) and alluvium (Qal) largely on the basis of surface morphology, supplemented by field observations and reference to the U.S. Fish and Wildlife Service's National Wetlands Inventory.

MODIFIED LAND AND FILL

Mostly we did not map modified land. Significant exceptions are the spit at Point Monroe, where bulkheads and fill have disguised the berm crest and probably raised the average level of the ground surface, and the extensive paved area around the shopping mall and high school north of Winslow. Mapped fill at the site of the former Port Madison sawmill includes anthropogenic peat, recognizable from fragments of dimension lumber. Because of their potential for failure during severe seismic shaking if they were not adequately compacted during construction, we mapped road fills wherever they are evident in high-resolution lidar topography.

STRUCTURE

The Quaternary deposits of the Suquamish quadrangle are significantly deformed. With poor exposure, unconsolidated deposits, and interest in small amounts of deformation, it is of some concern whether observed deformation is tectonic or due to landsliding, ice push, or syndepositional failure of sediment deposited on a slope. We have omitted all observations of bedding that obviously has been deformed by landsliding. In a few places, bedding measurements have been reduced in number for the purposes of presentation at map scale. Measurements that are “approximate” (symbols with open centers) have significant uncertainty in the reported measurement, because of poor exposure or strong cross-bedding. Measurements that are not “approximate” describe the orientation of structures to within a few degrees.

Locales where deformation is evident are discussed below.

AGATE POINT

Sediments of pre-Vashon age, including some of glacial origin, that crop out on the bluff within ¼ km southeast of Agate Point are folded and faulted. A small fault strikes NE, is nearly vertical, and has an observed dip separation of less than a meter. Bedding attitudes define a northeast-trending fold as well.

Clay, silt and peat that crop out in the intertidal zone farther southeast of Agate Point, beneath a landslide on the bluff, are deformed. The deformation pattern is sufficiently consistent that landslide-related deformation seems unlikely. A small NE-trending fold is evident in outcrop. Bedding strike is parallel to the fold axis and to the axis of the fold defined by bedding farther northwest, closer to Agate Point. Several small NW-trending faults cut the section with an aggregate left-lateral separation of 1.5 meters.

To the southwest of Agate Point, at Seabold, on strike with these dipping beds, topographically higher pre-Vashon deposits are horizontal. Perhaps these higher deposits are younger, deposited after the folding recorded on the beach southeast of Agate Point.

ARROW POINT

Fine sand, silt, and clay exposed in shoreline bluffs 2/3 km southwest of Arrow Point are strongly folded, with dips locally in excess of 45°. This section shows local intrastratal deformation that is probably syndepositional; the longer-wavelength folding of the section as a whole is probably younger. Bedding attitudes suggest folding about a northwest trend.

WEST OF MANITOU BEACH

West of Manitou Beach, in the interior of the island, center of Sec 15, T25N, R2E, an isolated outcrop of thin-bedded fine sand and silt evinces an east dip of 34º. There is no indication that this is landslide-related deformation. We did not find other outcrops nearby to verify this attitude. On the strength of this one observation, as well as the inference that beds of University Point are missing in this vicinity, section C depicts a significant anticline in this area. We infer protracted folding, as there appears to be a significant angular unconformity at the base of a discontinuous glacial unit that underlies the University Point beds. Farther north, subsurface data (section B) suggest University Point beds are folded by the northern continuation of this anticline.

SEATTLE FAULT ZONE

The Seattle fault zone (Gower and others, 1985; Blakely and others, 2002) crosses Bainbridge Island, with most deformation directly south of the Suquamish quadrangle. Along the east shore of Port Orchard south of Fletcher Bay and from there west to the head of Eagle Harbor, the Esperance Sand and older strata dip to the north. The northern limit of dipping beds runs from Yeomalt to Fletcher Bay. Sections D and E depict this homocline, which appears to mark the northern limit of late Quaternary deformation associated with the Seattle fault.

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DESCRIPTION OF MAP UNITS

POST-GLACIAL DEPOSITS

m **Modified land (Holocene)**—Sand and gravel as fill, or extensively graded natural deposits. Mapped only where modification is sufficiently extensive that the underlying deposit cannot be inferred. Locally mapped as:

f **Artificial fill**—Sand, gravel, and wood waste placed as fill. Mapped especially in road prisms where compaction by seismic shaking is a predictable hazard

Qw **Wetland deposits (Holocene)**—Silt, sand, muck, and peat deposited in wetlands. Mapped on basis of surface morphology or presence of surface water and wetland vegetation

Qal **Alluvium (Holocene)**—Well-sorted, unconsolidated sand, gravel, and silt deposited by post-glacial streams. Locally may contain intercalated poorly-sorted debris-flow deposits

Qb **Beach deposits (Holocene)**—Sand, gravel, and logs deposited by wave action. Underlies nearshore flats. Beach deposits not mapped seaward of the high water line. Locally includes mud and peat deposited in wetlands developed inboard of the beach berm

Qls **Landslide deposits (Holocene and Pleistocene?)**—Diamict, sand, gravel, silt, and soil transported in deep-seated landslides. Deposits commonly less dense than parent materials. Commonly water-saturated. Largely mapped on basis of morphology. Some landslide deposits may be latest Pleistocene in age

LATE-GLACIAL DEPOSITS

Qeg **Emergence gravels (Pleistocene)—**Moderately sorted gravel and sand, 1–3 m thick, that mantles till and older deposits at low elevations. Beach and stream deposits formed when late-glacial sea level was higher than at present, or along shores of late-glacial ice-marginal lakes. Mapped from exposures in shoreline bluffs, local artificial exposures, and surface morphology

GLACIAL AND OLDER NON-GLACIAL DEPOSITS

Vashon Drift (Pleistocene)—Divided into:

Qvi **Ice-contact deposits**—Gravel, sand, and diamict deposited against stationary ice. Commonly reworked by slumping. Mapped on basis of surface morphology

Qvt **Till**—Mostly dense sandy diamict. Pebbles are matrix supported; most are well-rounded. Rare clasts larger than 10 cm are commonly sub-angular to angular. Lenses of bedded sand, silt, and gravel are common. Wave-etched exposures commonly show sub-horizontal foliation in diamict and isoclinal folding of silt and sand lenses. In many upland locales, till is mapped on basis of clayey, pebbly subsoil, commonly with gray to green-gray hue indicative of minimal oxidation. Good shoreline bluff exposures indicate that most till of the Vashon Drift is subglacial lodgement till. Locally mapped as:

Qvtg **Gravel**—Coarse, cross-bedded gravel that grades into overlying till

Qve **Esperance Sand Member**—Quartzofeldspathic medium-fine to medium sand, locally pebbly or with small amounts of gravel or silt. Little cemented, though locally supports vertical faces. In deep exposures, commonly little oxidized. Sub-soils derived from this unit are mostly loose sand, light-colored when dry. Advance outwash deposits. Local cross-beds and large foresets suggest deposition in fluvial or deltaic setting; elsewhere, pervasive decimeter-thick planar beds and low-angle cross-beds suggest deposition by prodelta turbidity currents

Qvlc **Lawton Clay Member—**Thin-bedded (5 mm to 15 cm) dark gray silt and clay, locally with dropstones and (or) lenses of ice-rafted sand and gravel. Lacustrine advance outwash deposits

DEPOSITS OLDER THAN VASHON STADE OF ARMSTRONG AND OTHERS (1965)

Qpv **Pre-Vashon-age deposits (Pleistocene)**—Sand, gravel, silt, peat, sandstone, mudstone, conglomerate, and diamict of fluvial, lacustrine, and glacial origin. May include marine deposits. Where outcrop is good, it is evident that much of material mapped as Qpv is interbedded sand and gravel of fluvial origin or thin-bedded fine sand and silt of indeterminate origin.

Mostly mapped where poor outcrop—typically, brown, sandy, pebbly subsoil—does not permit a more detailed classification. Probably includes deposits elsewhere mapped as Qpvf, Qup, and Qpog. May include minor Qve and Qvlc. Locally mapped as:

Qpvf **Fine-grained deposits**

DEPOSITS OLDER THAN OLYMPIA INTERGLACIATION OF ARMSTRONG AND OTHERS (1965)

Qpog **Glacial deposits (Pleistocene)—**Till, pebbly mud, and tillite and associated silt, sand, gravel, and conglomerate. Subsurface deposits recognized as glacial on the basis of identifiable till fragments and (or) predominance of clasts suggestive of northern provenance: granitic and (or) metamorphic clasts in gravel; garnet, epidote, magnetite, and (or) metamorphic rock fragments in sand. In subsurface, locally divided into:

Qpogf **Fine-grained glacial deposits**—Silt, clay, sandy silt, gravelly silt, gravelly sandy silt, clayey silt, and silty clay. Present in subsurface only

Qpogc **Coarse-grained glacial deposits**—Diamict, gravel, sand, sandy gravel, silty gravel, clayey gravel, gravelly sand, gravelly silty sand, silty sand, gravelly clayey sand, and clayey sand. Present in subsurface only

Qpogm **Glaciomarine deposits**—Fine-grained (silt, clay) deposits with minor sand and gravel and associated marine shells. Present in subsurface only

Qpon **Non-glacial deposits (Pleistocene)**—Present in subsurface only. Sand, gravel, silt, clay, and peat. Identified as non-glacial by the presence of in-situ peat, paleosols, plant fragments, plant-fragment impressions, and (or) in-situ volcanic deposits (ash, pumice, mud-flow). Locally, predominance of volcanic clasts suggests central Cascade Range provenance. Present in subsurface only. Locally divided into:

Qponf **Fine-grained non-glacial deposits—**Silt, clay, sandy silt, clayey silt, silty clay, and peat. Present in subsurface only

Qponc **Coarse-grained non-glacial deposits—**Sand, gravel, sandy gravel, gravelly sand, gravelly silty sand, silty sand, clayey sand, and peat. Present in subsurface only

Qpof **Fine-grained deposits (Pleistocene)—**Clay, silt, fine sand, and shale of indeterminate origin. Present in subsurface only

Qpoc **Coarse-grained deposits (Pleistocene)—**Sand and gravel, minor silt and clay, of indeterminate origin. Present in subsurface only

Qup **Beds of University Point (Pleistocene)**—Variably lithified fluvial gravel and sand, locally cross-bedded, with interbedded silt and peat. Gravel commonly oxidized. Gravel has high concentration of dark basaltic sandstone and basalt clasts that suggest an ultimate source in the Olympic Mountains. Gravel beaches below bluffs of University Point beds are noticeably darker than typical central Puget Sound beaches. Presence of a small fraction of granitoid pebbles in conglomerate and absence of pervasive clayey alteration of sandstone distinguish University Point beds from the Blakely Harbor Formation (exposed 3 km south of map area), which they otherwise resemble.

At University Point and north of Fletcher Bay, shoreline bluff exposures display 2–3 m thick fining-upward sequences indicative of meandering stream deposits; silt and peat are overbank facies

Qpor **Unit of Rockaway Beach (Pleistocene)—**Massive to disrupted silt, clay, and sand. Some silt is waxy-textured. Most disruption appears to be non-tectonic. Present in subsurface only

Explanation of map Symbols

Shoreline

Fossil shoreline

Contact—Continuous where estimated location uncertainty less than 30 meters; long dash where estimated location uncertainty 30 to 100 meters; short dash where estimated location uncertainty greater than 100 meters

Strike and dip of bedding

Inclined—Facing direction observed in outcrop, upright

Inclined—Facing direction not observed

Inclined—Facing direction not observed, approximate orientation

Horizontal

Strike and dip of foliation

Inclined

Horizontal

Minor fold axis, with plunge

^{14}C age locality with sample number

Borehole—From GeomapNW database, used in construction of cross sections. Adjacent number is borehole identifier EXPLOID

Observation point—Outcrop, dug or augured hole, or record from GeoMapNW database

Geographic coordinates: North American Datum of 1927

Contours and shaded-relief base image calculated from 6-ft lidar DEM, Puget Sound Lidar Consortium, and 30-ft bathymetric DEM compiled by David Finlayson, *http://www.ocean.washington.edu/data/pugetsound/psdem2005.html*

Public Land Survey System from Washington Department of Natural Resources

Roads from Kitsap County

Place names modified from USGS Geographic Names Information System

Geology mapped by R.A. Haugerud, 1999-2005, E.A. Thoms, 2004, and Brett Cox, 2005

Database and digital cartography by R.A. Haugerud

Edited by ______

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