U.S. Department of the Interior
U.S. Geological Survey

Open-File Report 2009-1033
Version 1.0
Sheet 1 of 2

INTRODUCTION

The Kitsap Peninsula, in the center of the Puget Lowland of Washington State, has been glaciated repeatedly during the last two million years, a history recently summarized by Booth and others (2004). Near-surface geology is dominated by the effects of the last (Vashon) glaciation (see, for example, Dragovich and others, 2002, and references therein). Glaciation and subsequent redistribution of materials by wind, waves, and running water have homogenized the chemical compositions of near-surface deposits. Variations in grain size, sorting, and compaction have consequences for agriculture, construction, and geologic hazards. The geologic history recorded by these deposits is significant to our understanding of crustal deformation, ground- and surface-water resources, the distribution of fishes, and other topics.

Much mapping of surficial deposits, especially in vegetated areas, is done on the basis of morphology. The geologist examines the landscape, aerial photographs, and topographic maps in order to discern the presence and extent of landslides, alluvial flats, debris-flow cones, wetlands, colluvium-mantled hillsides, and areas of bedrock outcrop. These inferences from morphology are corroborated by examination of outcrops and the occasional hand-dug pit, but the interpretation typically is dominated by morphologic considerations. Where deposits preserve their primary depositional upper surface, these inferences can be extremely robust. Where deposits subsequently have been eroded, differences in bedding style and competence may affect the erosional process and provide clues sufficient to infer the subjacent material from surface morphology alone.

Recent high-resolution lidar (*LI*ght *D*etection *A*nd *R*anging; also known as airborne laser swath mapping, or ALSM) topographic surveys of much of the Puget Lowland (Harding and Berghoff, 2000; Haugerud and others, 2003) provide a more accurate depiction of the morphology of this forested landscape than previously has been available. More accurate morphology promises more accurate mapping of unconsolidated deposits and a more detailed earth history, particularly in this low-relief, forested region where outcrops are not abundant and many deposits are similar in composition. This map is a step towards realizing this promise. In order to clarify the chain of observation and inference that proceeds from morphology to geologic map, I mapped morphologic units—the two-dimensional surfaces that bound near-surface deposits. I leave the inference from morphology to substrate to future geologic maps (for example, Haugerud, 2005). Mapping of morphologic units has, in places, the advantage of disclosing erosional events that left no discernible trace in the depositional record described by traditional geologic maps.

METHODS

Geomorphic mapping is the systematic subdivision and classification of topographic surfaces on the basis of morphology, position, inferred genesis, and relative age. Geomorphic mapping is more widespread in Europe than in North America: see Salomé and van Dorsser (1982) for an instructive set of examples. Gustavsson and others (2006) discussed several geomorphological mapping systems. Giles (1998) presented a North American example using automatic classification of digital source data. These geomorphic mapping systems are characterized by deduction of a vocabulary of map units, commonly on the basis of existing theories of landscape process and (or) slope angle. Inspired by the North American Stratigraphic Code (Anonymous, 1983), which emphasizes mappability as a fundamental characteristic of map units, and aware of our limited knowledge of subglacial processes, I have adopted a different approach and defined map units inductively—for example, are there areas of ground having similar associated surface characteristics (slope, elevation, texture, etc.) that can be consistently identified? Once identified, these associations often can be, and should be, interpreted in terms of their probable genesis. Cross-cutting relations and additional knowledge of local geologic history suggest ages for these map units.

This mapping was guided by several principles: All of an area (quadrangle, county, study area) should be mapped. Mapping should be relatively consistent. Map units should be area-filling and continuous (for example, fluted glaciated surface, accreted beach surface), not quasi-discrete entities (for example, drumlin, spit). Map units should not be blindly deduced from a catalog of likely geomorphic processes but should arise inductively from observed morphologies and positions and, where appropriate, be consistent with known geomorphic processes; this allows for recognition of map units that correspond to heretofore unrecognized processes. The map should lead to a geomorphic history that is internally consistent and obeys our understanding of geologic process: for example, water flows downhill, a glacier slopes towards its terminus, and its flow is driven by its surface slope. Mapping is scale-dependent, or, in the scale-free digital context, dependent on the resolution of the underlying topography.

I have found it most productive to work from digital elevation models (DEMs). This map was interpreted from 6-foot lidar DEMs provided by the Puget Sound Lidar Consortium (*http://pugetsoundlidar.org*). The lidar DEMs were derived from 1 pulse/m² lidar surveys conducted in early 2000 and winter 2001-2002. The lidar surveys produced point clouds composed of as many as four returns per pulse, each return produced by scattering of the laser beam by ground, vegetation, structures, vehicles, and (locally) open water. For these surveys, laser returns were automatically classified as 'ground' or 'not-ground' using the despike algorithm of Haugerud and Harding (2001). From a DEM, I calculated four images: a northeast-illuminated gray hillshade; a northwest-illuminated gray hillshade; a color image in which hue corresponds to local slope; and a color image in which hue is calculated from elevation and darkness as a nonlinear function of local slope, to make small variations of slope at low slopes visible at the expense of suppressing the visibility of similar variations at higher slopes. I found the latter to be the most useful. Using these images as interchangeable backdrops, I digitized geomorphic unit boundaries on-screen in a GIS environment, interpreting on the fly. The ability to pan and zoom at will while working on-screen is most appreciated, but the limited spatial context is at times challenging. At intervals I made large-format plots of the in-progress map to establish context and, thus, resolve areas where an interpretation was not obvious, as well as to edit the emerging map for consistency.

The accuracy of the DEM-derived geomorphic map is limited in several ways. Most unit boundaries are located on slope breaks. Without careful modeling, slope breaks can be located no more accurately than two to three DEM cells (12 to 18 ft). Boundaries not on slope breaks are less accurately located. For example, boundaries between varieties of glaciated surface were drawn at subtle changes in texture; thus, all such contacts are shown as scratch boundaries. Subsequent work may lead to substantial revision of these boundaries. Some lines were automatically smoothed after digitizing in order to minimize artifacts. Visualization scale provides another limit: my experience is that I do not place lines any more accurately than a few pixels at the visualization scale. On a 75 pixel-per-inch computer display, my usual working scale varied from 1:3,000 to 1:12,000. One's stratigraphic concepts further limit accuracy. Misconceived map units—for example, units that require subdivision of a spectrum of morphologies that result from a single process, or lumping of surfaces that result from distinct processes—may result in a map that is thematically wrong or (more commonly) requires unit boundaries that cannot be located precisely. A particular challenge is posed by overprinted ground, such as glaciated ground modified by marine and (or) lacustrine processes. Although this map is presented at a scale of 1:36,000, accuracy and completeness of much of the underlying digital map data should allow their use at scales as large as 1:12,000, that is, a nominal accuracy of +/- 30 feet (U.S. Geological Survey, 1999).

The quality of the lidar base limits interpretation in three settings: (1) In dense, unthinned second-growth forest, very few laser beams reached the ground, and so the topography is particularly ill defined. (2) The despike algorithm is prone to misclassifying bluff edges as vegetation, leading to common scalping of edges. (3) Interpolation from scattered ground returns to a continuous surface tends to bridge across narrow ravines and shoreline angles; this bridging is common particularly where steep slopes meet open water and there are few returns from the water surface, as specular reflection (instead of scattering) has directed incident laser light away from the lidar instrument. Such bridging results in local anomalies such as contours that cross water bodies. Wherever possible, I have attempted to map through defects in the base; that is, I mapped the interpreted landscape. Similarly, I have attempted to map the landscape as it was prior to human modification. Exceptions are major road corridors, mapped as modified land to help orient the map user visually, and the surfaces of highway fills, mapped because of their propensity to fail during severe seismic shaking. Mapping the premodification landscape was particularly challenging along the north side of southern Hood Canal, between Ayres Point and the Union River, where a roadway is superimposed on a possible uplifted mid-Holocene beach flat.

On this map, alluvial flats are grouped by age into several groups (units hal, ohal, al, owm, owb, owr). In many places, one alluvial flat is incised into another of the same age group. Where the separations are sufficiently distinct, I mapped internal contacts. These multiple flats probably reflect some combination of change in base level (because of isostatic rebound, a consequent change in the drainage network, or local fault displacement) and change in stream dynamics.

Waterlines mark the edges of water bodies *at the time of survey* and the consequent limit of topographic data. Along the marine shoreline, their position reflects the tide stage at the time when a stretch of beach was surveyed. Waterlines are not contours, nor are they necessarily at mean sea level, mean high water, or any other vertical datum. Shorelines are the morphologic upper edge of the beach, drawn at the contact between beach face and hillslope or backshore surface. Possible late Pleistocene shorelines were drawn on the basis of (1) a lower limit to gullying, (2) an inflection in slope, and (or) (3) an upper limit to smoothed topography; these are subtle features and, in places, I am likely to have erred in identifying them.

LANDSCAPE EVOLUTION

The Kitsap Peninsula lies within the southern part of the Salish Lowland (Haugerud, 2004), a broad fore-arc depression that extends from Chehalis, Washington, to Campbell River, British Columbia, and separates the Cascade Range and Coast Mountains to the east from the Coast Range, Olympic Mountains, and Vancouver Island Range to the west. Long-term uplift of the mountains to the east and west reflects convergence of the Juan de Fuca and North American plates over the last 35 million years or more. Locally, there has been significant uplift and subsidence within the southern Salish Lowland during the last 15 million years: Eocene volcanic and plutonic rocks are exposed at elevations as high as 500 m on Green and Gold mountains, and latest Eocene to Oligocene strata are exposed near sea level near Point Glover and on southern Bainbridge Island, whereas equivalent strata to the northeast of the Seattle Fault Zone lie 6 to 10 km below sea level (Johnson and others, 1994; ten Brink and others, 2002). North-south shortening across the Seattle Fault Zone is a response to northwards migration of much of California and western Oregon, a far-field effect of strike-slip coupling between the Pacific and North American plates (Wells and others, 1998).

Bedrock outcrops and deep boreholes within the Salish Lowland are limited. Available geologic evidence does not distinguish between spatially averaged long-term stability of the lowland and net subsidence. Much of the accomodation space within which thick sections of Quaternary strata are locally preserved (see, for example, Jones, 1996) could have formed by subglacial and interglacial erosion.

During the last glacial episode—the Vashon stade of the Fraser Glaciation of Armstrong and others (1965)—the Cordilleran ice sheet overrode all of the Kitsap Peninsula. Maximum ice thickness at Bremerton was about 900 m (Thorson, 1980). The Vashon-age ice sheet advanced south from the Coast Mountains of British Columbia, is inferred to have reached Bremerton by about 17,400 calibrated years ago, advanced to a maximum extent south of Olympia, and then retreated rapidly; Kingston was ice free by about 16,300 years ago (Porter and Swanson, 1998). Vashon-age deposits, which locally exceed 100 m in thickness, include extensive (though localized) advance outwash deposits, an intermittent sheet of till that has been described as dense lodgement till, and significant recessional-outwash deposits (see, for example, Deeter, 1979; Yount and others, 1993; Haeussler and Clark, 2000; Booth and Troost, 2005; Haugerud, 2005).

The Salish Lowland was glaciated many times prior to the Fraser Glaciation (Booth and others, 2004) but, because of extensive deposition and local erosion during the Vashon stade, all details of the Kitsap Peninsula landscape are Vashon age or younger. Surfaces at elevations above about 140 m may, in part, preserve an earlier history (Booth, 1994), but it is likely that they were significantly reworked during Vashon time. Landscape surfaces on the Kitsap Peninsula were formed in three phases: ice-sheet glaciation; deglaciation, including large changes in local base level due to isostatic rebound; and ongoing Holocene erosion and deposition. Locally, significant uplift associated with large late Holocene earthquakes on the Seattle and Tacoma Faults has preserved mid-Holocene beach surfaces and valley floors.

LATE PLEISTOCENE GLACIATION

The Kitsap Peninsula comprises a low-relief upland cut by broad troughs (for example, all the marine waterways, Dewatto valley, lower Tahuya valley, Gorst-Belfair valley, Long Lake valley) and punctuated by a few isolated highs (Green and Gold mountains). Booth (1994) suggested that the low-relief upland formed as a broad plain, leveled and filled by meltwater streams issuing from the advancing Vashon-age Cordilleran ice sheet. The troughs must have formed afterwards, as they are incised into the upland, but before the ice sheet decayed, as they are modified by glacial scour. Subglacial fluvial erosion is the likely genesis of the troughs (Booth, 1994). Upland, troughs, and isolated highs are strongly overprinted by glacial scour and subsequent erosion and (or) deposition and are not distinguished on this map.

Most of the Kitsap Peninsula preserves a little-modified glaciated surface that can be divided into several textural types. Where bedding traces are evident, or lumpy topography suggests that the surface is controlled by fractures and other competency contrasts in underlying bedrock, *glaciated bedrock surface* (gb) is mapped. Elsewhere, much of the glaciated surface has long, subparallel flutes and is mapped as *fluted glaciated surface* (gf). At the southwest lobe of the Kitsap Peninsula, in the vicinity of the Tahuya River, flutes are superimposed on transverse rolls, creating a scalloped pattern (*scalloped glaciated surface*, gs). Fluting reflects basal sliding of the ice-sheet (Brown and others, 1987). The mechanism by which scallops developed is not evident. On Bainbridge Island, coastal-bluff outcrops and numerous augured holes demonstrate that much of the fluted surface is not underlain by glacial till; rather, it is eroded into older stratified deposits (Haugerud, 2005).

Locally, transverse ripples that have amplitudes of a few meters and wavelengths of 100 to 300 m are superimposed on fluted and scalloped glaciated surfaces; these areas are mapped as *rippled fluted glaciated surface* and *rippled scalloped glaciated surface* (gfr, gsr). The origin of this rippled ground is unknown. Perhaps it is a form of ribbed or Rogen-moraine (Lundqvist, 1989, 1997), though the rippled ground of Kitsap Peninsula is less extensive than much of the ribbed moraine figured in the literature (for example, Lundqvist, 1989, 1997; Aylsworth and Shilts, 1989). A wide variety of mechanisms have been suggested for formation of such ribbed moraines, including subglacial thrust stacking of basal till and ice, as well as crevassing at the base of an ice sheet and injection of till upwards (or aqueous deposition of sorted material) into the ice fractures.

Some fluted glaciated surface is marked with irregular pits and pockmarks and is mapped as *pockmarked glaciated surface* (gp). Locally, pockmarked ground grades into kame-kettle topography, which suggests that pockmarked ground is also ice melt-out terrain. Pockmarked ground is not end moraine, as it does not outline any plausible ice-sheet margin. Some pockmarked ground appears to lie beneath the enveloping surface defined by surrounding fluted ground, rather than lying above it as dead-ice deposits would. Perhaps it reflects the local incorporation of ice into ground moraine beneath the ice sheet and melting of this ice after ice-sheet movement had ceased.

Locally, the presence of a subtle slope break allows trough walls to be distinguished from adjacent glaciated upland. Below this break the hillside is steeper, and near the toe of the slope the ground is commonly lumpy. I mapped such areas as *glacial trough wall* (gtw).

LATEST PLEISTOCENE DEGLACIATION

A sequence of superposed proximal to distal surfaces record the disappearance of the Vashon-age Cordilleran ice sheet. There are no terminal moraines on the Kitsap Peninsula; thus, I infer that there was no still-stand of the margin of a retreating, actively flowing glacier. In contrast, there is abundant evidence for the presence of undeforming ice and, thus, the strong presumption that the ice sheet thinned, stopped moving, and then melted in place.

The most proximal deglacial features are somewhat enigmatic, rounded *channels* (ch) that are eroded across fluted and scalloped glaciated surfaces. The sinuous forms and relatively low width/depth ratios of these channels argue strongly that they were carved by flowing water. Many channels start on a hillside, cross the adjacent ridge crest, and end on the opposite hillside, without evident source or sink; this seems to require that they formed beneath the ice sheet. The lack of subsequent smoothing indicates that the ice sheet was no longer moving. The U-shaped cross sections of these channels, in contrast to the V-shaped sections of Holocene gullies, suggest that the channels were wetted entirely and not formed by shallow streams that undercut adjacent hillslopes that were dominated by mass wasting. Some channels (for example, 5 km northwest of Belfair and 2 km north-northeast of Burley) were sourced from, and (or) flowed to, outwash flats.

Intimately associated depositional flats, ice-melt hollows, and related slumps present in the Union River valley between Gorst and Belfair, in the upper Tahuya River drainage, and elsewhere are mapped as *kame-kettle surface* (kk). Locally, individual *kettles* (k) and *eskers* (e) are distinguished. Like the channels described in the previous paragraph, these features record melting of static ice. They differ by (1) evidence of significant deposition and (2) evidence that water flow was dominantly parallel to earlier ice-sheet flow, as evidenced by the trend of glacial flutes. Localization of kame-kettle topography implies that certain parts of the ice sheet were especially rich in debris and (or) that meltwater streams concentrated debris in certain zones within or at the margin of the decaying ice sheet.

Streams that drained the decaying ice sheet eroded and deposited extensive alluvial flats. These latest Pleistocene outwash surfaces are distinguished from Holocene alluvial flats by their perched positions and, in some cases, by their association with underfit modern streams. The retreating ice front and ongoing isostatic rebound established several base levels for these outwash streams. I exploited this history of changing base level to assign relative ages to outwash features largely on the basis of their elevation relative to an approximate late-glacial vertical datum (Fig. 1) that rises to the north at 1 m/km (Thorson, 1989). When assigning relative ages to outwash surfaces, I also considered the necessity of an ice-sheet source for many streams, constraints from outside the map area on the position of the ice-sheet margin, and the likelihood that Thorson's simple model for isostatic rebound is not exact.

Outwash flats of Russell age (owr)—By the time the southern Kitsap Peninsula was ice free, a large lake had been established in the southern Puget Lowland. Impounded on the north by the ice margin and drained to the south into the Chehalis River via a spillway at Black Lake, glacial Lake Russell, which was named by Bretz (1913) for geologic pioneer Israel Russell (see Willis, 1898), included the present-day area of southern Puget Sound and adjoining low-elevation areas. Slightly higher glacial Lake Hood (Thorson, 1989) occupied Hood Canal and drained into glacial Lake Russell via a large channel-and-delta complex that extended from the lower Skokomish River valley to Shelton, south of the Kitsap Peninsula. After further ice retreat, the Clifton channel south of Belfair, situated at an isostatic-compensation-restored lower elevation, opened and connected glacial Lakes Hood and Russell (Thorson, 1989). Extensive alluvial flats south and southwest of Port Orchard, southwest of Gorst, along the Tahuya River, in the Rensland and Anderson Creek drainages, in the Chico Creek drainage, near Bangor, and, locally, west of Big Valley north of Poulsbo were graded to glacial Lake Russell. The large flat several kilometers northwest of Long Lake provides especially clear evidence for an ice margin immediately to the north that provided a source for meltwater. Russell-age flats near Chico Creek probably record flow of meltwater to the west and north, as evidence suggests that Hood Canal cleared of ice early during recession, before the central part of Puget Sound.

Outwash flats of Bretz age (owb)—As the ice sheet thinned and the ice margin retreated, a new, lower elevation drainage outlet opened west of northern Hood Canal, draining north into Port Discovery and the eastern Strait of Juan de Fuca (northwest of the Kitsap Peninsula). Waitt and Thorson (1983) named the resulting lower elevation lake glacial Lake Bretz, after J Harlan Bretz. Unpublished geomorphic mapping of eastern Jefferson County has shown that glacial Lake Bretz had several spillways, each farther north and at a lower elevation than its predecessors, and that the highest glacial Lake Bretz spillway was almost at the elevation of glacial Lake Russell (contrast with Thorson, 1980, 1989). The lowest Bretz spillway was not much higher than coeval local sea level. As a result, it is, in places, difficult to distinguish glacial Lake Bretz-associated features from features associated with glacial Lake Russell or the marine limit.

At about the same time as the establishment of glacial Lake Bretz, the retreating ice margin opened a drainage path from Poulsbo to Lofall and allowed glacial Lake Russell to drain to the northwest. On the Kitsap Peninsula, the most extensive alluvial flats graded to glacial Lake Bretz are along the Poulsbo channel. Bretz-age outwash flats also are present south of Hansville, north of Indianola, and west of Brownsville. In all of these locales, the coeval ice-sheet margin must have been nearby, either to provide a source for meltwater or to block lower elevation alternate drainage paths. Minor Bretz-age flats in the lower Tahuya River drainage probably formed as the Tahuya River re-equilibrated to a lower, post-Russell base level, quarrying upstream deposits and redepositing the debris in the lower reaches of the Tahuya glacial trough.

Outwash flats graded to marine limit (owm)—After further retreat of the ice margin, Admiralty Inlet opened and Hood Canal and Puget Sound became marine. Isostatic compensation for the weight of the Cordilleran ice sheet and delayed rebound resulted in an initial marine shoreline that was, at the north end of the Kitsap Peninsula, some 30 m above present-day sea level (Dethier and others, 1995). As isostatic rebound continued, shorelines descended the hillsides to eventually reach positions below present-day sea level (Dethier and others, 1995; Clague and James, 2002). Increasing global ocean volume brought local relative sea level back to near-present-day levels in the early or middle Holocene (Mathews and others, 1970; Clague, 1989; Clague and James, 2002). If the extensive alluvial flat north of Lofall is of Bretz age, as shown on the map, one implication is that Hood Canal was connected to the world ocean before Puget Sound was; otherwise, there would not have been sufficient discharge through Big Valley north of Poulsbo to construct the Lofall flat.

At the downstream ends of some outwash flats are deltas. Delta tops are mapped as outwash flats, and the sloping fronts of apparent constructional origin are mapped as delta fronts. Beyond delta fronts and elsewhere, low-elevation surfaces smoothed by sublacustrine and (or) submarine deposition and (possibly) erosion are identifiable locally.

The ages of some alluvial surfaces are indeterminate. This is largely because the late Pleistocene marine limit coincided with modern sea level at the latitude of central Bainbridge Island, and, thus, certain surfaces are plausibly assigned either a latest Pleistocene age or a Holocene age. The ages of alluvial surfaces in closed basins are also indeterminate, as they could have formed at any time between deglaciation and the present. Alluvial-fan surfaces also are not differentiated by relative age because in very few places can one rule out the possibility that they are entirely Holocene.

Upon deglaciation, undercutting by stream and wave erosion and consequent mass wasting began forming surfaces mapped as *hillslope* (h) and *landslide* (ls). Many of these surfaces are Holocene, but a significant fraction, such as those hillslopes that formed adjacent to and above outwash flats, are clearly latest Pleistocene. I have not attempted to differentiate hillslope and landslide surfaces of differing ages.

In the Seabeck Creek drainage, west of Gorst, along the coast between Brownsville and Keyport, and elsewhere, hillslopes are segmented, with higher elevation, less steep slopes (h0) and lower elevation steeper slopes (h). Both steeper and less steep slopes have relatively constant internal slopes and distinct upper and lower bounding slope breaks. These observations rule out the lessening of slope angles by diffusion and suggest that the higher, less steep slopes formed in earlier, different conditions—perhaps without vegetation—when the angle of repose was less. Different slope gradients could reflect differences in substrate strength; however, in the Seabeck drainage and north of Brownsville, the disposition of steeper and less steep slopes is not controlled by elevation, which argues against substrate control because the underlying geologic units are approximately horizontal (Deeter, 1979; unpublished mapping).

A majority of the mapped landslides are probably of late Holocene age, as they are localized along actively incising streams and the modern, late Holocene, marine shoreline. Some low-relief landslides nestled amid the glaciated upland (for example, the queried landslides northwest of Long Lake) may have formed in late Pleistocene time as the Vashon-age ice sheet melted and subjacent slopes lost their ice buttress. Shallow debris flows observed in the field along the coastal bluffs commonly are not evident in the lidar DEM. This suggests that those landslides that are evident in the lidar DEM are deep seated. For an independent estimate of landslide extent that is based on interpretation of the same lidar DEM, see McKenna and others (2008).

HOLOCENE EVENTS

A variety of surfaces are forming and being maintained by present-day processes. As noted above, many hillslope, landslide, and alluvial-fan surfaces are modern. Some alluvial flats grade to modern base level. Wetland surfaces are active today, though some may not have changed much since latest Pleistocene deglaciation.

Local relative sea level appears to have generally risen through the early Holocene and locally stabilized at near-modern levels in the mid-Holocene (Shipman, 1990). Beach surfaces in equilibrium with modern sea level are, thus, no older than mid-Holocene.

A large earthquake in the Seattle Fault Zone at about A.D. 900 (Atwater, 1999) uplifted a region that extends from Eagle Harbor south to Blake Island and west at least as far as Ostrich Bay (Bucknam and others, 1992; Sherrod and others, 2000). As much as 9 m of uplift isolated and preserved now-fossil beach surface—largely equivalent to the modern beach face and tideflat—that is present around the south end of Bainbridge Island, especially at Restoration Point and Rockaway Beach; along the Kitsap Peninsula shoreline from Southworth to the town of Port Orchard; and locally along the south shore of Dyes Inlet (Harding and others, 2002). It is likely that the extensive near-shore flat upon which the Bremerton shipyard was constructed is also fossil beach, although this is obscured by extensive human modification of the topography. Stranded alluvial flats (mapped as unit al) in lower Seabeck Creek valley and the middle reach of Big Beef Creek may also record late Holocene uplift above the Seattle Fault. Haugerud and Tabor (2008) observed that deformed Russell-age outwash flats in the vicinity of William Symington Lake suggest at least 24 m of postglacial differential uplift, indicating perhaps three large earthquakes in latest Pleistocene and Holocene time.

At about the same time as the A.D. 900 earthquake on the Seattle Fault, one or more large earthquakes on the Tacoma Fault (Sherrod and others, 2004), which lies south of the map area, uplifted an area to the north of the fault. Nearshore flats at the mouth of the Tahuya River, Lynch Cove, North Bay, and Burley Lagoon were uplifted and preserved by this event. Portions of the mid-Holocene Coulter Creek and Burley Creek alluvial flats were also uplifted and preserved by this event.

Distinct Holocene surface ruptures are recognized in several places. The Toe Jam Hill scarp, which crosses Bainbridge Island south of Blakely Harbor, was trenched at several locations, and multiple late Holocene faulting events were confirmed (Nelson and others, 2003a). Faulting along the Macs Pond scarp, about two-thirds kilometer north of Blakely Harbor, also has been confirmed by trenching (Brian L. Sherrod, oral commun., 2003). An unnamed west-northwest-trending scarp two-thirds kilometer farther north also appears to be the result of faulting, as it is similar in character to the Macs Pond scarp (Haugerud, 2005). South of Rich Passage, trenching has confirmed that late Holocene faulting produced the Waterman Point scarp (Nelson and others, 2003b). All of these scarps lie within the Seattle Fault Zone. South and east of Belfair, the northeast-trending Sunset Beach scarp probably is the result of faulting, although trench studies (Alan Nelson, oral commun., 2006) are unable to rule out the possibility that this feature is the headscarp of a very unusual large landslide.

NOTE ON BASE MAP

This map is published with a custom base that includes a minimum of detail. Existing maps of roads, stream courses, and shorelines—for example, standard U.S. Geological Survey 7.5' quadrangle maps at 1:24,000 scale—generally are not as accurate as the high-resolution lidar topography from which I interpreted this geomorphic map. Base map features include a shaded-relief topographic image, calculated from the 30-ft DEM compiled by Finlayson (2005) that merges the lidar topography with available bathymetric data; 10-m contours calculated from the 30-ft DEM; Public Land Survey System (township, range, and section) lines obtained from Washington Department of Natural Resources (http://www3.wadnr.gov/dnrapp6/dataweb/dmmatrix.html); and stream courses from USGS 1:100,000-scale digital line graphs (DLGs). In many places, mapped stream courses do not correspond to the detailed topography. There are many minor errors in the contours, especially along shorelines, where the surface interpolated from individual lidar points has bridged from the bluff to the beach, and in some densely forested areas where no lidar ground returns were identified.

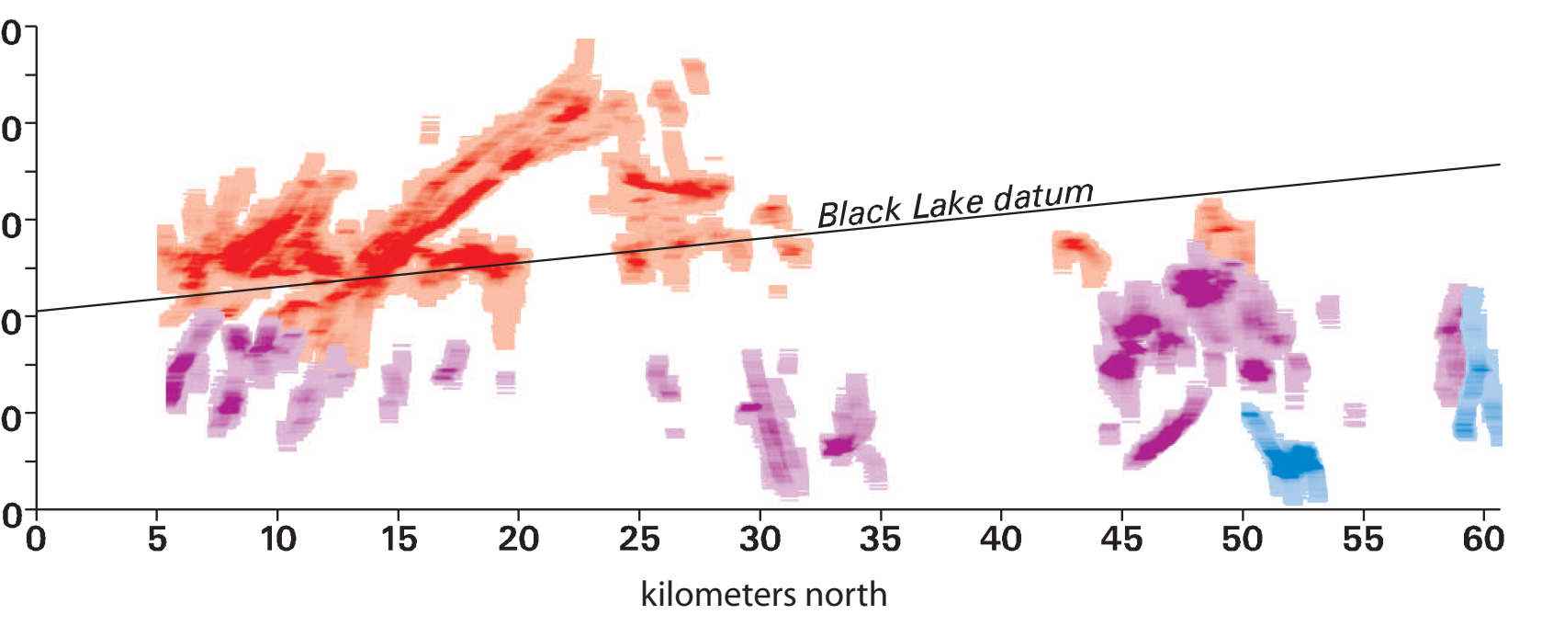


Figure 1. Elevations of Kitsap Peninsula outwash surfaces projected onto north-south section. Elevations grouped by age: red, Russell; violet, Bretz; blue, marine maximum. Color saturation corresponds to relative abundance of elevations within each group. *Black Lake datum* is approximate late-glacial horizontal surface that is at present-day elevation of 42 m at Black Lake, south of Olympia, and rises 1 m/km to north because of postglacial isostatic rebound (Thorson, 1989). Too-low elevations for some Russell-age outwash surfaces and overlapping elevation ranges reflect departures from Thorson's simple 1 m/km up-to-north isostatic rebound model, original nonzero stream gradients, subsequent tectonic deformation, minor digitizing errors and errors in DEM, and, perhaps, erroneous assigned ages. Values of "kilometers north" (horizontal axis) are measured from south edge of map area.

ACKNOWLEDGMENTS

I thank my colleagues in the Puget Sound Lidar Consortium, including David Harding (NASA), Jerry Harless and Diana Martinez (Puget Sound Regional Council), Phyllis Mann (Kitsap County), and Sam Johnson and Craig Weaver (USGS) for their efforts to acquire high-resolution public-domain lidar data for the Puget Lowland. Discussions with Richard Pike (USGS) have been helpful. Reviews by Kevin Schmidt (USGS) and Kathy Troost (University of Washington) have led to substantial improvements in this map.

REFERENCES CITED

Anonymous, 1983, North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841–875.

Armstrong, J.E., Crandell, D.R., Easterbrook, D.J., and Noble, J.B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, p. 321–330.

Atwater, B.F., 1999, Radiocarbon dating of a Seattle earthquake to A.D. 900-930 [abstract]: Seismological Research Letters, v. 70, p. 232.

Aylsworth, J.M., and Shilts, W.W., 1989, Bedforms of the Keewatin ice sheet, Canada: Sedimentary Geology, v. 62, p. 407–428.

Booth, D.B., 1994, Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation: Geology, v. 22, p. 695–698.

Booth, D.B., and Troost, K.G., 2005, Geologic map of the Olalla 7.5' quadrangle, King, Kitsap, and Pierce Counties, Washington: U.S. Geological Survey Scientific Investigations Map 2902, scale 1:24,000, http://pubs.usgs.gov/sim/2005/2902.

Booth, D.B., Troost, K.G., Clague, J.J., and Waitt, R.B., 2004, The Cordilleran ice sheet, *in* Gillespie, A.R., Porter, S.C., and Atwater, B.F., editors, The Quaternary Period in the United States, International Union for Quaternary Research, Elsevier Press, p. 17-43.

Bretz, J H., 1913, Glaciation of the Puget Sound region: Washington Geological Survey Bulletin 8, 244 p.

Brown, N.E., Hallet, B., and Booth, D.B., 1987, Rapid soft bed sliding of the Puget glacial lobe: Journal of Geophysical Research, B, Solid Earth and Planets, v. 92, p. 8985-8997.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, Abrupt uplift within the past 1,700 years at southern Puget Sound, Washington: Science, v. 258, p. 1611-1614.

Clague, J.J., 1989, Late Quaternary sea level change and crustal deformation, southwestern British Columbia: Geological Survey of Canada Paper 89-1E, p. 233-236.

Clague, J.J., and James, T.S., 2002, History and isostatic effects of the last ice sheet in southern British Columbia: Quaternary Science Reviews, v. 21, p. 71-87.

Deeter, J.D., 1979, Quaternary geology and stratigraphy of Kitsap County, Washington: M.S. thesis, Western Washington University, Bellingham, 175 p., map scale about 1:48,000.

Dethier, D.P., Pessl, F., Keuler, R.F., Balzarini, M.A., Pevear, D.R., 1995, Late Wisconsinan glaciomarine deposition and isostatic rebound, northern Puget Lowland, Washington: Geological Society of America Bulletin, v. 107, p. 1288-1303.

Dragovich, J.D., Logan, R.L., Schasse, H.W., Walsh, T.J., Lingley, W.S., Jr., Norman, D.K., Gerstel, W.J., Lapen, T.J., Schuster, J.E., and Meyers, K.D., 2002, Geologic map of Washington--Northwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-50, 3 sheets, scale 1:250,000, with 72 p. text.

Finlayson, D.P., 2005, Combined bathymetry and topography of the Puget Lowland, Washington State: University of Washington, http://www.ocean.washington.edu/data/pugetsound/

Giles, P.T., 1998, Geomorphological signatures; classification of aggregated slope unit objects from digital elevation and remote sensing data: Earth Surface Processes and Landforms, v. 23, p. 581–594.

Gustavsson, M., Kolstrup, E., and Seijmonsbergen, A.C., 2006, A new symbol-and-GIS based detailed geomorphological mapping system: Renewal of a scientific discipline for understanding landscape development: Geomorphology, v, 77, p. 90-111.

Haeussler, P.J., and Clark, K.P., 2000, Geologic map of the Wildcat Lake 7.5' quadrangle, Kitsap and Mason Counties, Washington: U.S. Geological Survey Open-file Report 00-356, scale 1:24,000, http://geopubs.wr.usgs.gov/open-file/of00-356.

Harding, D.J., and Berghoff, G.S., 2000, Fault scarp detection beneath dense vegetation cover: Airborne lidar mapping of the Seattle fault zone, Bainbridge Island, Washington State: Proceedings of the American Society of Photogrammetry and Remote Sensing Annual Conference, Washington, D.C., May, 2000, 9 p. See http://pugetsoundlidar.ess.washington.edu/data/raster/lidar/harding.pdf.

Harding, D.J., Johnson, S.Y., and Haugerud, R.A., 2002, Folding and rupture of an uplifted Holocene marine platform in the Seattle fault zone, Washington, revealed by airborne laser swath mapping: Geological Society of America Abstracts with Programs, v. 34, no. 5, p. A-107.

Haugerud, R.A., 2004, Cascadia—Physiography: U.S. Geological Survey, Map I-2689, scale 1:2,000,000.

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

Haugerud, R.A., and Harding, D.J., 2001, Some algorithms for virtual deforestation of lidar topographic survey data: International Society for Photogrammetry and Remote Sensing, Commission 3, Working Group 3, Annapolis, MD, 7 p., http://www.isprs.org/commission3/annapolis/pdf/Haugerud.pdf

Haugerud, R.A., Harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S., and Sherrod, B.L., 2003, High-resolution topography of the Puget Lowland, Washington—A bonanza for earth science: GSA Today, v. 13, n. 6, p. 4-10.

Haugerud, R.A., and Tabor, R.W., 2008, Geomorphic evidence for multiple large post-glacial earthquakes on the western Seattle Fault: Eos Trans. AGU, v. 89, Fall Meet. Suppl., Abstract T23-05,

Johnson, S.Y., Potter, C.J., and Armentrout, J.M., 1994, Origin and evolution of the Seattle fault and Seattle basin, Washington: Geology, v. 22, p. 71-74.

Jones, M.A., 1996, Thickness of unconsolidated deposits in the Puget Sound Lowland, Washington and British Columbia: U.S. Geological Survey Water-Resources Investigations Report 94-4133, map scale 1:455,000.

Kitsap County GIS, 2006, Wetland mosaic (GIS data layer): available at http://www.kitsapgov.com/gis/metadata/

Lundqvist, J., 1989, Rogen (ribbed) moraine—identification and possible origin: Sedimentary Geology, v. 62, p. 281–292.

Lundqvist, J., 1997, Rogen moraine—an example of two-step formation of glacial landscapes: Sedimentary Geology, v. 111, p. 27–40.

Mathews, W.H., Fyles, J.G., and Nasmith, H.W., 1970, Postglacial crustal movements in southwestern British Columbia and adjacent Washington State: Canadian Journal of Earth Sciences, v. 7, p. 690-702.

McKenna, J.P., Lidke, D.J., Coe, J.A., 2008, Landslides mapped from LIDAR imagery, Kitsap County, Washington: U.S. Geological Survey Open-File Report 2007–1292, 81 p., http://pubs.usgs.gov/of/2008/1292/

Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Wells, R.E., Sherrod, B.L., Pezzopane, S.K., Bradley, L., Koehler, R.D., and Bucknam, R.C., 2003a, Late Holocene earthquakes on the Toe Jam Hill fault, Seattle fault zone, Bainbridge Island, Washington, Geological Society of America Bulletin, v. 115, p. 1388-1403.

Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Sherrod, B.L., Wells, R.E., Okamura, K., Bradely, L., Bogar, R., and Personius, S.F., 2003b, Field and laboratory data from an earthquake history study of the Waterman Point fault, Kitsap County, Washington: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2423, http://pubs.usgs.gov/mf/2003/mf-2423.

Porter, S.C., and Swanson, T.W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, p. 205-213.

Salomé, A.I., and van Dorsser, H.J., 1982, Examples of 1:50,000-scale geomorphological maps of part of the Ardennes: Zeitschrift für Geomorphologie N.F., v. 26, p. 481–489.

Sherrod, B.L., Bucknam, R.C., and Leopold, E.B., 2000, Holocene relative sea-level changes along the Seattle fault at Restoration Point, Washington: Quaternary Research, v. 54, p. 384-393.

Sherrod, B.L., Brocher, T.M., Weaver, C.S., Bucknam, R.C., Blakely, R.J., Kelsey, H.M., Nelson, A.R., and Haugerud, R., 2004, Holocene fault scarps near Tacoma, Washington, USA: Geology, v. 32, p. 9-12.

Shipman, H., 1990, Vertical land movement in coastal Washington: Washington Geologic Newsletter, v. 18, no. 1, p. 26-32.

ten Brink, U.S., Molzer, P.C., Fisher, M.A., Blakely, R.J., Bucknam, R.C., Parsons, T., Crosson, R.S., and Creager, K.S., 2002, Subsurface geometry and evolution of the Seattle fault zone and the Seattle basin, Washington: Bulletin of the Seismological Society of America, v. 92, p. 1737-1753.

Thorson, R.M., 1980, Ice sheet glaciation of the Puget Lowland, Washington, during the Vashon stade: Quaternary Research, v. 13, p. 303–321.

Thorson, R.M., 1989, Glacio-isostatic response of the Puget Sound area, Washington: Geological Society of America Bulletin, v. 101, p. 1163-1174.

U.S. Geological Survey, 1999, Map Accuracy Standards: USGS Fact Sheet FS-171-99, http://egsc.usgs.gov/isb/pubs/factsheets/fs17199.html

Waitt, R.B., Jr., and Thorson, R.M., 1983, The Cordilleran ice sheet in Washington, Idaho, and Montana: *in* H.E. Wright, Jr., editor, 1983, Late-Quaternary Environments of the United States, Volume 1: The Late Pleistocene (Stephen C. Porter, editor): University of Minnesota Press, 407 p., Chapter 3, p.53-70.

Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Fore arc migration in Cascadia and its neotectonic significance: Geology, v. 26, p. 759-762.

Willis, B., 1898, Drift phenomena of the Puget Sound: Geological Society of America Bulletin, v. 9, p. 111–162.

Yount, J.C., Minard, J.P., and Dembroff, G.R., 1993, Geologic map of surficial deposits in the Seattle 30' x 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.

DESCRIPTION OF MAP UNITS

HOLOCENE SURFACES

m	**Modified land**—Filled and (or) graded area. Generally not mapped except along major roads and where filling and grading is sufficiently extensive to preclude inference of precursor surface. Locally, mapped as:
f	**Artificial fill**—Surface of fill bodies beneath highways and railways, mapped because of possibility of failure during severe seismic shaking
w	**Wetland**—Planar surface of low slope. Mapped on basis of geometry, position in topographic lows, and distinctive surface texture that probably reflects wetland vegetation. Identification as wetland corroborated by approximate correspondence with third-party wetland inventories (Kitsap County GIS, 2006) and limited field checking
hal	**Holocene alluvial flat**—Stream valley floor. Recognized by low slope, planarity, and position in topographic lows along active drainage paths
bs	**Backshore area**—Flat built by modern beach accretion. Elevation near mean high water. Commonly has distinct berm crest at seaward edge. Locally, mapped as:
lag	**Lagoon**—Areas within backshore that commonly are flooded at high tide
bf	**Beach face**—Steeper upper beach, commonly above mean low-water elevation. At upper edge, bounded by berm crest or toe of bluff
tf	**Tide flat**—Low-slope lower beach. Commonly at elevations below mean lower low-water; higher at heads of inlets
ohal	**Older alluvial flat**—Mid-Holocene stream valley floor, uplifted and isolated by one or more large earthquakes at about 900 AD
ob	**Old beach**—Fossil beach at supra-tidal elevations. Mapped at heads of Lynch Cove, North Bay, Burley Lagoon, in Manchester-Port Orchard area, and on southern Bainbridge Island. May include equivalents of modern backshore, beach face, and tide flat. In all locales, presence records coseismic uplift during one or more large earthquakes at about A.D. 900. Locally, mapped as:
obb	**Old beach berm**—Low ridge along former shoreline

HOLOCENE AND LATEST PLEISTOCENE SURFACES

al	**Alluvial flat**—Stream-shaped surface, either depositional or strath. Could be latest Pleistocene or Holocene in age. Locally (for example, west of Harper) includes nearshore flat formed by wave action
af	**Alluvial fan**—Moderately sloping (mostly 2-5º) surface, mostly conic, at drainage confluences and along toes of valley walls. Slope suggests sediment transport is dominated by debris flow or infrequent floods
h	**Hillslope**—Steep (commonly, 20-35º) surface that appears to be dominated by colluviation, debris-flow, shallow-landslide, and other mass-movement processes. Mostly with distinct breaks in slope at upslope and downslope margins. Cut into adjacent topography. As mapped, includes narrow alluvial flat on floors of minor gullies. Lack of significant rounding at tops and toes of hillslope suggests that, in this terrain and in limited age of these slopes, diffusive processes have not been significant. For clarity, most small areas of unit are unlabelled. Locally, mapped as:
h0	**Older hillslope**—Lower gradient slope located uphill of hillslope that have higher, more typical gradients. Position and lower gradient argue that older hillslope developed in a regime of lower slope stability, perhaps without vegetation cover
r	**Rilled slope**—Steep older, glaciated surface dissected by pervasive minor parallel gullies
ls	**Landslide**—Surface of deep-seated landslide, recognized by uphill scarps, bulbous toes, position in hillslope hollows, and (locally) rumpled surface. Queried where identity as landslide is less certain. Some landslides, particularly those nestled in glaciated upland, may be inactive and stable in current conditions

LATEST PLEISTOCENE SURFACES

sm	**Submarine surface**—Older surface, mostly glacial; smoothed by tidal and subtidal currents, marine deposition, and wave action. Mapped on basis of subdued topography and position below late Pleistocene marine limit
owm	**Outwash flat graded to marine limit**—Alluvial flat graded to upper limit of latest Pleistocene marine waters
df	**Delta face**—Smooth moderate-slope surfaces at and below opening of alluvial flats onto lower elevation areas. Larger delta fronts and associated delta tops are common sites for quarries (mapped as modified land, unit m). Queried where identity is less certain
owb	**Outwash flat of Bretz age**—Alluvial flat graded to glacial Lake Bretz. Queried where Bretz age is less certain
owr	**Outwash flat of Russell age**—Alluvial flat graded to glacial Lake Russell. Russell-age alluvial flats in Union River and Burley Creek drainages, and perhaps elsewhere, formed as kame terraces confined between valley walls and now-absent ice. Locally (for example, west of Belfair, east of Burley) includes some surfaces carved by wave action along shore of glacial Lake Russell
sl	**Sublacustrine surface**—Older surface, mostly glacial; smoothed by subaquatic slumping and lacustrine deposition. Mapped on basis of subdued topography and position
kk	**Kame-kettle surface**—Irregular ground characterized by steep-walled closed depressions (kettles), collapse features, eskers, and common alluvial flats. Locally, mapped as:
e	**Esker**—Sinuous narrow ridge
k	**Kettle**—Closed depression that has moderately to steeply sloping sides; commonly embedded in outwash flat
ch	**Channel**—Smooth-walled channels, apparently water-carved, but without apparent source or sink for flowing water. As mapped, includes both near-horizontal floors and steeper walls. Most have smooth transitions between floor and wall. Lack of floor-wall slope break suggests that channels were entirely filled with flowing water, not carved by water flowing across floor and subsequent collapse of valley sidewalls. Lack of obvious source or sink suggests presence of surrounding ice when channels formed

LATE PLEISTOCENE GLACIAL SURFACES

g	**Glaciated surface**—Ground modified by flowing ice. Mostly subdivided into:
gf	**Fluted glaciated surface**—Characterized by well-organized flutes that have elongation ratios (length/width) typically greater than 10. Flutes are typically hundreds of meters wide, heights are 10 to 30 m. Locally, mapped as:
gfr	**Rippled fluted glaciated surface**—Fluted glacial surface that has transverse ripples or "chatter marks." Wavelengths of transverse ripples are 40 to 100 m. Ripple height can be as great as a few meters; perhaps ripples originated as crevasse fillings
gs	**Scalloped glaciated surface**—Characterized by well-developed swales that cross fluted surface and form nearly equant hills that have diameters of about 1 km and heights of 10 to 40 m. Most hills are mantled with typical flutes. Locally, mapped as:
gsr	**Rippled scalloped glaciated surface**—Scalloped glaciated surface that has transverse ripples
gp	**Pockmarked glaciated surface**—Weakly fluted ground that has irregular pits and lumps. In many places, appears to be gradational between rippled glaciated surfaces and kame-kettle topography
gtw	**Glacial trough wall**—Steep, ice-molded surface; commonly has distinct slope break at up-slope margin; commonly is transverse to general direction of ice flow; commonly grades to lumpy ice-disintegration terrane at base of slope
gb	**Glaciated bedrock surface**—Ice-modified ground that has lumps or transverse ribs (eroded bedding) indicative of erosion from bedrock rather than from unconsolidated material. Queried where identity is less certain

EXPLANATION OF MAP SYMBOLS

contact—Contacts between units kk, g, gf, gfc, gs, gsc, gp, gtw, and gb commonly are indistinct boundaries drawn at subtle changes in surface texture; these contacts are shown as scratch boundaries without a black line

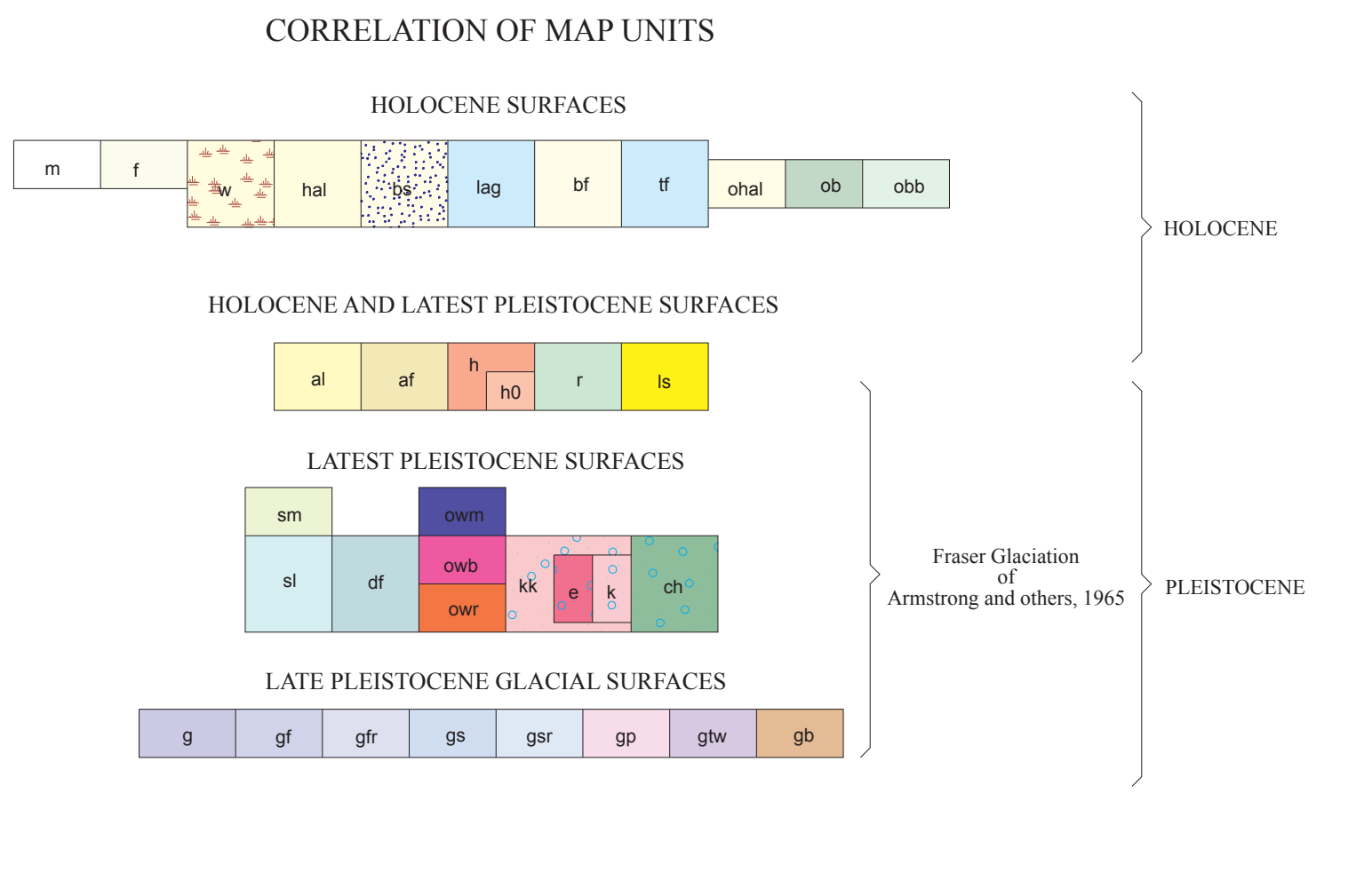
waterline—Edge of water body at time lidar data were acquired. Lateral position and elevation vary with tide stage

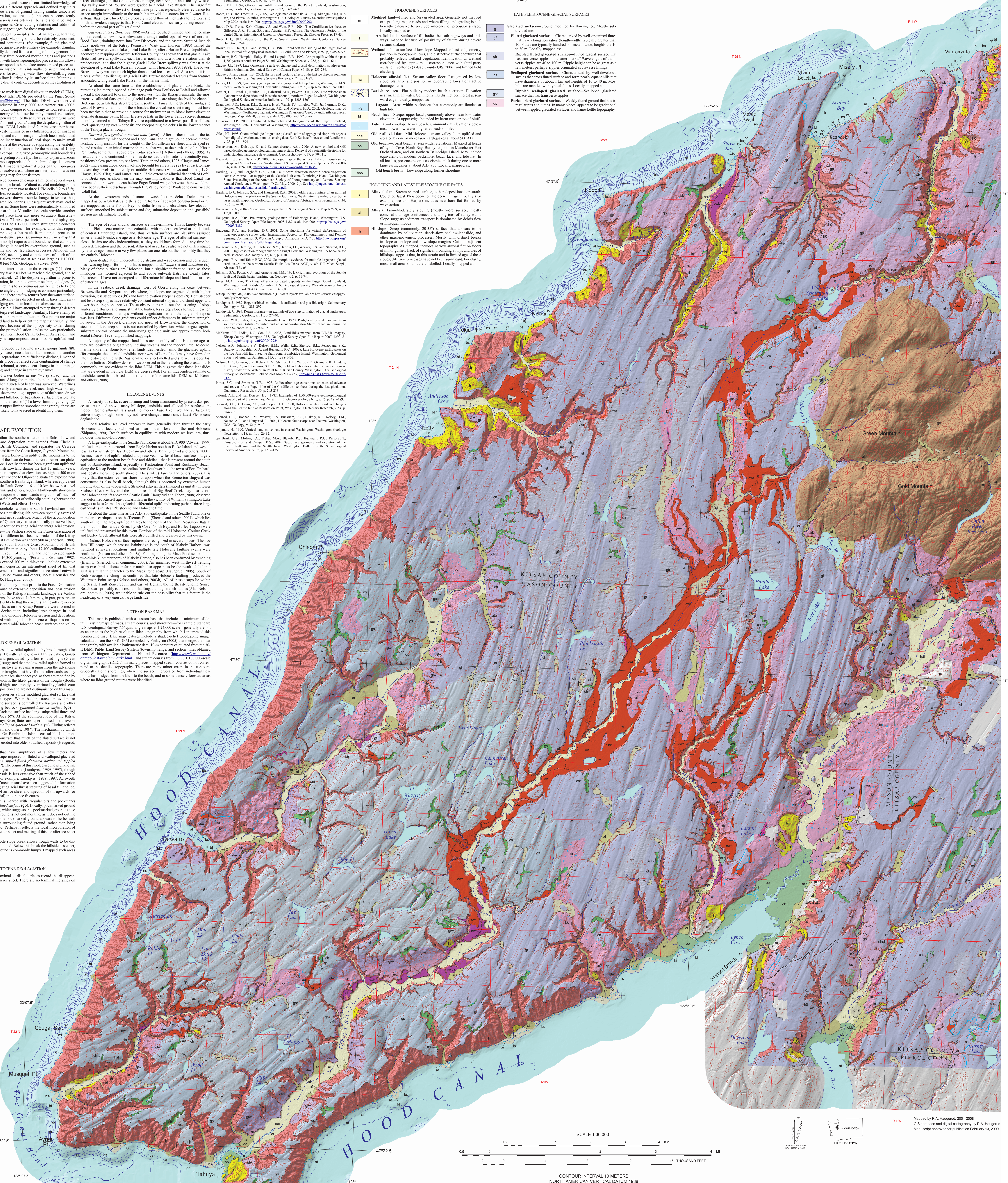
shoreline—Morphologic break at uphill edge of modern marine beach, commonly at base of shoreline bluff (shoreline angle of many authors)

possible late Pleistocene shoreline—Morphologic discontinuity inferred to mark former marine or lacustrine shoreline

fault scarp—Aligned minor scarps and gullies formed by surface rupture, commonly somewhat degraded by subsequent scarp collapse

CORRELATION OF MAP UNITS





SCALE 1:36 000

CONTOUR INTERVAL 10 METERS
NORTH AMERICAN VERTICAL DATUM 1988
BATHYMETRIC CONTOUR INTERVAL 10 METERS

Washington State Plane projection, north zone, NAD83
Map base:
Shaded relief, topographic contours, and bathymetric contours calculated from 30-ft digital elevation model compiled by Finlayson (2005)
Public Land Survey System (township, range, and section lines) and county boundaries from Washington Dept. Natural Resources
Hydrography from U.S. Geological Survey 1;100,000-scale digital line graphs, Mt Olympus, Seattle, Shelton, and Tacoma 30- by 60-minute quadrangles
Place names modified from Geographic Names Information System, U.S. Geological Survey

Mapped by R.A. Haugerud, 2001-2008
GIS database and digital cartography by R.A. Haugerud
Manuscript approved for publication February 13, 2009

Preliminary geomorphic map of the Kitsap Peninsula, Washington

By

Ralph A. Haugerud
2009

This map was printed on an electronic plotter directly from digital files. Dimensional calibration may vary between electronic plotters and between X and Y directions on the same plotter, and paper may change size due to atmospheric conditions; therefore, scale and proportions may not be true on plots of this map.

For sale by U.S. Geological Survey, Information Services, Box 25286,Federal Center, Denver, CO 80225, 1-888-ASK-USGS
Digital files available at *http://pubs.usgs.gov/of/2009/1033/*